PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE
SCHOOL OF ENGINEERING
AALTO UNIVERSITY
SCHOOL OF ELECTRICAL ENGINEERING

# REGULATION FOR DYNAMIC SPECTRUM MANAGEMENT

**ARTURO BASAURE**

Thesis submitted to Pontificia Universidad Católica de Chile and Aalto University of Finland, in partial fulfillment of the requirements for the Degree of Doctor of Science in Engineering

Advisors:
**RICARDO PAREDES**
**VLADIMIR MARIANOV**
**HEIKKI HÄMMÄINEN**
Santiago de Chile, September, 2016

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## ABSTRACT

Spectrum management is in the core of Internet access and therefore of vital importance for assuring the most important processes of our society. The increasing demand for new services makes the spectrum scarcer and urges *national regulatory authorities* (NRAs) to promote a more efficient spectrum usage. In this context, *dynamic spectrum access* (DSA) technologies and the related *dynamic spectrum management* (DSM) provide new ways of managing spectrum, by dynamically reassigning the underutilized spectrum (i.e. white spaces).

This thesis employs a combined approach consisting of *agent-based modelling* and *system dynamics* to study spectrum management by means of dynamic neo-institutional economics. Thus this work combines transaction cost and evolutionary economics into the modelling and analysis of the constantly evolving ICT ecosystem.
DSA decreases the costs associated with spectrum transactions and help to clearly define spectrum usage rights, and therefore it provides the basic conditions for the Coasean implications on policy, pushing gradually spectrum management towards a property rights regime.

From the analysed scenarios, this thesis shows that indoor deployment is most promising for DSA technologies. Indoor networks transmitting in higher frequency bands require less coordination for achieving mutual benefits from the performed spectrum transactions. Therefore, this thesis emphasizes that spectrum reforms, allowing spectrum transactions, should focus on higher frequency bands and new indoor network deployments, such as small-cells, 5G, IoT and M2M services. NRAs should facilitate flexibility in spectrum assignment in the higher frequency bands, by means of a property rights regime or a flexible licensing regime, to provide indoor deployments with the ability to respond more dynamically to the changes in demand. Moreover, such spectrum reforms may drive spectrum decentralization to stimulate user-centric innovation.

Finally, this thesis compares DSA with other alternative mechanisms, such as national roaming and end-user multihoming. The three compared mechanisms may improve the economic efficiency of mobile networks. In indoor networks, while end-user multihoming and national roaming addresses coverage problems, DSA may increase the efficiency further by addressing congestion problems. In outdoor networks, national roaming and end-user multihoming may improve coverage problems.

**Keywords**: Dynamic spectrum access and management, transaction cost economics, evolutionary economics, agent-based modelling, system dynamics.

PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE
ESCUELA DE INGENIERIA

# REGULACIÓN PARA UN MANEJO DINÁMICO DEL ESPECTRO

Tesis cotutelada entre la Pontificia Universidad Católica de Chile y la Universidad Aalto de Finlandia, para optar al grado de Doctor en Ciencias de la Ingeniería

Arturo Basaure

## RESUMEN

La administración del espectro radioeléctrico está en el corazón del acceso a Internet móvil e inalámbrico y es por eso de importancia vital para asegurar los procesos más importantes de nuestra sociedad moderna. El incremento en la demanda por nuevos servicios urge a las autoridades de regulación nacional (NRAs) a promover un uso más eficiente del espectro. En este contexto, las tecnologías de acceso dinámico del espectro (DSA) y su relacionado manejo dinámico (DSM) pueden proveer nuevos medios para administrar el espectro, asignando dinámicamente aquel espectro que no está siendo eficientemente utilizado (espacios blancos).

Esta tesis combina el modelamiento basado en el agente con la dinámica de sistemas para estudiar el manejo del espectro desde el punto de vista de la economía neo-institucional dinámica. Es decir, este trabajo combina las teorías económicas de costos de transacción con la evolutiva para analizar al ecosistema de las TICs, que se caracteriza por constantes cambios.

DSA disminuye los costos asociados a las transacciones de espectro y ayuda a definir claramente los derechos de uso del espectro. De esta forma, DSA cumple con las condiciones básicas para implementar un esquema Coasiano, llevando al espectro gradualmente a un régimen basado en derechos de propiedad.

Apoyándose en los escenarios analizados, esta tesis muestra que las redes del interior son las más prometedoras para implementar tecnologías DSA. Éstas redes, que transmiten en frecuencias más altas, requieren una menor coordinación para obtener los beneficios mutuos debido a las transacciones de espectro. Por esta razón, esta tesis enfatiza que las reformas a la política de espectro, que persigan permitir transacciones, deberían enfocarse en las frecuencias más altas y en las implementaciones de redes del interior, tales como small-cells, 5G, IoT y servicios M2M. Las autoridades deberían entonces permitir una mayor flexibilidad en la asignación de las frecuencias más altas, ya sea a través de un régimen de derechos de propiedad o a través de un licenciamiento con condiciones flexibles, que permitan a las redes del interior responder con mayor flexibilidad a las volatilidades de la demanda. Más aún, estas reformas deberían llevar a una mayor descentralización del espectro e incentivar una innovación centrada en el usuario final.

Finalmente, esta tesis compara a DSA con otros mecanismos alternativos, tales como roaming nacional y multihoming del usuario final (end-user multihoming). Cada uno de estos tres mecanismos puede mejorar la eficiencia económica de las redes móviles. En las redes del interior, mientras end-user multihoming y roaming nacional solucionan problemas de cobertura, DSA puede adicionalmente aumentar la eficiencia solucionando problemas de congestión. En las redes del exterior, national roaming y end-user multihoming pueden solucionar problemas de cobertura.

**Palabras claves**: Acceso y manejo dinámico del espectro, economía de los costos de transacción, economía evolutiva, modelamiento basado en el agente, dinámica de sistemas.

# Preface

"If you are going through hell, keep going"
—Winston Churchill

"Silloin kun on loppunut, se on loppunut"
—Tapio Soikkeli

This has been a long trip, but a nice one. A trip with smiles and sorrows, with light and darkness, summer and winter. Looking backward I realized that I have been a lucky man, who has worked with extremely valuable people, literally speaking from all around the world.

First of all, I want to show my enormous gratitude to professor Heikki Hämmäinen. He has a deep knowledge of the industry and an extraordinary capacity to put interesting people and topics together into an enjoyable and unique research environment. I have learnt a lot from Heikki, going from the *big picture* (i.e. the general perspective) to the *devil* (i.e. details). I also had the opportunity to share a lot of funny moments with him and the members of his team, for example in the so-called winter and summer events, which included sports, sauna and nice food.

Also I want to thank to my dear supervisors from the PUC of Chile: professors Ricardo Paredes and Vladimir Marianov. They have been extremely flexible, patient and supportive, giving always their perspectives and ideas to continue this thesis as a very unusual cotutelle until a successful completion.

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Helsinki, 19th August 2016
Santiago de Chile, 2nd September 2016

Arturo Basaure

# Contents

# List of Abbreviations

| | |
|---|---|
| 2G | 2nd Generation |
| 3G | 3rd Generation |
| 3GPP | 3rd Generation Partnership Project |
| 4G | 4th Generation |
| 5G | 5th Generation |
| ABM | Agent-based modelling |
| ARPU | Average revenue per user |
| CA | Carrier aggregation |
| CAPEX | Capital expenditures |
| COST | European Cooperation in Science and Technology |
| CR | Cognitive radio |
| CRS | Cognitive radio system |
| D2D | Device-to-device |
| DSA | Dynamic spectrum access |
| DSM | Dynamic spectrum management |
| eSIM | Embedded subscriber identity module |
| ETSI | European Telecommunications Standards Institute |
| FDD | Frequency division duplex |
| IEEE | Institute of Electrical and Electronics Engineers |
| IEFT | Internet Engineering Task Force |
| IoT | Internet of things |
| ISM | Industrial, scientific and medical frequency band |
| ITU | International Telecommunications Union |
| LAA | Licensed assisted access |

| | |
|---|---|
| LAN | Local area network |
| LAO | Local area operator |
| LSA | Licensed shared access |
| LTE | Long term evolution |
| M2M | Machine-to-machine |
| MD | Mobile device |
| MNO | Mobile network operator |
| MNP | Mobile number portability |
| MPTCP | Multi-path transport control protocol |
| MVNO | Mobile virtual network operator |
| NRA | National regulatory authority |
| OPEX | Operational expenditures |
| PAWS | Protocol to Access white space (WS) database |
| PL | Pluralistic licensing |
| PLMN | Public land mobile network |
| PMSE | Programming making and special event |
| QoE | Quality of experience |
| QoS | Quality of service |
| RAN | Radio access network |
| RAT | Radio access technology |
| RF | Radio frequency |
| RRS | Radio reconfiguration system |
| SAS | Spectrum access system |
| SD | System dynamics |
| SDO | Standard developing organization |
| SDR | Software defined radio |
| SIM | Subscriber identity module |
| SINR | Signal to interference and noise ratio |
| TDD | Time division duplex |
| TVWS | TV white space |
| Wi-Fi | Wireless fidelity |

| | |
|---|---|
| WLAN | Wireless local area network |
| WRAN | Wide regional area network |
| WRC | World Radio Conference |
| WSD | White space device |

# List of Publications

This doctoral dissertation consists of a summary and of the following publications which are referred to in the text by their numerals

**1.** Basaure, A., Marianov, V., & Paredes, R. (2014). Implications of dynamic spectrum management for regulation. Telecommunications Policy. Vol 39 (7), 563–579, DOI: 10.1016/j.telpol.2014.07.001

**2.** Basaure, A., Holland, O. (2015). Optimizing spectrum value through flexible spectrum licensing. IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN), 130-141, DOI: 10.1109/DySPAN.2015.7343897

**3.** Kliks, A., Holland, O., Basaure, A., & Matinmikko, M. (2015). Spectrum and license flexibility for 5G networks. IEEE Communications Magazine, 53(7), 42-49, DOI: 10.1109/MCOM.2015.7158264

**4.** Basaure, A; Sridhar, V; Hämmäinen, H. (2015). Adoption of Dynamic Spectrum Access technologies: A System Dynamics approach. Telecommunication systems. DOI: 10.1007/s11235-015-0113-7

**5.** Suomi, H., Basaure, A., & Hämmäinen, H. (2013, October). Effects of capacity sharing on mobile access competition. In 21st IEEE International Conference on Network Protocols (ICNP), 2013, 1-6, DOI: 10.1109/ICNP.2013.6733661

**6.** Basaure, A., Suomi, H., & Hämmäinen, H. (2016). Transaction vs. Switching Costs - Comparison of Three Core Mechanisms for Mobile Markets. Telecommunications Policy. Vol 40 (6), 545-566, DOI: 10.1016/j.telpol.2016.02.004

# Author’s Contribution

**Publication 1:** Implications of dynamic spectrum management for regulation

Paredes suggested the suitability of the Coase theorem for this topic, Basaure did the analysis, the simulation and wrote the manuscript, which was discussed with and revised by Marianov and Paredes.

**Publication 2:** Optimizing spectrum value through flexible spectrum licensing

The analyzed scenarios were defined by Holland and Basaure. Basaure did the simulation, analysis and wrote the manuscript, and Holland provided constant feedback and support, especially related to technical aspects of the simulations.

**Publication 3:** Spectrum and license flexibility for 5G networks

Kliks coordinated the manuscript. Holland and Matinmikko provided the most important ideas for the manuscript and Basaure did the scenario analysis and simulations.

**Publication 4:** Adoption of Dynamic Spectrum Access technologies: A System Dynamics approach

Basaure wrote the draft version of the paper, including the analysis and the simulations. Sridhar provided constant feedback and revised the paper. Hämmäinen revised the paper and participated in discussions.

**Publication 5:** Effects of capacity sharing on mobile access competition

Hämmäinen suggested the initial idea for the analysis. Suomi wrote the main ideas of the manuscript, including the analysis on switching costs. Basaure wrote the analysis related to transaction costs. Suomi and Basaure revised the paper.

**Publication 6:** Transaction vs Switching Costs - Comparison of Three Core Mechanisms for Mobile Markets

In a first stage, the paper was written by Basaure with the constant feedback and support from Suomi. In a second and final stage, the paper was finalized by Basaure, with the constant feedback and support from Hämmäinen.

# 1. Introduction

## 1.1 Motivation

Spectrum management is in the core of mobile and wireless communications and therefore of vital importance for assuring the role of Internet as an enabler of societal processes. In recent decades, Internet has progressed from a useful network to a necessity, and its importance is expected to grow further. From this perspective, radio spectrum enables interconnection of stationary infrastructures (cities, houses, hospitals, schools, etc.), activities (health, education, public transport, production, logistic, entertainment, etc.) and mobile users (humans, devices and even animals).

Spectrum is a scarce resource subject to technical and economic constraints. Technology enables increasingly efficient use of spectrum. Based on technology developments, national regulatory authorities (NRA) continuously update the rules for accessing the spectrum. Their main purpose is to promote efficient spectrum usage; for example, by stimulating competition between spectrum holders, including mobile network operators (MNOs). As part of the economic efficiency objective, NRAs aim to improve the service supply and its quality-to-price ratio in the long run. In other words, together with the productive efficiency driven by the adoption of new technologies, regulation aims at increasing allocative, distributive and dynamic efficiencies. Furthermore, an increase in productive efficiency provides room for additional improvement in the other components of economic efficiency.

The increasing demand for new services makes the spectrum scarcer and urges NRAs to allocate additional spectrum to mobile services. The recent allocation of the new spectrum released by the digitalization of TV broadcast (i.e. digital dividend) to mobile network operators (MNOs) is one such example. In addition, new technologies increase the efficiency in spectrum assignment.

In this context, dynamic spectrum access (DSA) technologies and the related dynamic spectrum management (DSM) have become a major topic of interest. A dynamic assignment of spectrum in time and place has a potential to significantly increase the economic efficiency by rapidly reallocating the spectrum over time (allocative efficiency), fostering innovation and emerging services (dynamic efficiency), and contributing in the redistribution of resources (distributive efficiency) by allowing new entrants. However, until this date, the academic and research activity has not been followed by the industry engagement. Since DSA technologies are disruptive in nature, they may bring more threats than opportunities to MNOs. In such an uncertain scenario, MNOs seem to be missing a sufficient reason for investing in these technologies.

Regulation plays an important role in facilitating the introduction of new DSA technologies. Moreover, DSA may drive major changes in regulation wherefore it is important to understand the related complexity. The needed techno-economic analysis is further complicated due to a diverse set of DSA technologies and standards that are still being developed.

## 1.2 Research problem and scope

This thesis contributes to a better understanding of the requirements and implications of deploying DSA technologies into the Internet access markets. The opportunities and risks of dynamically assigning spectrum are assessed, focusing on regulation as a means to stimulate economic efficiency. In other words, the thesis aims at answering the following main question:

Q: Which are the efficiency gains obtained from a dynamic spectrum management and which are the main regulatory requirements that allow those gains?

More specifically, when answering the main question, the following sub-questions are elaborated:

Q1: How do benefits from spectrum transactions vary for different dynamic spectrum management scenarios?

Q2: How could DSA adoption happen in mobile and wireless Internet markets?

Q3: How does DSA compare against other alternative mechanisms for increasing economic efficiency of mobile and wireless Internet markets?

The first sub-question requires a feasibility analysis of different cases of spectrum transactions. The second sub-question addresses the conditions for a successful adoption of DSA technologies. Finally, the third sub-question aims at comparing DSA with other mechanisms that may increase economic efficiency. Each sub-question provides a different perspective for answering the main question.

This thesis comprehends the regulatory aspects of spectrum management for wireless and mobile Internet access, both wide-area cellular networks and local-area networks with wireless access, such as Wi-Fi. The chosen scope includes standards developing organizations (SDOs), such as the 3rd Generation Partnership Project (3GPP), the European Telecommunications Standards Institute (ETSI), the Institute of Electrical and Electronics Engineers (IEEE) and the Internet Engineering Task Force (IEFT). From a stakeholder perspective, the scope includes MNOs, other operators providing Internet access such as the so-called local area operators (LAOs), network and device manufacturers, end-users and finally national regulatory authorities (NRAs) and policy makers.

This thesis excludes issues related to pure fixed Internet access services and their possible interaction with mobile services, such as fixed-mobile service bundling or competition between fixed and mobile services.

## 1.3 Research approach and methods

This thesis applies a multidisciplinary research approach which combines natural and design sciences. It employs two modelling and simulation methods, namely agent-based modelling and system dynamics. While agent-based modelling studies a complex system of interacting agents from a bottom-up perspective, system dynamics analyses holistically the most important characteristics of a system from a top-down perspective. In general, this thesis builds models to evaluate the potential gains obtained from managing spectrum dynamically and the regulatory requirements allowing those gains.

## 1.4 Content of the thesis

This compilation thesis consists of the following introductory chapters and six publications. This chapter introduces the motivation, research questions and the content of the thesis. Chapter 2 presents the most relevant literature review and background information related to the research questions. Chapter 3 provides an overview of the underlying economic theories supporting the performed analysis. Chapter 4 describes the research approach, process and methods of this thesis. Chapter 5 summarizes the main results of the publications. Finally, Chapter 6 discusses the results and limitations, and provides the main conclusions of the thesis. In addition, the original publications are included as appendices.

## 1.5 Main economic and technical concepts

This thesis is a multidisciplinary study combining economics with technology. Consequently, some terms coming from the technology domain may have another meaning in the economic domain, and vice-versa. This section provides a summary of the most important terms to help readers with either technical or economic orientation to rapidly capture the necessary parts of the other domain.

The main economic concepts employed in this thesis are defined as follows:

Allocative efficiency: the state in which the production represents consumer preferences or, in other words, a point in which the marginal cost equals the marginal price.

Competition: the effort of two or more parties acting independently to secure the business of a third party by offering the most favourable terms (Merriam-Webster Online dictionary).

Cooperation: similar or complementary coordinated actions taken by firms in interdependent relationships to achieve mutual outcomes or singular outcomes with expected reciprocation over time (Anderson & Narus, 1990).

Distributive efficiency: the ability of the economy to redistribute resources (or purchasing power) to maximize social welfare.

Dynamic efficiency: addresses the trade-off between the short and long terms to generate the maximum value creation. It includes innovation as key aspect.

Economic efficiency: general term to indicate that scarce resources are optimally utilized to maximize social welfare. It can be subdivided into allocative, productive, distributive and dynamic efficiencies.

Ex-ante regulation: regulatory rules based on predefined obligations imposed to involved firms for a particular case or event.

Ex-post regulation: regulatory monitoring based on a general law prohibiting anticompetitive behaviours. This type of regulation includes arbitration and law enforcement.

Productive efficiency: the ability to maximize the output with the minimum amount of input.

Property rights: regime in which actors own the resource until they sell it to a new owner.

Retail market: refers to those economic transactions happening between a firm and a consumer (business-to-consumer relationship).

Switching costs: are one-time costs that a buyer faces when switching from one provider to another (Porter, 1980) and explain the market concentration and the monopoly power of incumbent firms.

Transaction costs: are those induced when employing the price mechanism offered by the market when transferring a resource from one holder to another (Coase, 1937) and they explain the level of vertical integration of an industry.

Usage rights: regime in which actors employ the resource during a predefined period of time as indicated in a license defined by a regulatory authority (or licensor).

Wholesale market: refers to those economic transactions happening between firms (business-to-business relationship).

The main technical concepts employed in this thesis are defined as follows:

Cognitive Radio (CR): initial concept as defined by Mitola (2000), according to which end-user devices can observe, orient, plan, decide, act and learn (i.e. cognitive cycle).

Cognitive radio system (CRS): “A radio system employing technology that allows the system to obtain knowledge of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained” (ITU, 2009). In this work, CRS is one type of implementation within dynamic spectrum access technologies.

Dynamic spectrum access (DSA) technologies: consist of a set of protocols and standards allowing end-users and operators to dynamically transmit in the unused or underutilized spectrum at different time and/or locations. In concrete, this work defines two types of DSA technologies. Firstly, operator-centric DSA enables two or more operators to transmit in the same frequency band, transferring spectrum from one base station to another between different operators. The spectrum transfer decision is made by the involved operators without the direct intervention of the end-user terminal. And secondly, user-centric DSA allows individual end-user devices to transmit in a spectrum band, while it is being employed by another party (i.e. end-user or operator). The spectrum is shared between end-users (e.g. as license-exempt) or it is transferred from one base station to another between different operators; however, driven by the decision of the end-user terminal, even though such transferring can be facilitated directly or indirectly (i.e. through a third party) by the spectrum holder. While operator-centric DSA permits operators to trade or share spectrum between them, user-centric DSA allows end-users to transmit in a spectrum band, causing spectrum to be shared or transferred from one party to another.

Dynamic spectrum management (DSM): is the process of dynamically assigning the spectrum in place and time enabled by DSA technologies.

End-user multihoming: refers in this context to any mechanism, solution or protocol enabling the end-user to maintain several simultaneous subscriptions to different MNOs. End-user multihoming allows end-user devices to access different networks enabling end-user traffic to be served by several MNOs (Suomi, 2014).

National Roaming: is a mechanism enabling an end-user device of a given MNO to obtain access from another MNO of the same country, anywhere, or on a regional basis. The availability of the obtained access depends on agreements between MNOs. National roaming allows MNO traffic to be served by another MNO.

Opportunistic access: refers to different type of user devices accessing the shared spectrum without high or any coordination, and thus the secondary or co-primary user does not require permission from the primary user to transmit. This term is not related to the economical meaning of opportunism (i.e. opportunistic behaviour).

Primary spectrum access: type of access in which the transmitting end-user terminal is not being constrained by the transmission of other end-user terminals having a higher priority.

Secondary spectrum access: type of access in which the transmitting end-user terminal is constrained by other end-user terminals having a priority access.

Software-defined radio (SDR): "A radio transmitter and/or receiver employing a technology that allows the radio frequency (RF) operating parameters including, but not limited to, frequency range, modulation type, or output power to be set or altered by software, excluding changes to operating parameters which occur during the normal pre-installed and predetermined operation of a radio according to a system specification or standard" (ITU, 2009).

Spectrum sharing: scheme in which two or more parties transmit in the same frequency band following some predefined transmission rules.

Spectrum transaction: one party holding spectrum transfers part of its spectrum to another party at a given price and with predefined rules (the price could equal zero, e.g., in case of commons). It could happen as a momentary lease or as a permanent sale and with different access conditions (e.g., secondary or co-primary access).

White space (WS) or spectrum hole: those points in frequency, time and space unoccupied by any transmission.

# 2. Background

## 2.1 New requirements for radio spectrum exploitation

The constant increase in demand for mobile and wireless Internet access urges MNOs, LAOs and NRAs to obtain more radio spectrum as well as more capacity from the given spectrum. According to CISCO (2015), the mobile data traffic of 2014 was nearly 30 times the amount of year 2000, during 2014 the mobile data grew 69%, and it is expected to grow tenfold between 2014 and 2019. Even though forecasts are typically inaccurate, these numbers indicate a clear tendency for a rapid traffic growth. For instance, smartphones represented only 29 % of total global handsets in use in 2014 but 69 % of total global handset traffic; and fourth-generation (4G) connections generated 10 times more traffic on average than 3G connections. This indicates considerable room for additional traffic growth. In addition, the importance of indoor traffic is increasing; in fact, 46% of total mobile data traffic was offloaded onto the fixed network through Wi-Fi or femtocell during 2014. Finally, new services related to the Internet of things (IoT) are reaching a considerable volume; for instance, globally there were nearly 109 million machine-to-machine (M2M) wearable devices in 2014.

Historically, mobile has substituted fixed in telephony; and a similar evolution is taking place due to the emergence of Internet and broadband (Grzybowski, 2014). Some authors argue that mobile broadband has a higher impact on economic development than fixed broadband (Thompson & Garbacz, 2011); moreover, mobile broadband may have the potential to fill the rural gap of digital divide (Prieger, 2013). On the other hand, the new demand for Internet access requires denser wireless networks, which stresses the importance of fixed infrastructure. In short, both fixed and mobile networks are likely to remain important in the future.

METIS[1] categorizes future network requirements in three types of services: very high data rate (extreme mobile broadband), high number of devices (massive machine-type communication) and high reliability (ultra-reliable machine-type communication). These requirements combine high density with high availability, and push the technology development towards different areas. One

[1] METIS is a consortium of 29 partners coordinated by Ericsson with the objective of laying the foundation for a future mobile and wireless communications system for 2020 and beyond. It is co-funded by the European Commission as an Integrated Project under the Seventh Framework Programme for research and development (FP7).

such area is the small-cellular network development for serving indoor traffic, which still faces technical challenges such as interference management (Hoydis, Kobayashi & Debbah, 2011; and Andrews, Claussen, Dohler, Rangan & Reed, 2012).

With the transition from analogue to digital broadcasting systems, the valuable released frequencies (i.e. digital dividend) are being allocated to mobile broadband services around the globe, indicating the need for additional spectrum for mobile Internet. However, the allocation of the digital dividend is only a temporal relief of the congestion and coverage problems suffered by mobile and wireless networks. Therefore, MNOs still need to manage their radio spectrum more efficiently, and the interest towards dynamic spectrum access persists.

## 2.2 Spectrum assignment

Auction is the most widely adopted mechanism to assign exclusive access rights to radio spectrum. In fact, auctions have been conducted in the US since 1994 and in Europe since 2000. Auctions have gradually become dominant replacing administrative mechanisms such as beauty contests. Ronald Coase (1959) was the first author suggesting the suitability of employing the price mechanism of the market (i.e. auctions) for assigning radio spectrum. It took however several decades before the first spectrum auction was finally organized[2].

Auctions are considered more efficient than administrative mechanisms (i.e. beauty contests), since they assign the spectrum to the one having the highest private valuation. However, challenges in auction design (Cramton, 2013) may cause harmful outcomes, such as overbidding (French, 2009). However, it is argued that no empirical evidence exists supporting that auctions are distortionary (Morris, 2005). In addition, auctions have facilitated new entrants (Madden, Bohlin, Tran & Morey, 2014).

On the other hand, the industrial, scientific and medical (ISM) band has been assigned for common access. First established by the ITU in 1947 and then defined in 1985 for spread spectrum technologies including WLAN networks such as Wi-Fi, the license-exempt regime has successfully served wireless Internet access during the last years (Negus & Petrick, 2009). The tragedy of the commons did not prevent the adoption of Wi-Fi, because such tragedy applies when the resource is *unmanaged* (Hardin, 1998), and systems transmitting in the ISM band have tight limits of transmission power.

In general, the spectrum can be assigned either through a license or with property rights. In the first case, the licensee has access right to a spectrum band for a predefined period of time and with predefined conditions; in the second case, the spectrum holder enjoys ownership. In addition, the spectrum is assigned to

[2] Even though the auctioned object is typically a license to transmit in a frequency band rather than the frequency band in itself, the assignment mechanism utilizes the price in line with Coase. In addition, the conditions of the licenses are becoming more flexible (i.e. market oriented).

one holder exclusively or to everybody for common use. Latest technology developments enable dynamic spectrum management (i.e. transactions) requiring new intermediate schemes between exclusive and commons assignments and a higher degree of flexibility in the conditions of the license.

## 2.3 Dynamic spectrum access (DSA) technologies

DSA technologies consist of a set of protocols and standards allowing end-users and operators (e.g., MNOs, LAOs, etc.) to dynamically transmit in the unused or underutilized spectrum at different time and/or locations. This enables two or more parties (e.g. operators) to employ the same frequency band. DSA technologies radically change the spectrum assignment mechanisms and may facilitate higher spectrum efficiency.

According to the original concept defined by Mitola as Cognitive Radio in 2000, the end-user device could observe, orient, plan, decide, act and learn (i.e. cognitive cycle). Several years later, IEEE (2008) defined the concepts and terminology related to DSA[3], and ITU (2009) defined Cognitive Radio Systems (CRS) and Software defined radio (SDR) (see definitions in section 1.5). At the same time, they recognized the need for further study on the benefits and applications of DSA.

World Radio Conference (WRC) showed in 2012 an emerging interest in the potential of Cognitive Radio Systems (CRS), even though it was decided not to change the ITU Radio Regulations. Around the WRC of 2012 most of the effort focused on the development of the dynamic access of TV white spaces (TVWS), due to their good propagation characteristics. Many expected that this may be a promising first step towards the diffusion of DSA technologies, for instance by enabling mobile broadband in rural areas or by allowing programming making and special event (PMSE) devices, such as wireless microphones, to operate in the TVWSs[4]. After years of standardization, testing and deployment work, the interest moved from TVWS towards other whitespaces at higher frequencies. From a technical perspective, the development work has gradually moved from devices deploying Software Defined Radio (SDR) capabilities towards coexistence of systems based on spectrum database; and from a primary-secondary (hierarchical) spectrum sharing towards a co-primary spectrum sharing scheme.

DSA standardization efforts come from different SDOs, such as IEEE, IETF, 3GPP and ETSI, as summarized in Table 1. Each effort is typically driven by specific industry players (operator, manufacturer, etc.), which explains the main design decisions and enabled applications.

The IEEE has defined a set of standards to facilitate the coexistence of systems in the TV frequency bands, such as IEEE 802.11af, 802.16h and 802.19 (Xiao,

[3] For this thesis, please refer to the definition of DSA in section 1.5. For a more general definition of this term, please refer to IEEE (2008).

[4] WRC 12 finally decided to allocate the 694 – 790 MHz band to mobile broadband services; however, it committed for WR15 to provide additional spectrum for mobile services including sharing compatibility issues, and to give a solution for white space devices (WSDs).

Hu, Qian, Gong & Wang, 2013). These standards enable, for instance, the Wi-Fi deployment in TVWSs (or so-called super Wi-Fi) (Flores, Guerra, Knightly, Ecclesine, & Pandey, 2013). In addition, the IEEE has developed the 802.22, an alternative standard, to provide rural broadband by means of a wide regional area network (WRAN) that may also be deployed for Device-to-Device (D2D) communication (Lei & Shellhammer, 2009). Finally, IEEE has more recently standardized, in the 802.11ah, a Wi-Fi extension for M2M applications in the license-exempt bands below 1GHz. This includes home networks, industrial process automation, video surveillance, and smart grid communications (Zhang et al., 2012).

**Table 1.** Summary of DSA standards (adapted from Publication 4)

| | **Driven by** | **Adopted by** | **Wide / local area** | **System design** | **Target frequencies** | **Status** | **Example of application** |
|---|---|---|---|---|---|---|---|
| **3GPP CA** | Network manufacturers and MNOs | Operator | Local | Modular | MNO´s frequencies, license-exempt | Standardized for LTE-A, license-exempt bands. May be extended for inter MNO | Indoor small cells deployment with licensed and license-exempt frequencies |
| **3GPP D2D** | | End-user | Local | Modular | License-exempt bands or MNO´s frequencies | Included in LTE (3GPP Release 12) for initial development | Communicate with nearby terminals (D2D), public safety (TETRA replacement) |
| **ETSI RRS LSA** | | Operator | Wide | Modular | 2.3 GHz | Ongoing standardization (ETSI TS 103 154 (10/2014), TS 103 235) | Get additional spectrum for MNOs |
| **ETSI RRS Reconfigurable MD** | Device manufacturers | End-user | Local | Modular | MNO´s frequencies | Ongoing standardization (TR 102 967, TS 103 094) | Through *Radio-apps* provide end-users additional radio functionality, extra coverage (indoor, outdoor through ad-hoc) |
| **ETSI WSD** | TV operators | End-user | Local | Integral | TVWS | Standardized (EN 301 598, TS 103 143) | PMSE (e.g., microphones), MCWSD (manually configurable WSD) |
| **IEEE 802.11af/.19/.16h** | Wi-Fi manufacturers | End-user | Wide | Modular | TVWS | Standardized | Wi-Fi in TVWS (super Wi-Fi) |
| **IEEE 802.11ah** | | End-user | Local | Modular | 900 MHz | Ongoing standardization | Wi-Fi extension for M2M applications |
| **IEEE 802.22** | Regulator | End-user | Wide | Integral | TVWS | Standardized | Rural broadband (WRAN) |
| **IETF PAWS** | Application developers | End-user | Wide | Integral | TVWS (initially) | Standardized | Secondary access through geolocation database |
| **Weightless (open standard)** | | Both | Wide | Integral | TVWS | Some deployments (Neul and other providers) | IoT (M2M, smart cities) |

On the other hand, the IETF initiated at the beginning of 2012 the standardization of the communication between mobile devices and a white space database, also referred as to Protocol to Access White Space or PAWS (Manusco, Probasco & Patil, 2013). The standardized database enables DSA by providing the geographical information on the available frequencies to mobile devices (Ghosh, Naik, Kumar & Karandikar, 2015 and Paavola & Kivinen, 2014). Simultaneously, ETSI Radio Reconfigurable Systems (RRS) works on several parallel standardization efforts (Mueck, 2014) described as follows. The ETSI RRS Reconfigurable mobile device (MD) provides mobile devices additional radio functionality through *radio-applications*, such as extra coverage at indoor or outdoor locations. The ETSI RRS licensed shared access (LSA) (Palola et al., 2014) enables a MNO or another operator to temporally acquire additional spectrum from another incumbent spectrum holder. Finally, ETSI white space device (WSD) allows mobile devices such as Programme Making and Special Events (PMSE) and Manually Configurable White Space Devices (MCWSD) to transmit in the TVWS band.

The 3GPP works in two standardization efforts. Firstly, the LTE Carrier Aggregation (CA) (4G Americas, 2014) creates a virtual wideband carrier from segments of spectrum across different bands. These bands can be licensed (Yuan, Zhang, Wang, Yang, 2010) or license-exempt (Alkhansa, Artail, & Gutierrez-Estevez, 2014). Secondly, the 3GPP device-to-device (D2D) has been included in the LTE operation (3GPP Release 12) (Lin, Andrews, Ghosh & Ratasuk, 2014) for initial development, allowing mobile devices to access the license-exempt spectrum. The 3GPP D2D has the purpose of replacing the public safety networks (Terrestrial Trunked Radio or TETRA). Finally, Weightless (Webb, 2012), an open standard developed by Neul (UK based company), is applied to some IoT applications such as M2M and smart cities.

## 2.4 Spectrum occupancy

Researchers have conducted measurements to assess the level of spectrum occupancy and to determine the possible benefits of DSA technologies. One of the early results (Janka & Dorfman, 2005) gave a surprising 6% of average occupancy; however, this study considered the whole available spectrum from 400MHz to 7.2GHz in both rural and urban areas. Studies on spectrum occupancy require a higher level of detail, since spectrum is more valuable in those places with higher demand and consequently with higher occupancy. Obviously aggregated data is not useful for drawing conclusions. In this line, McHenry & McCloskey (2006) presented a measurement comparison of several cities of USA, in which the average occupancy highly varied over frequency bands and locations, ranging from 5% to 75%, being the TV bands (25-75%), the cellular bands (30-50%) and the license-exempt band in the 2.4GHz (10-30%) the most utilized. Other bands presented a considerable room for occupancy improvement. Moreover, Wellens, Wu and Mähönen (2007) reported that, according to their measurement performed in Aachen, Germany, the frequencies from 20MHz to 3GHz are highly occupied, while those higher than 3GHz are rarely occupied. Additionally, when measurements were performed indoors, those frequencies from 1 GHz to 3GHz were also found underutilized in some periods of time. A summary of different spectrum measurement campaigns can be found in Patil, Prasad and Skouby (2011).

## 2.5 Impact of DSA on market dynamics

The standards described in section 2.3 enable multiple scenarios of spectrum transactions. From a general perspective, DSA technologies decrease costs associated with spectrum transactions at two different levels: wholesale (inter-operator transactions) and retail (end-user driven transactions). Transaction costs are incurred when employing the price mechanism offered by the market, when performing an economic exchange. The importance of these costs was firstly recognized by Coase (1937). Transaction costs can be categorized into (i) search and information costs; (ii) bargaining costs, which in this case can be identified with coordination costs; and (iii) policing and enforcement costs, which in practice are costs of measuring the output (Dahlman, 1979). Additionally, Alston and Gillespie (1989) include (iv) asset specificity costs (e.g., spectrum specificity); (v) agency costs (e.g., if principal-agency problem arises when outsourcing an activity); and (vi) shrinking costs (e.g., if a party cannot be controlled by the counterpart).

At retail level, user-centric DSA standards reduce end-user switching costs by permitting individual user devices to transmit in a spectrum band while the same spectrum is being employed by another party (i.e. end-users or operator). In this case, switching costs include also the transaction costs of end-user trading (Klemperer, 1987). For clarity, this thesis analyses separately inter-operator transaction costs and end-user switching costs. Switching costs are defined as one-time costs that a buyer faces when switching from one provider to another (Porter, 1980) and they constitute an entry barrier, since they determine the monopoly power of incumbent firms. Burnham et al. (2003) characterize switching costs by classifying the types of resulting costs into financial, procedural and relational. If switching costs are high, firms have higher bargaining power towards buyers. Consequently, this thesis claims that DSA decreases inter-operator transaction costs (business-to-business relationship) and end-user switching costs (business-to-consumer relationship). DSA standards, which decrease inter-operator transaction costs, stimulate wholesale trading and cooperation between involved operators; while DSA standards decreasing user switching costs promote retail competition between operators.

Figures 1 and 2 depict the evolution of transaction and switching costs caused by DSA technologies. In both figures, the first stage represents the current status, in which no spectrum transactions take place between parties. In the second stage of Figure 1, standards such as 3GPP Carrier Aggregation (CA), ETSI RRS LSA and in some cases 3GPP D2D enable spectrum transactions between MNOs. 3GPP CA may also take advantage of the license-exempt bands. In such a situation, all cost items considerably decrease: spectrum becomes less specific, while the information, coordination and measurement costs are decreased due to automation. DSA technologies based on spectrum database enables spectrum transactions between operators. Such transactions may be driven by end-user terminals (second stage of Figure 2) or by operators (third stage of Figure 1). In a user-centric transaction, standards such as ETSI WSD, IEEE 802.11af or IEEE PAWS push user-switching costs down related to financial and procedural costs, since a database approach provides the end-user with the ability to transmit in different frequency bands. In an operator-centric transaction, DSA technologies decrease costs related to spectrum specificity and information costs. Finally, in an operator-centric evolution (fourth stage of Figure 1), spectrum transactions based on sensing technologies, for instance ETSI RRS Reconfigurable MD, may decrease coordination and measurement costs until its minimum. In a user-centric one, sensing technologies diminish procedural costs (third stage of Figure 2).

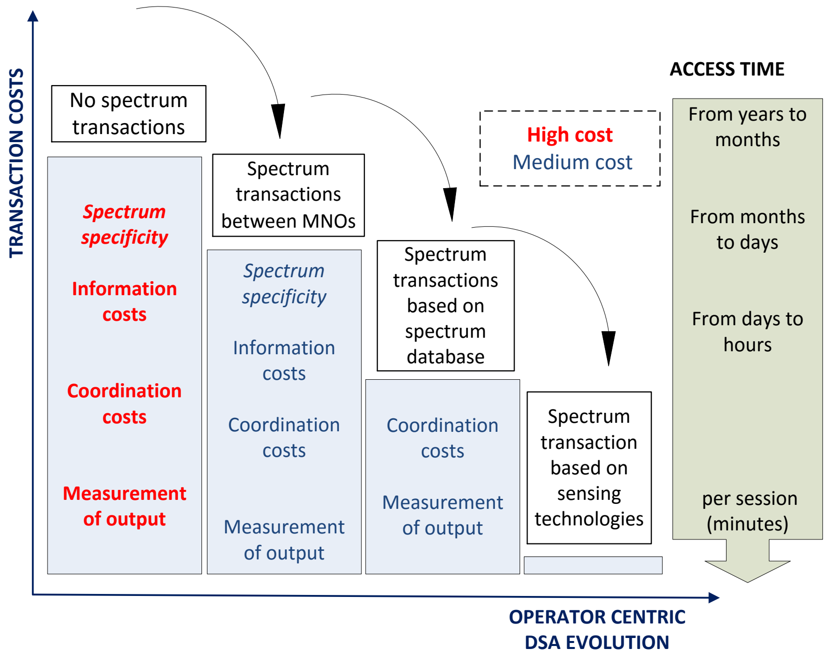


**Figure 1.** Evolution of transaction costs due to DSA (adapted from Publication 1)

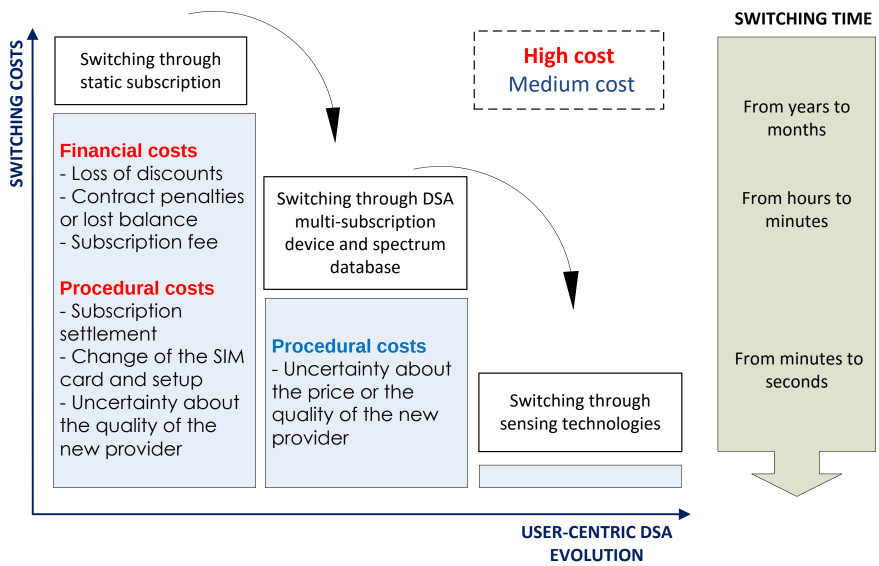


**Figure 2.** Evolution of user switching costs due to DSA (adapted from Publication 5)

The aforementioned cost elements may also depend on the implemented trading mechanism, and in particular, on the level of centralization. A high level of centralization demands higher CAPEX to reduce coordination costs, while a decentralized system requires less coordination (and CAPEX). Besides this, the development of DSA technologies gradually reduces OPEX related to the maintenance of trading information, allowing more sophisticated trading mechanisms. As an example, Yoon, Hwang and Weiss (2012) compare three alternative trading mechanisms, and conclude that under current assumptions of technology, direct trading still performs better than the alternative mechanisms (brokerage system and auction based mechanism).

## 2.6 End-user versus operator centric adoption scenarios

A successful adoption of DSA technologies requires a coordinated effort of all stakeholders, including end-users, mobile device manufacturers, network equipment manufacturers, MNOs, other spectrum holders, SDOs, NRAs and policy makers. From an adoption perspective, this work defines two alternative scenarios: user-centric and operator-centric adoption, to indicate the stakeholder who is making the final adoption decision. In a user-centric adoption, the user device having the DSA capabilities transmits in the available spectrum on a dynamic basis. The transmission decision is performed by the end-user devices, and it is supported by the operator network or, in some cases, it is performed in a D2D fashion. In the user-centric case, the spectrum can be shared as commons or it can be transferred between operator networks; however, driven by the decision of end-user terminals. On the other hand, in an operator-centric adoption, the operators deploy DSA and its associated dynamic spectrum management into their networks to employ spectrum more efficiently. The dynamic transmission logic is provided by the network equipment manufacturer and it does not require a direct intervention of the end-user terminal. In this case, spectrum is transferred between two or more operators. These scenarios are summarized in Table 2.

**Table 2.** Summary of DSA adoption scenarios (adapted from Publication 4)

| Adoption scenario | User-centric | Operator-centric |
|---|---|---|
| Definition | The end-user adopts a mobile device, capable of transmitting dynamically in a common spectrum or in a spectrum band belonging to another party. The transferring of spectrum is driven by the decision of end-user terminals. | The operator adopts the DSA functionality in their network, to dynamically transmit in a spectrum band belonging to another party. Spectrum is transferred between operators. |
| Provider | Device manufacturers provide DSA capabilities to the user device. End-user spectrum access is supported by the operator. | Network manufacturer provides DSA capabilities to the network elements. |

In addition to the adoption mode, DSA technologies can be characterized by the type of competition they encounter in the market. A technology competes with network effect, if an increase in the number of adopters increase the benefits of end-users or operators adopting the technology. Network effect produces in the adopted technology a critical mass requirement, beyond which it exponentially diffuses until a saturation point at which the adopter number stabilizes. On the other hand, if a new technology replaces an older one, such technology is competing with substitution effect. In this type of competition, the replacement could involve an internal process or an end-user service, and it typically happens at the saturation point of the older technology.

Previous Table 1 identifies different standards competing with network or substitution effects. Those standard with modular design act as an enabler by replacing an older module or process, and thus typically exhibits substitution effect. For instance, 3GPP CA, ETSI RRS LSA and IEEE 802.11af are substituting an older mechanism by adding a new functionality (the capability of aggregating different frequencies, of communicating with a spectrum database or transmitting in a new frequency band). Thus, a substitution may happen at different levels; as an internal process of an operator, as the case of 3GPP CA, or as a service offered to the end-user. Examples of this last case may be a M2M or D2D service based on DSA functionality replacing a similar service based on older technology; or a small-cellular (indoor) coverage facilitated by DSA substituting a macro-cellular coverage, which does not support DSA. Moreover, sometimes the substitution happens at end-user or service level, even though the technical change has happened at a process level. Standards may also compete with network effect when they offer a similar functionality. For instance, IEEE 802.11af with IEEE 802.22; and 3GPP D2D or 3GPP CA with ETSI RRS Reconfigurable MD. Finally, standards competing against an older established system also exhibit network effect. Examples of such case may be ETSI WSD deployment of PMSE devices or Weightless deployments of M2M applications.

## 2.7 New spectrum regimes

Exclusive licensing and license-exempt regimes have successfully coexisted favouring the emergence of cellular and wireless Internet access technologies. Nevertheless, the latest technology developments permit managing spectrum more dynamically.

On one hand, license conditions may become more flexible in terms of service and technology neutrality and reselling rights. Thus, the spectrum regime may evolve from a *command-and-control* towards a property rights regime, in which the spectrum holder has ownership over the spectrum and decides the access conditions; however, within some minimum set of restrictions defined by the NRA. On the other hand, the current regime based on exclusive and commons licensing may evolve towards spectrum sharing schemes, which allows multiple parties to coexist within the same frequency band. In such a scheme, spectrum holders are allowed to perform transactions by selling or leasing part of their spectrum (in place or/and time).

From a general perspective, DSA can enable three types of spectrum sharing schemes (Zhao & Sadler, 2007) : (i) *dynamic exclusive sharing* in which the incumbent operator employs the exclusively assigned spectrum with certain flexibility, including reselling rights of the whole or part of the assigned band; (ii) *hierarchical access sharing* in which one user group can transmit with priority in a spectrum band while the other group transmits with secondary rights without harmfully interfering the primary user as defined by policies and (iii) *open sharing* in which all users transmitting in the shared spectrum band enjoy equal priority. Each sharing scheme requires a different level of coordination between involved parties. Depending on whether the secondary or co-primary user needs permission to transmit, the deployed scheme may be further classified into cooperative or non-cooperative spectrum sharing (Chapin and Lehr, 2007). Non cooperative spectrum sharing does not involve trading between operators, but it is rather driven by the end-user terminal as an opportunistic access. Cooperative spectrum sharing typically involves spectrum trading driven by the operators.

The above mentioned three-tiered categorization has been adopted by both the USA and the EU; however, with different approaches. The following Figure 3 summarizes the three types of spectrum sharing, indicating the terminology used in the EU and the USA for each level.

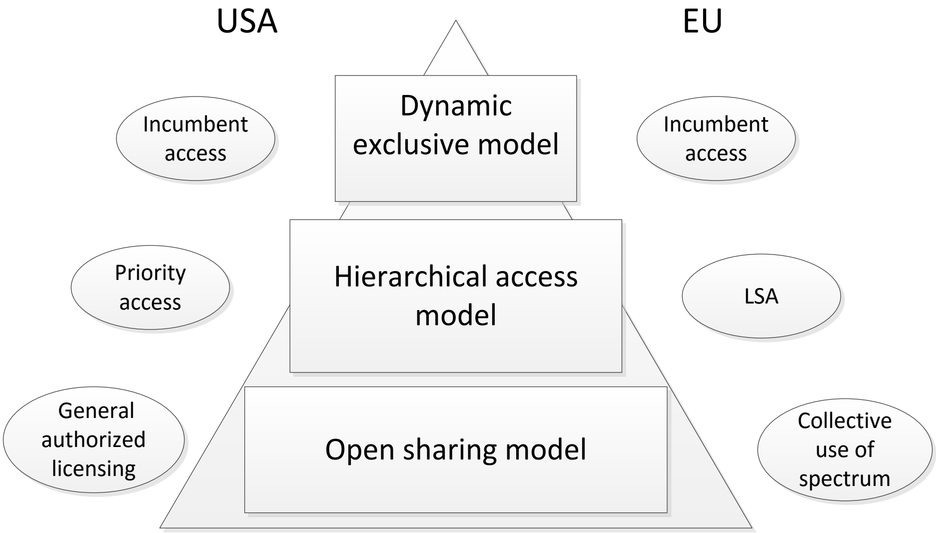


**Figure 3.** Three-tiered spectrum sharing framework.

In Europe, the most important efforts for introducing new spectrum regimes have been the Licensed Shared Access (LSA) and Collective Use of Spectrum (CUS) approaches.

In LSA, a spectrum holder accepts a secondary operator to transmit in the same frequency band with a predictable quality for the involved parties (EC COM, 2012, 478). LSA was originally developed by network manufacturers (Qualcomm and Nokia), intended for MNOs as a means to obtain additional spectrum. Later, the European Commission extended this concept to include other cases. More generally, LSA allows spectrum transactions with predictable interference levels and it has been recently standardized by ETSI (ETSI RRS LSA).

CUS is a general framework allowing individual users and devices to transmit in the same frequency band and at the same time; in a particular area and under well-defined conditions. One such example is Light licensing (ECC Report 132, 2009) which enables common access to a frequency band, with certain guarantee for quality of service. Light licensing requires a more simplified issuing procedure than an exclusive licensing regime, but a more detailed registration mechanism than a license-exempt regime. Light licensing permits a coordinated sharing mechanism in which different types of users are supported (RSPG11-392, 2011), however easing the burden of coordination, registration and licensing. Light licensing may also work as private commons in which users set the conditions for license-exempt transmission. Light licensing is mostly suitable for systems with limited interference.

Finally, pluralistic licensing (Holland et al., 2012) was introduced in 2012 as a new flexible licensing regime which considers explicitly the interference as a tradable characteristic of the spectrum. Pluralistic licensing enables the spectrum holder to accept secondary or co-primary transmissions in a spectrum band, under the condition that the interference produced by these transmissions are defined by parameters and rules that are known beforehand by licensees and can be agreed and adjusted as needed. These parameters can be implemented in several alternative ways; for instance, as a fixed amount of interference or as a known formula with changing values and a related revenue mechanism. In addition, pluralistic licensing can be mediated by the regulator (via license fees linked to the produced interference) or through a price mechanism offered by the market. Since pluralistic licensing is a flexible and wide concept, it may allow any of the three types of spectrum sharing through co-primary or primary-secondary schemes. However, until the date, this regime has not been deployed.

In the USA, the Spectrum Access System (SAS) proposes a hierarchical model with three types of end-users implemented through a geolocation database: incumbent, secondary and tertiary users. Incumbent end-users can transmit in a spectrum band with priority, since such spectrum has been already allocated to incumbent operators. A secondary license permits an operator to provide secondary access to users, who are registered in a spectrum database. Finally, tertiary users, who have a very light license condition, similar to the current Wi-Fi users, can transmit in those pieces of spectrum which are not being used by primary or secondary end-users. In other words, tertiary end-users transmit opportunistically by means of a general authorization.

All the aforementioned licensing schemes facilitate spectrum sharing through transactions or as a common (free) access. Additionally, a spectrum regime allowing transactions may be based on property rights, meaning that spectrum holders have ownership over the spectrum instead of usage rights defined by a license with a predefined expiration date. A property rights regime provides the best incentives to perform transactions under low spectrum concentration and high industry coordination. High spectrum concentration disincentivizes transactions since incumbent operators prefer to maintain their monopoly power, and low industry coordination (for instance, if industry players choose different non compatible standards) increases transaction costs. In both cases, the spectrum owner or holder needs to manage the generated interference based on predefined rules (i.e. ex-ante regulation) to incentivize compatibility. From this perspective, spectrum transactions may be classified according to the traded rights: mode (use or ownership), extent (complete transfer or shared spectrum) and duration (short/long lease versus short/permanent sale) (Caicedo & Weiss, 2007). The evolving nature of technology and changing conditions of the market makes that most NRAs have favoured, until this moment, a scheme based on licenses rather than on ownership.

## 2.8 Spectrum transaction scenarios

This thesis analyses different types of spectrum transactions on a case-by-case basis. Thus, it performs a sensitivity analysis for five different scenarios which represent the most interesting cases from a regulatory perspective. These cases are diverse in terms of the chosen frequency bands, system and end-user requirements. The main technical focus of interest is the interference produced by the end-user devices and network elements coexisting in the same frequency band. This study assesses the parameters affecting the benefits generated by the analysed spectrum transactions to discover the most feasible cases.

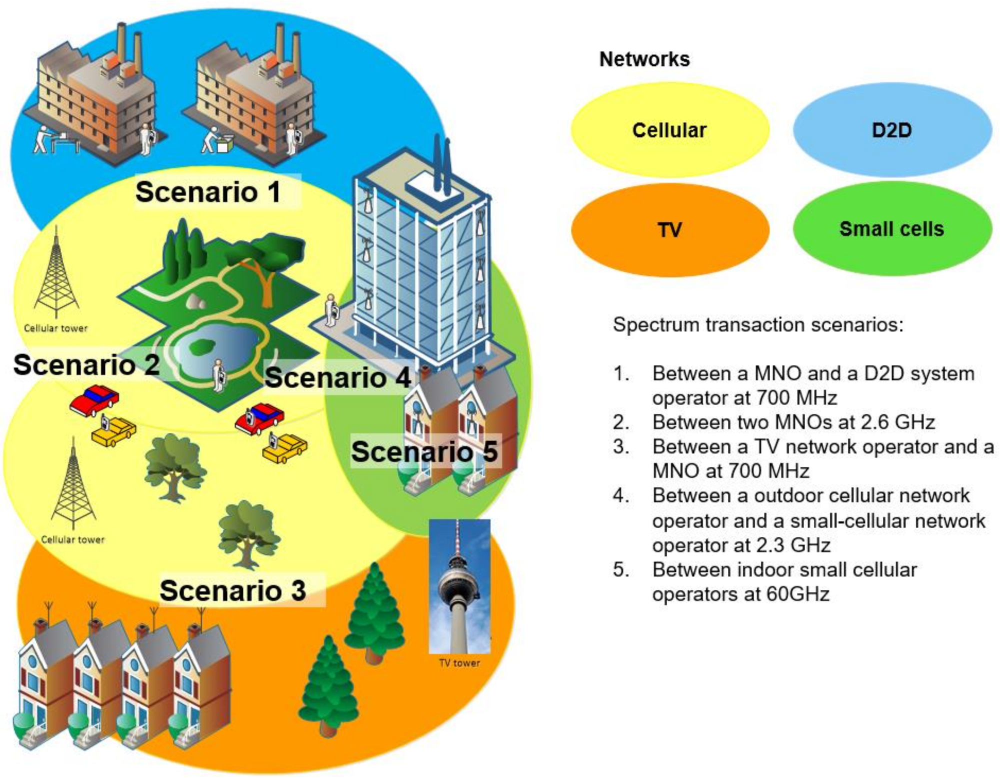


**Figure 4.** Spectrum transaction scenarios

The scenarios are summarized in Figure 4. Scenarios 1 and 3 deal with systems transmitting in the 700MHz (i.e. digital dividend). This band is chosen because it started the discussion on spectrum sharing, even though latest efforts have focused on higher frequency bands. In scenario 1, a cellular network shares spectrum with a D2D system in adjacent locations. In scenario 3, a cellular network transmits in TVWSs, while the TV network coexists in the same frequency band. Scenarios 2 and 4 analyse other mobile bands of interest below the 3GHz; namely the 2.3GHz and 2.6GHz bands. In scenario 2, two cellular networks belonging to different MNOs transmit in the 2.6GHz band in adjacent areas, one network having priority over the other. Scenario 4 analyses the interaction between an outdoor cellular network transmitting in the 2.3GHz band and an indoor small-cellular network transmitting in the same frequency band. Finally, scenario 5 presents the interaction between different indoor small-cellular deployments transmitting in the so-called millimetre-waves (i.e. 60GHz).

Each of these scenarios can be linked to a type of spectrum sharing model, as illustrated in Figure 5. Scenario 1 represents a dynamic exclusive model, in which the incumbent allows secondary transmission of D2D devices. This case can be easily extrapolated to other type of services, for instance M2M communication deployed in a factory environment. Scenarios 2, 3 and 4 represent a hierarchical access model, such as LSA, in which one party has priority over the other. These scenarios may be deployed by means of a geolocation database, which works as an authoritative register allowing the transmission of secondary users. This database maintains information on primary devices to decide on secondary transmission based on statistical information. Scenarios 4 and 5 represent an open sharing model in which individual networks transmit in the same spectrum band with equal priority. In such cases, the coordination between adjacent networks will impact on the quality of service (QoS) and experience (QoE). Note that scenario 4 can lie under two models.

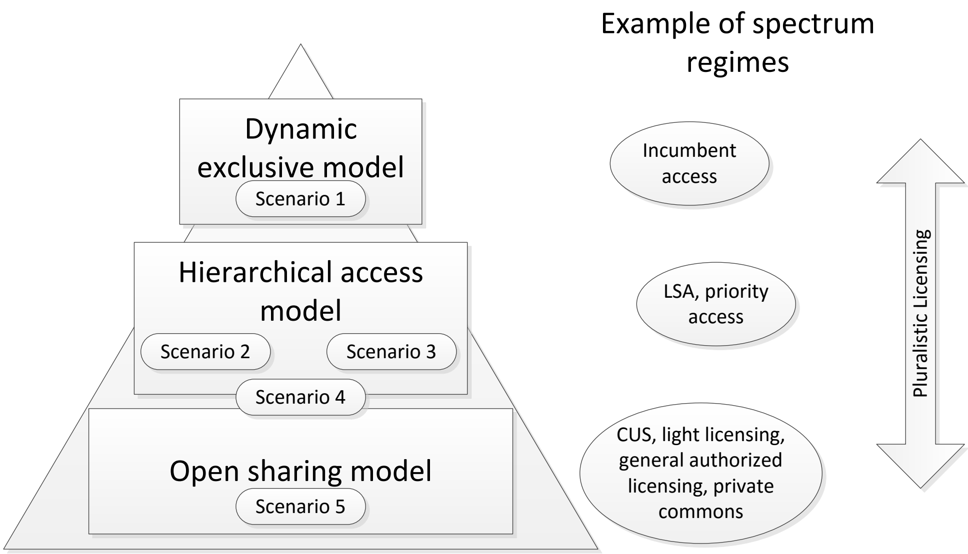


**Figure 5.** Analysed scenarios mapped in the three-tiered sharing framework and with different spectrum regimes.

## 2.9 Other competing mechanisms

DSA technologies decrease costs of spectrum transactions and thus they induce economic efficiency. In addition to spectrum transactions, this thesis touches other competing technologies which can decrease inter-operator transaction costs or end-user switching costs.

The thesis compares three mechanisms which increase economic efficiency by decreasing transaction or switching costs, within the scope of MNOs. Besides DSA, national roaming[5] decreases costs of network capacity transactions between two MNOs. In addition, end-user multihoming[6] enables the end-user device to maintain simultaneous subscriptions to different MNOs and thus to significantly decrease switching costs. Markendahl (2009) compares different existing cooperative mechanisms, including national roaming, mobile virtual network operators (MVNOs) and infrastructure sharing. This thesis chooses national roaming from the list of existing mechanisms, and compares it with two emerging mechanisms: end-user multihoming and DSA. Each mechanism stimulates cooperation or competition at a different level (spectrum, capacity or user traffic), which makes this comparison especially relevant for understanding the importance of DSA.

**Table 3.** Comparison of the target mechanisms (adapted from Publication 6)

| Mechanism | DSA | National Roaming | End-user multihoming |
|---|---|---|---|
| ***Market mode*** | Operator-driven | Operator-driven | End-user driven |
| ***Cost impact*** | Inter-MNO transaction costs (search and information costs) | Inter-MNO transaction costs (search and information costs) | End-user switching costs (financial and procedural costs) |
| ***MNO-subscriber relationship*** | Static subscription | Static subscription | Fast switching between subscriptions |
| ***MNO-MNO relationship*** | Spectrum trading through brokerage system | Roaming contracts (home MNO controls) | Competition for user choice |
| ***Trading type*** | Wholesale | Wholesale | Retail |
| ***Trading event*** | Access to spectrum band, (e.g., minutes, hours, days) | End-user session | End-user session |
| ***Spectrum management*** | Dynamic | Static | Static |
| ***Required CAPEX (MNO)*** | High | Low | Low |
| ***Required OPEX (MNO)*** | Medium | Medium | Low |
| **New spectrum regulation needed** | Yes | No | No |
| **Standards development needed** | Yes | No | No |
| **Other requirements** | Spectrum trading mechanism | Access price regulation | Metered pricing |

Table 3 summarizes a comparison between the three mentioned mechanisms. First of all, each mechanism has a different cost impact; either on transaction or switching costs. As a consequence, each mechanism affects differently the MNO-subscriber and inter-MNO relationships, as indicated in the Table. Regarding the capital requirements, DSA demands major investments; however, it depends on the detailed implementation. End-user multihoming and national roaming are not capital intensive. DSA requires a brokerage trading system

[5] See definition in section 1.5

[6] See definition in section 1.5

which does not own or hold spectrum, but it mediates trading to maximize social welfare by matching demand and supply. Such system could be run by the regulator or by a third party. In addition, DSA requires MNOs to deploy base stations capable of accessing spectrum dynamically (e.g., Anchora, Mezzavilla, Badia & Zorzi, 2012), and it requires operational and capital expenses related to running a centralized server database, and maintaining real-time information on spectrum trading. Note that in this case the higher the frequencies, the lower the coordination requirements.

In the case of national roaming, additional costs are incurred due to home network routing and the related double book-keeping MNOs should maintain. Finally, in the case of end-user multihoming, the number of subscriptions is increased, causing additional costs to maintain up-to-date SIM and location information. Additionally, end-users may not be willing to maintain several flat-rate subscriptions, and consequently MNOs need to deploy, for instance, metered pricing, which also adds complexity to the charging and billing process.

The deployment of DSA decreases inter-MNO spectrum transaction costs related to search and information, while the related brokerage system decreases bargaining, and policing and enforcement costs. A national roaming mechanism decreases searching and information costs, while the related trading arrangement (how MNOs make the book-keeping and charge to each other) decreases the bargaining and policing and enforcement costs. Finally, end-user multihoming decreases both financial and procedural costs of switching.

Besides the above mentioned requirements, while end-user multihoming may face the unwillingness of MNOs, national roaming and DSA encounter regulatory challenges. For national roaming, the regulator should monitor roaming prices and conditions to maintain a fair competition. DSA requires a new spectrum regime allowing and promoting transactions to secure the spectrum supply and to avoid market concentration.

# 3. Relevant economic theories

This section presents an overview of the main economic theories related to the area of study of this thesis.

## 3.1 Transaction cost economics (Ronald Coase)

This thesis analyses spectrum transactions from technical and economic perspectives. In economic theory, Ronald Coase was the first in recognizing the importance of transaction costs for explaining the existence of the firm and the dynamics of the market (1937, 1960). According to the Coase theorem, a sufficiently low (ideally zero) transaction cost and clearly defined property rights induce transactions which result in an efficient outcome, regardless of the initial resource assignment. Most notably, Coase was the first author in suggesting auctions as an efficient mechanism for spectrum assignment (1959), several decades before the first auction was finally organized. After Coase, several authors have further analysed the firm and the market from a transaction cost viewpoint, one main contributor being Williamson (1975). Williamson expanded the work of Coase into a field called New Institutional Economics (NIE), in which he distinguishes four levels of social analysis: social theory, economics of property rights, transaction costs economics and neo-classical economics. In this framework, the first level deals with informal institutions, such as customs, traditions and norms. The second level is related to the institutional environment (the rules of the game). The third level deals with the governance. Finally, the fourth level refers to the market, in which transactions occur and prices are adjusted. This research deals mainly with the second and third levels; in other words, with the rules of the game and the game in itself. In a perfect world (i.e. property rights are well defined and transaction costs are zero) the government can step aside, except for law enforcement and arbitration when needed. Currently, spectrum management is gradually evolving due to technology development, and therefore the rules and the governance of spectrum may go through a regulatory and management evolution. As stated by Williamson, processes at these levels are slow and they typically take several years.

## 3.2 Evolutionary economics (Joseph Schumpeter)

Together with transaction costs, this research addresses the evolutionary behaviour of spectrum management. Since most of DSA technologies are still under development, an evolutionary approach provides us with the right tools for analysing such scenario. Though founded by Veblen (1898), evolutionary economics have been later developed by Joseph Schumpeter (1934), who explained the driving forces of economic development endogenously. Thus, the development of technology happens from within the system; from the entrepreneur individual initiative. Schumpeter (1934) highlights the role of the entrepreneur for the economic development, who produces innovations by new combinations of productive factors, such as labour and land. Schumpeter explains the economic world as having a cyclical behaviour (i.e. business cycles), and the innovation as the main factor for initiating a new cycle. In this context, he defines *creative destruction* as the "*process of industrial mutation that incessantly revolutionizes the economic structure from within, incessantly destroying the old one, incessantly creating a new one*" (Schumpeter, 1942).

This field is considered as belonging to non-equilibrium economics (as opposite to equilibrium or neoclassical economics), in which economic agents dynamically learn from the environment and cause changes by means of innovations.

The ideas of Schumpeter on economic growth and industrial dynamics stimulated a set of new modelling techniques, the so-called Schumpeterian or evolutionary models. These models emphasize the diversity and heterogeneity of economic agents (and their behaviours), and the notion that economic change or evolution is endogenous (it comes from within rather than exogenous, which comes from outside the system).

Even though Schumpeter did not support the idea of applying biological analogies to economic analysis (1954), many neo-Schumpeterian authors have incorporated them into their models. The first such author was Alchian (1950), who described the behaviours of firms by means of natural selection. Later, with the development of computer technology, Nelson and Winter (1982) presented a model, in which the firm is the basic unit of evolution, and the macroeconomic properties are affected from the microeconomic behaviours of these units (i.e. agents). This work is summarized in a well-known book, which frequently serves as a starting point for many Schumpeterian models. Other important characteristic of Schumpeterian models is the fact that firms are categorized into innovative and imitative firms (Winter, 1984).

Since Nelson and Winter, neo-Schumpeterian models have proliferated in the literature. This thesis focuses on the so-called artificial life (a-life) or agent-based models.

## 3.3 Coase meets Schumpeter

This thesis addresses the regulation of spectrum from an evolutionary and transaction cost perspectives and thus it combines transaction costs (i.e. institutional) and evolutionary economic theories. Such combination has been suggested in the literature; however, it has not been widely applied and therefore, it still involves certain level of novelty. Some references supporting a research approach including Coase and Schumpeter perspectives are summarized as follows. Foss (1994) argues that a neo-institutional economics requires an evolutionary perspective to address the analysis of the market dynamics. He denominates this resulting research field as *dynamic neo-institutionalism*. In the urban planning area, Lai and Lorne (2014) identify that Coasean transaction cost reduction and Schumpeterian innovations have no inherent contradictions, but Coasean institutional arrangements enable both Coasean exchange efficiency and Schumpeterian innovations. In this way, a new regulation can promote innovation while also being a mechanism to reduce transaction costs. On the other hand, Zawislk et al. (2012) investigate the characteristics of the firm, and claim that any firm when born is primarily focused on technological development (Schumpeterian innovation) or transactional efficiency (Coasean transaction costs), and in a second stage, managerial (management of innovations) or operational (operational efficiency due to decreased transaction costs). Finally, Langlois (2007) emphasizes that transaction costs are always costs of novelty and change, and therefore the firm, which is always entrepreneurial, faces the problem of coordination and achieves a cost advantage in the market, when the design and direction of tasks add value and higher coordination to manage uncertainty.

In line with the above cited literature, this thesis approaches spectrum management and regulation from a dynamic neo-institutional perspective, analysing transactions by means of neo-Schumpeterian simulation tools.

# 4. Research design and methods

This section describes the overall research design of the thesis: the research approach and process, together with the methods for analysing the research questions. This section additionally compares the utilized methods based on the obtained results.

## 4.1 Research approach

This thesis combines design and natural science research approaches (March & Smith, 1995). Natural science is concerned with explaining the natural phenomena (how and why the nature is), including traditionally research in physical, biological, social, and behavioural domains. Design science deals with artefacts (artificial phenomena as opposed to natural phenomena) and how they are built to attain a goal. In other words, while natural science investigates the reality, design science studies human creations. This thesis constantly combines natural and design approaches in every analysis. For instance, the main studied phenomena are: (i) spectrum, which is a natural resource and (ii) the technologies managing such resource, which are artefacts. In addition, the regulatory and economic perspectives are also subject of natural science, since they are related to social and behavioural domains. Natural science consists of discovery and justification. Discovery generate and propose scientific claims to theorize. Justification employs the hypothetico-deductive method to deduct theories from observational hypotheses. Design science, rather than proposing theories, creates in different forms: constructs (conceptualization to characterize and describe the phenomena), models (representation of the reality), methods (set of underlying constructs and a representation –model- of the solutions) and implementations (realization of an artefact in its environment). In short, if natural science theorizes and justifies, the design science builds and evaluates.

Being more concrete, this thesis contributes to, and utilizes the methods of systems and management sciences. Systems science analyses systematically a system. Management science is concerned with the quantitative analysis and solutions in business and management (North & Macal, 2007). From this perspective, this thesis analyses the management of a system, from top-down and bottom-up approaches, and both qualitatively and quantitatively.

By employing the framework of March & Smith (1995) which combines natural and design sciences, Figure 6 illustrates the performed research activities of this thesis: build, evaluate, theorize and justify; and the main research output: models, to provide policy guidelines and prescriptions. Models are based on multidisciplinary constructs and methods, and look at instantiations to justify their assumptions (implementations, standardization, testbeds, etc.). The main contribution of this thesis is to provide novel linkages between concepts (i.e. constructs) of different disciplines within the scope of spectrum regulation.

| | | Research activities | | | |
|---|---|---|---|---|---|
| | | Build | Evaluate | Theorize | Justify |
| Research outputs | Constructs | | | | |
| | Model | | | | |
| | Method | | | | |
| | Implementation | | | | |

**Figure 6.** Research activities and output of this thesis indicated in yellow.

Modelling and simulation activities have a longer tradition in system engineering (Sinha, Paredis, Liang & Khosla, 2001), but their importance is increasing in organizational and management fields (Harrison, Lin, Carroll & Carley, 2007). In fact, this thesis suggests that system level modelling and simulation are a powerful means to analyse regulatory challenges of complex systems, such as the constantly evolving ICT ecosystem.

## 4.2 Research process

The research process applied herein can be described as *iterative and incremental*; and in concrete, incremental discovery, design, and development of models and simulations (such as described by North and Macal, 2007). This process has its roots in the *iterative and incremental development* of software engineering, which opposes to a sequential or *waterfall* development process (activities such as requirement, design, implementation and verification are performed sequentially). The iterative and incremental process has been formalized by the *agile manifesto* in 2001, but its practice has been applied since mid-1950s (Larman & Basili, 2003). The main idea of such process is to develop a model incrementally, allowing the researcher to take advantage of what has been learned during the development of the previous incremental of the model. At each iteration, design modifications are made either by simplifying the model or by adding functionality.

In the discovery phase, modelling allows partial models to be build offering insights on industry dynamics. The discovered insights can lead to improvement to either real-world issues or model design. Then, such design improvements lead to further model development and consequently this process is repeated incrementally until the model is mature enough to obtain answers to the pursued research questions.

## 4.3 Research methods

This section presents the applied modelling and simulation methods; agent-based and system dynamics modelling. Both are based on evolutionary economics and can be linked with the neo-Schumpeterian tradition.

### 4.3.1 Agent-based modelling

Agent-based modelling has its roots in artificial life, a multidisciplinary field of research developed by mathematicians and computer science specialists. Von Neumann and Ulam proved in the early 1950s that an initial configuration of cells could reproduce itself by following a set of rules (Kwasnicki, 2007). The artificial life was called agent-based modelling to distinguish it from the alternative approach of describing an interactive population of individuals based on differential equations (e.g., Lotka-Volterra equations). Agent-based modelling performs a bottom-up study of complex adaptive systems, which emphasizes the adaptation of individuals given a simple set of rules. Thus, it employs local information to analyse emerging system behaviours. Currently, agent-based modelling is being utilized to study a broad set of complex adaptive systems, such as biological, social, engineering, manufacturing, financial and business systems. Recent references of agent-based modelling include various research areas; for instance, technology diffusion (Palmer, Sorda, & Madlener, 2015), the dynamics of insect infestation (Anderson & Dragicevic, 2015) and smart grid energy networks (de Durana, Barambones, Kremers & Varga, 2014).

An agent-based approach is suitable when the natural representation of a problem consists of interacting agents. Agent-based modelling involves (Macal & North, 2010): (i) a set of agents, which are self-contained, autonomous, have a state, are social, adaptive, goal-directed and heterogeneous; (ii) agent relationships, meaning that agents are connected through a network or topology; in other words, they have a neighbourhood; and (iii) agent environment which is the spatial location related to other agents and characteristics, that constraint agent actions.

Agent-based modelling studies a complex adaptive system which includes a planner unit (i.e. regulator) that is reactive and goal-directed, and it can change the rules of the game. Thus, it analyses whether designs proposed for economic policies, institutions and processes will result in socially desirable system performance over time. According to Tesfatsion (2006) an agent-based model has the following characteristics: (i) constructive understanding of processes involved in the model, such as production, pricing, and trade processes, from the perspective of the interacting agents; (ii) agents are constantly striving for survival and they should be able to prosper over time; (iii) agents (e.g., firms) are necessarily in rivalry with other agents competing for market power; (iv) the interaction between agents is based on their behaviour, which brings uncertainty, and on their learning process; (v) agents are able to interact, the model should define the role of organizations and conventions, which determine, for instance, the trading process, the exit and entry requirements, etc.; (vi) the resulting model describes the emerging performance obtained from the complex interactions among structural attributes, institutional arrangements, and individual behaviours. In an agent-based model everything affects everything else.

Agent-based modelling carries some disadvantages. One such disadvantage is that every model requires the construction of an economic model which is dynamically complete; for instance, it should not need the intervention from the modeller during the simulation. Other disadvantage is the scalability constraint with large-scale systems with thousands of agents. Finally, the difficulty of validating the models against empirical data because of the mentioned drawbacks. As a main advantage, agent-based modelling possesses high flexibility for describing real-world phenomena, bringing together micro-individual behaviours, interaction patterns and global regularities. Recent advances of computational tools are making this approach more suitable for solving and analysing a broader set of real-world problems.

### 4.3.2 System dynamics

System dynamics is another simulation technique developed by Jay Forrester in the 1950s for analysing business, technical and social problems encountered by managers in corporate systems (Forrester, 1958). System dynamics models a whole system or process which is dynamic and changes over time, from a top-down perspective (as opposed to bottom-up perspective of agent-based modelling). A system dynamics model analyses complex systems by means of flows and stocks, endogenous feedback loops and time delays. One central concept in system dynamics is the feedback loop which exists whenever decisions made by agents in a system affect the overall state of the system.

The roots of system dynamics go back to control engineering. Nevertheless, as a modelling technique it belongs to evolutionary economics, since it typically follows one or more of the following characteristics (Radzicki and Sterman, 1994): (i) path dependency; (ii) ability of self-organization; (iii) multiple equilibria; and (iv) chaotic behaviour. In addition, the non-linear relationship between variables causes that the active structures of a system change as simulation proceeds and therefore such a model is evolutionary. Moreover, in system dynamics, the iterative process of making the perceptions explicit and testing through simulation generate the real value of a model.

Thus, system dynamics is suitable for analysing complex adaptive systems from a top-down perspective. It offers a complete approach to study dynamic economic systems consisting of non-linearities and feedback processes which are not in equilibrium and evolve over time. The most recent references belong to various research areas; for instance, healthcare system (Rashwan, Abo-Hamad, & Arisha, 2015), social behaviours (Babader, Ren, Jones & Wang 2015) and systems planning and production (Kuai, Li, Cheng & Cheng, 2015). In telecommunications, Casey (2013) extensively applies system dynamics modelling in his doctoral thesis to study the evolution of wireless access technologies.

### 4.3.3 Comparison of research methods

Both agent-based and system dynamics modelling can be classified as neo-Schumpeterian methods, since they analyse evolving market dynamics. However, their modelling approach and focus are different, for instance, in the relationship among entities in the model and in the level they perform their analysis (Parunak, Savit & Riolo, 1998). While agent-based modelling focuses on entities (i.e. agents), system dynamics focuses on observables which are measurable characteristics of interest. Thus, agents interact with each other through their behaviours, and observables relate to each other by system level equations.

Agent-based modelling is more recent than system dynamics and they present different advantages. Agent-based modelling is more appropriate when the analysed system is characterized by a higher level of localization and decisions are more distributed. On the contrary, system dynamics is more suitable if the system is analysed as a whole, and therefore by its centralized characteristics.

Agent-based modelling and system dynamics may also be combined, as Borshchev & Filippov (2004); Scholl (2001); and Swinerd & McNaught (2012) suggest. However, this interesting approach is out of the scope of this work. This thesis prefers to analyse DSA technologies by means of these two methods separately, since each method is suitable for answering a different research question. Based on the obtained results, Table 4 briefly compares these methods. Agent-based modelling analyses the individual agent behaviours from a bottom-up approach, by defining their behaviours and analysing their emergent system-level interactions. This method is flexible in terms of the level of abstraction, but it tends to describe the details of agent behaviours, and thus it requires a low to medium level of abstraction. Due to the previous fact, the time frame of analysis is short to medium (from hours to months) and indicates a low ability to scale, being especially useful for analysing local behaviours of agents. On the other hand, system dynamics modelling applies a top-down analysis of the system, by describing the relation between system-level observables. Thus, it possesses a higher level of abstraction since it focuses on the most important feedback loops of the whole system, aiming at simplifying the model as much as possible. Moreover, it indicates a high ability to scale and its time frame is typically longer (from months to years).

**Table 4.** Comparison between agent-based modelling and system dynamics

| | ***Agent-based modelling*** | ***System dynamics*** |
|---|---|---|
| ***Approach*** | Bottom-up | Top-down |
| ***Focus*** | Agent behaviours | System-level observables |
| ***Level of abstraction*** | Low-Medium | High |
| ***Ability to scale*** | Low | High |
| ***Time frame*** | Short-medium | Long |

## 4.4 Research output

The research output consists of six publications which are summarized in Table 5. Publication 1 answers the main research question in general by analysing the conditions of the Coase theorem and its implications for spectrum management. Publication 1 is the starting point for the whole thesis and it introduces the other publications. Publications 2-6 additionally incorporates an evolutionary perspective into the analysis of DSA technologies. Publications 2 and 3 performs a feasibility analysis for different cases of spectrum transactions. Publication 4 investigates the adoption of DSA technologies and how market structure (and policy decisions) affects such adoption. Finally, Publications 5 and 6 compare DSA technologies with other alternative mechanisms that could be used for increasing the economic efficiency of the Internet access market.

Methodwise, the thesis combines top-down and bottom-up analyses. Publications 1, 2, 3 and 6 are based on agent-based modelling, which is a bottom-up approach, since it analyses the individual behaviour of agents. On the other hand, Publication 4 employs system dynamics modelling, which is a top-down approach and it focuses on the overall system (or industry) level dynamics and characteristics. Publication 5 presents a qualitative analysis of transaction and switching costs. In general, besides the type of approach, all publications are supported by literature review, expert interviews (even though they were not formalized), and a constant interaction with a testbed implementation project (End-to-end cognitive radio testbed, EECRT) and other views from an international research project (COST Action IC0905 TERRA). Additionally, each publication typically combines both bottom-up and top-down approaches, since it analyses economics and technology. However, in each paper, one of these components is more relevant. As illustrated in Figure 7, Publication 1 combines a bottom-up method with a top-down analysis. Publications 2 and 3 have a strong bottom-up component, since they explore the interference management, the main technical constraints of spectrum usage. Publications 5 and 6 still employs a bottom-up approach, however their top-down component is more relevant, since they analyse the overall market. Finally, Publication 4 performs a top-down analysis of the interaction between market structure and technology adoption.

**Table 5.** Summary of publications

| ID | Type of publication | Authors | Title | Research Question(s) | Methods |
|---|---|---|---|---|---|
| **1** | Journal paper (Telecommunications policy) | Basaure, Marianov & Paredes | Implications of DSM for regulation | Q | Agent-based modelling |
| **2** | Conference paper (DySPAN 2015) | Basaure & Holland | Optimizing spectrum value through flexible spectrum licensing | Q, Q1 | Agent-based modelling |
| **3** | Journal paper (Communication Magazine) | Kliks, Holland, Basaure & Matinmikko | Spectrum and licence flexibility for 5G networks | Q, Q1 | Agent-based modelling |
| **4** | Journal paper (Telecommunication systems) | Basaure, Sridhar & Hämmäinen | Adoption of Dynamic Spectrum Access technologies: A System Dynamics approach | Q, Q2 | System dynamic modelling |
| **5** | Conference paper (CSWS 2013) | Suomi, Basaure & Hämmäinen | Effects of capacity sharing on mobile access competition | Q, Q3 | Qualitative analysis based on literature review |
| **6** | Journal paper (Telecommunications policy) | Basaure, Suomi & Hämmäinen | Transaction vs. Switching Costs - Comparison of Three Mechanisms for Future Mobile Market | Q, Q4 | Agent-based modelling |

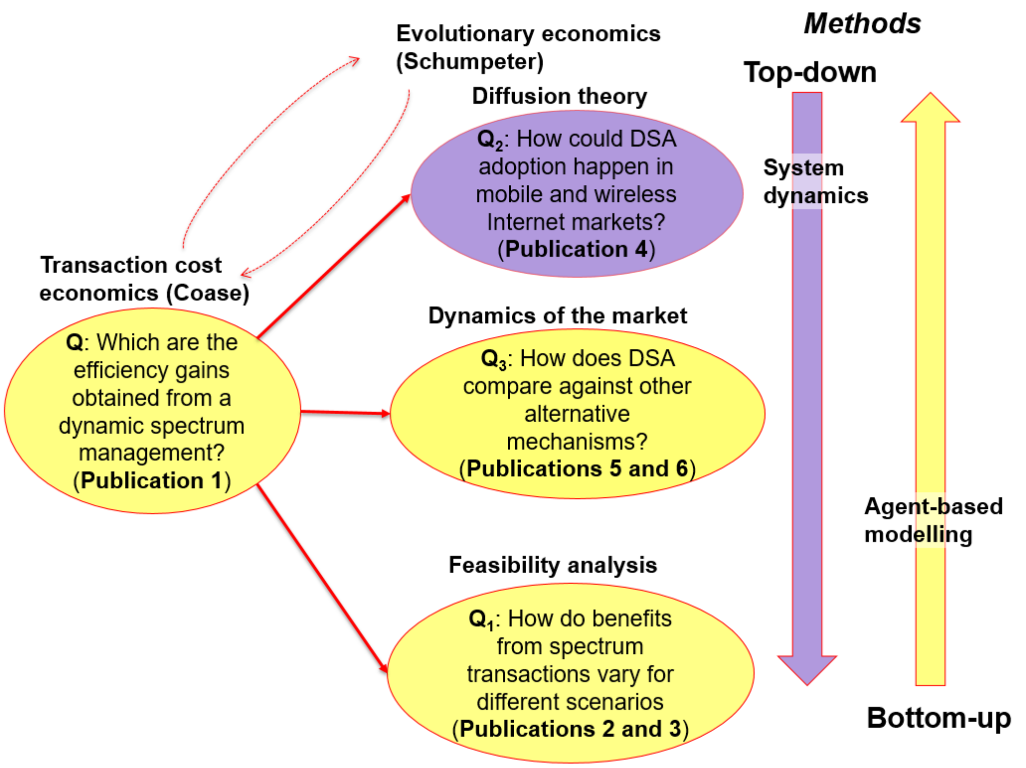


**Figure 7.** General scheme of research output

# 5. Modelling, Analysis and Results

The following section presents the most important models developed in this thesis for analysing the set research questions. These models and the related analysis summarize the research output of the thesis. Each model is presented with its corresponding results.

## 5.1 Implications of DSA for regulation

This first modelling exercise focuses on an ideal mobile market in which DSA technologies are fully deployed and transaction costs are zero. The purpose is to compare different spectrum regimes in a scenario with zero transaction costs. By comparing these regimes, the study assesses the potential benefits of deploying DSA technologies. Thus, this model aims to answer the main research question from a general perspective without dealing with the topics of the three subquestions.

This model is not intended to describe the reality in detail, but rather to understand the potential gains of spectrum transactions and the factors determining these gains. Therefore, it is a conceptual model, which employs the Coase theorem as the underlying economic framework explaining the gains from transactions. Factors determining the value of the spectrum are listed as follows: (i) transactions are valuable because spectrum is scarce and its valuation is heterogeneous (i.e. varies with place, time, frequency and usage); (ii) DSA decreases spectrum transaction costs; (iii) DSA helps to clearly define spectrum property (or usage) rights, especially regarding interference management between the involved parties; and (iv) spectrum transactions require a competitive market (i.e. low market concentration) [7]. The following model is built based on these factors and compares different spectrum regimes which have been proposed in the context of DSA.

### Model

The model simulates a competitive market allowing spectrum transactions. The simulation assumes three similar MNOs and four LAOs per type of area (home, office or public). This setup emphasizes diversification of operators to

[7] See Publication 1 for further details

enable all beneficial transactions. This model presents a general scheme of capacity transaction between MNOs and of spectrum sharing between LAOs under different spectrum regimes. A mobile user is served by an MNO or LAO. This model additionally emphasizes the heterogeneity of service demand, in terms of capacity and quality requirements, and the diversification of service supply.

The simulation setup depicted in Figure 8 assumes that spectrum and network capacity transactions are performed between MNOs and between MNOs and LAOs. A centralized trading system acts as a mediator by publishing trading information each hour, 24 times a day. Spectrum is traded at operator level, but the access is granted at user level. In such case, the mobile user requests permission from a local spectrum database, which grants access under predefined conditions of interference and QoS. Such access can be provided by MNOs or LAOs. The model assumes 20 types of services, categorized by QoS class (from 1 to 4) and capacity requirement, as indicated in Table 6. Since transaction costs are zero, mobile users can be served by any MNO or LAO if the user is in the same coverage area (home, office, or public). Users follow traffic and location patterns obtained from measurements performed in Helsinki (see Publication 1 for further details).

Finally, the value of the service is defined by its capacity and quality requirements. Thus, each served unit of traffic has the following valuation: Unit Value (QoS 1) > Unit Value (QoS 2)> Unit Value (QoS 3)> Unit Value (QoS 4).

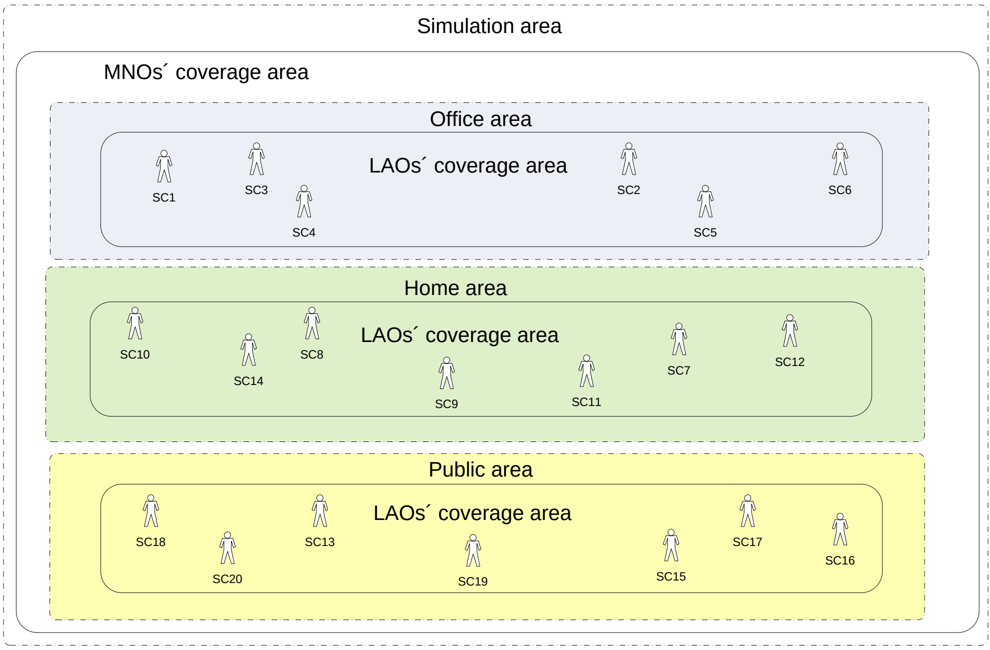


**Figure 8.** Simulation setup.

**Table 6.** Service categorization (adapted from Publication 1)

| Service type (capacity requirement) \ Traffic class (QoS requirement) | Conversational (QoS 1) | Streaming (QoS 2) | Interactive (QoS 3) | Background (QoS 4) |
|---|---|---|---|---|
| **Super-high multimedia (e.g., premium service)** | SC1 | SC6 | SC11 | SC16 |
| **High multimedia (e.g., video streaming)** | SC2 | SC7 | SC12 | SC17 |
| **Medium multimedia (e.g., Internet browsing)** | SC3 | SC8 | SC13 | SC18 |
| **Low rate data and low multimedia (e.g., messaging services)** | SC4 | SC9 | SC14 | SC19 |
| **Very low rate data (e.g., M2M services)** | SC5 | SC10 | SC15 | SC20 |

Table 7 summarizes the simulation scenarios. The first scenario describes the current situation of MNOs consisting in a combination of exclusive and commons regimes, which includes mobile offloading in Wi-Fi networks (i.e. LAOs). The second scenario simulates a cooperation scenario, in which MNOs can share or trade spectrum and network capacity between them, but maintaining the current exclusive regime. This may occur by allowing network operators to join their licenses for a shared access or through any type of cooperation mechanism, such as infrastructure sharing. In addition, mobile users offload their traffic to local-area networks based on a commons regime. For the remaining scenarios (LSA, pluralistic and light licensing) network capacity and spectrum are traded in the market. User access spectrum by means of a spectrum database, which holds real-time information. Different regimes achieve different levels of QoS. For instance, while light licensing can provide end-user with QoS level 3, LSA is able to achieve QoS level 2. Pluralistic licensing can provide from QoS levels 4 to 1, depending on the agreed conditions. Additionally, the adaptive pluralistic licensing regime assumes that each operator can modify its interference level over time according to the information they have on the demand.

**Table 7.** Simulation scenarios, assumptions (adapted from Publication 1)

| **Scenario for Simulation** | **Transactions allowed** | **Available QoS (1 highest, 4 lowest)** | **Adapt interference in time?** |
|---|---|---|---|
| Mobile offloading based on opportunistic use of commons | No | QoS 4 | No |
| Operator cooperation based on commons and exclusive regimes | No | QoS 1 (exclusive) and QoS 4 (commons) | No |
| Spectrum market based on LSA licensing | Yes | QoS 1(from mobile operators) and QoS 2 (from local operators) | No |
| Spectrum market based on Light licensing | Yes | QoS 1 (from mobile operators) and QoS 3 (from local operators) | No |
| Spectrum market based on Pluralistic licensing, fixed interference | Yes | QoS 1 (from mobile operators) and QoS 1 to 4 (from local operators) | No |
| Spectrum market based on Pluralistic licensing, adaptive interference | Yes | QoS 1 to 4 (from mobile and local operators) | Yes |

## Results

The simulation results are summarized in the following Figure 9. These graphs show, in average, the amount of traded or shared spectrum and network capacity capacity per each QoS class (from 1 to 4). Figure 9 (a) depicts the starting point or current situation based on opportunistic mobile offloading. Figure 9 (b) includes cooperation or spectrum sharing between wide area networks of MNOs, and others allows spectrum transactions between MNOs and LAOs based on different spectrum regimes: LSA (Figure 9(c)), light licensing (Figure 9(d)), and pluralistic licensing (Figures 9(e)(f)).

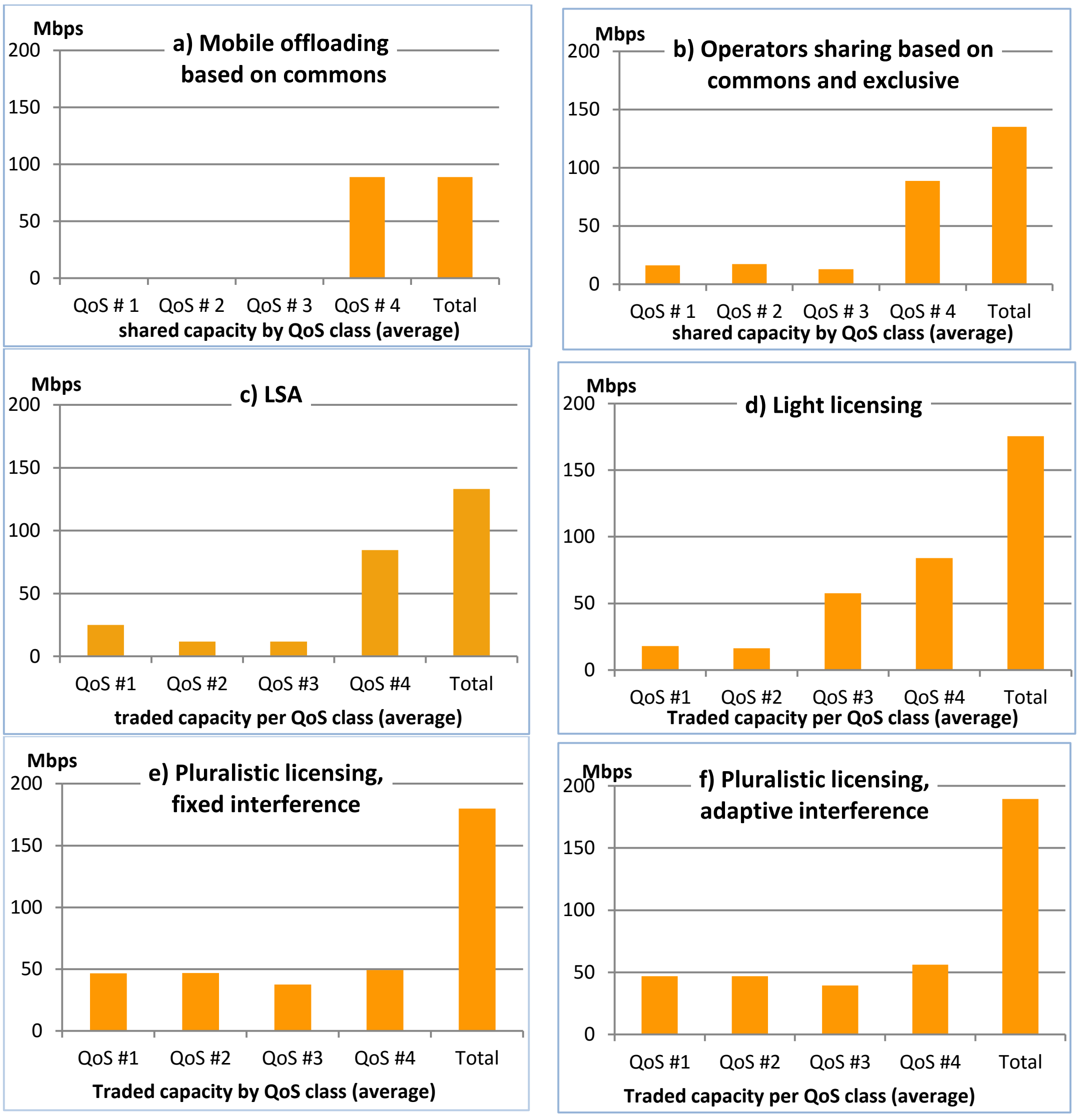


**Figure 9.** Simulation results (adapted from Publication 1)

The simulations results show significant potential gains with a flexible spectrum regime allowing transactions. These results are based on the assumption of heterogeneity of service valuation, and the ability of DSA technologies for detecting these valuations and to trade accordingly. Even though these technologies are still under development and have not been successful deployed, DSA can effectively decrease transaction costs if spectrum usage rights are better defined. DSA facilitates detecting and trading spectrum on a real-time basis (or near real-time) by establishing interference parameters as a tradable characteristic of the spectrum. Thus, DSA decreases transaction costs and improves the definition of usage rights.

This is an important observation, since both a reduction in transaction costs and clearly defined property (or usage) rights provide the conditions for the Coasean implications on policy.

The obtained gains are significant and rely on the changing nature of the service demand, which varies in time and place. This creates diversity and volatility in service valuation, which further increase when the spectrum is scarce. Even though this simulation model highly simplifies the reality, it addresses an important issue by claiming that the widely adopted exclusive and commons regimes offer considerable room for improvement.

Pluralistic licensing has been recently proposed by Holland et al. (2012) to address the increasing sophistication required by spectrum transactions. From a Coasean perspective, transactions should take place between private participants, i.e. through contracts between MNOs, rather than being defined by the regulator. Thus, private contracts are more dynamic with changing conditions of the market, since the interference tolerance may be adapted if initial conditions change. In addition, local licenses may be bought and sold to adapt the network supply to the changing demand. From a technical perspective, local area networks (such as Wi-Fi or small cells) are far more flexible than wide area cellular networks for adapting to changing conditions.

## 5.2 Feasibility study on spectrum transaction cases

Based on the previous results, the following model simulates different bilateral spectrum transactions based on real world conditions. The previous section analysed spectrum transactions without technical details. This section conducts a feasibility study comparing the obtained benefits from different spectrum transaction scenarios, considering the interference as a tradable characteristic of the spectrum. Thus, this section performs a sensitivity analysis of the parameters affecting spectrum transactions between private operators to develop a general framework which facilitates spectrum trading. The analysed cases describe different types of operators and end-users. For each case, the model finds the conditions for spectrum value optimization. Note that from a regulatory perspective, the NRA is a facilitator, which defines the rules for enabling transactions, increasing coordination and lowering transaction costs. Prices are a private decision of the involved parties, and therefore this section does not perform any calculations on pricing. This section answers the following research question: How do benefits from spectrum transactions vary for different dynamic spectrum management scenarios?

## Model

This following model performs a feasibility analysis of the five scenarios presented in section 2.8. It models spectrum transactions between two operators, based on a primary-secondary or co-primary scheme. In a primary-secondary transaction, the primary and secondary users have different priorities, while co-primary users transmit with equal priority. This model is intended to reflect a pluralistic licensing scheme, however, it can be easily extrapolated to other more general schemes allowing spectrum sharing; for instance, to the three tiered sharing framework (see Figure 5). Specifically, this model assumes that the coordination between the involved operators is provided by a spectrum database, which knows or calculates the technical characteristics and geographical coverage of the primary users to allow the secondary or co-primary users to transmit. An example of rules for the co-primary and secondary transmissions have been defined by the FCC (2010). Thus, such database grants permission to transmit within a predefined area (coverage area) and within certain mobility restrictions (leasing distance). The performance of the co-primary and secondary transmissions may be further improved by means of more advanced sensing capabilities to obtain real-time information on primary location.

The first scenario represents an urban area in which the primary system consists of five-cells-wide section of a cellular network. The secondary users are transmitting directly through device-to-device (D2D) communication system, outside the primary coverage area and without any specific network infrastructure (see Figure 10 for a graphical representation). Both systems transmit in the 700 MHz band and the simulation describes the downlink behaviour in a FDD scheme. The secondary users request the spectrum database each time they move over their leasing distance.

The second scenario models two separate cellular networks transmitting in the 2.6GHz frequency band in close geographical proximity, as depicted in Figure 11. The two networks and their users have similar characteristics, except that one system has a priority over the other (i.e. primary and secondary). The simulation describes the downlink behaviour in a FDD scheme. This scenario can also be modelled as a co-primary spectrum transaction.

The third scenario describes a TV primary system coexisting with a cellular secondary system located in the surrounding area of the TV coverage, both transmitting in the 700MHz band, following a TDD scheme, as depicted in Figure 12. The analysed scenario and related frequency band have been subject of public discussion (EU COM, 2013), and they can also be a reflection of the ETSI WSD standard. Cellular devices access the TVWSs after checking with a spectrum database, as in the first scenario. TV primary receivers require a strict minimum level of signal-to-interference-and-noise-ratio (SINR) which is assured through a margin representing a certain confidence level.

The fourth scenario, depicted in Figure 13, represents a spectrum transaction between an outdoor cellular network (e.g., macro or micro cells) acting as the primary system and an indoor small-cellular network (e.g., femto cells) acting as the secondary system, both transmitting in the 2.3 GHz band. The coverage areas are delimited by the outdoor-indoor interface and a spectrum database works as an authoritative register for secondary users.

Finally, the fifth scenario analyses two adjacent indoor areas; for instance, two buildings separated by a street in a residential area, each one deploying a local area network by means of a small cellular network (e.g., pico or femto cells), as depicted in Figure 14. This scenario implements a co-primary scheme, in which each local network is managed autonomously, and all systems are transmitting in the 60GHz band (i.e. millimetre-waves).

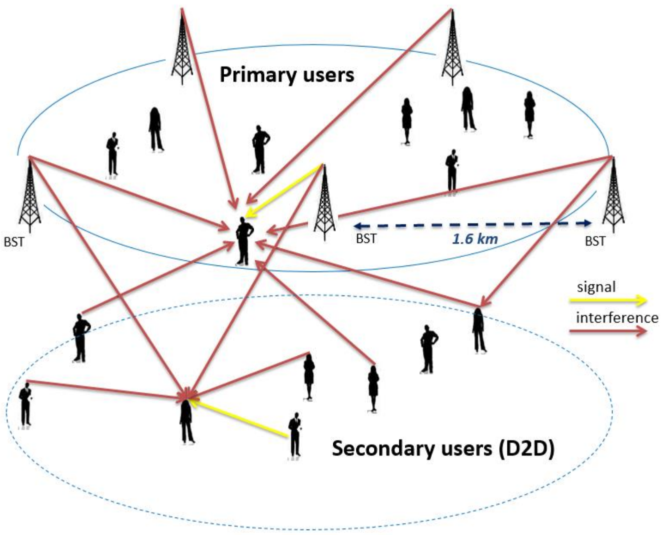


**Figure 10.** Scenario 1 (adapted from Publication 2)

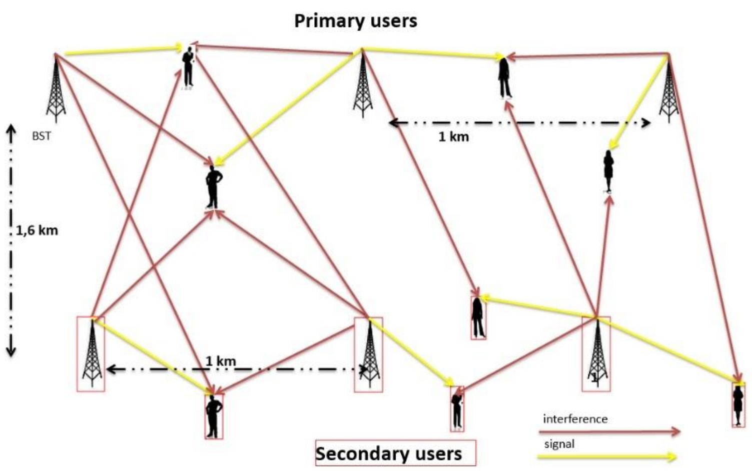


**Figure 11.** Scenario 2 (adapted from Publication 3)

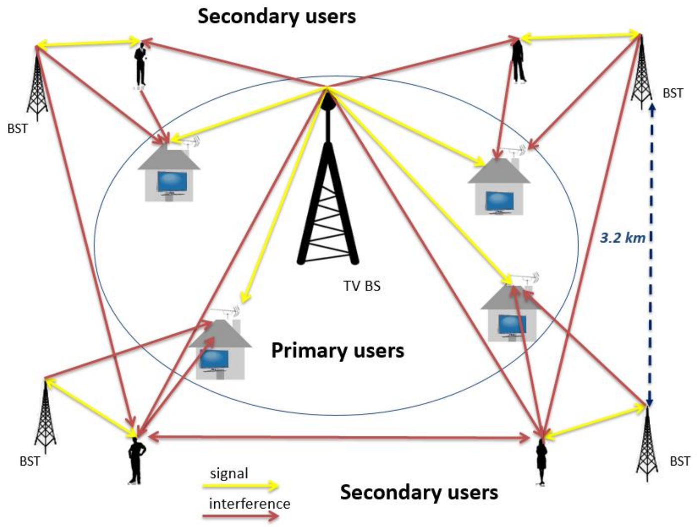


**Figure 12.** Scenario 3 (adapted from Publication 2).

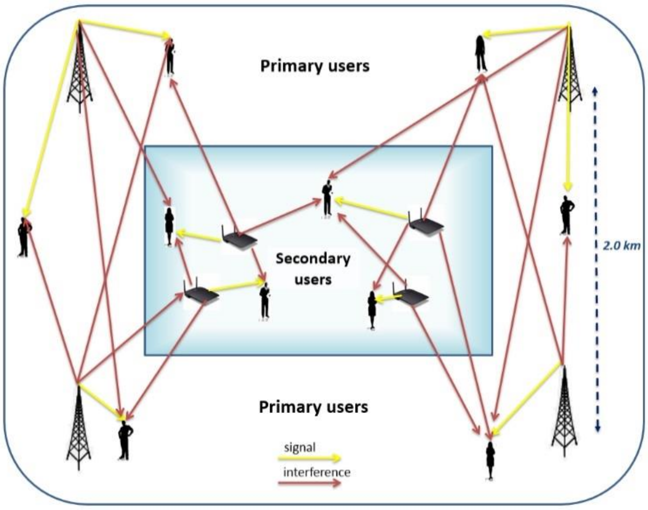


**Figure 13.** Scenario 4 (adapted from Publication 2)

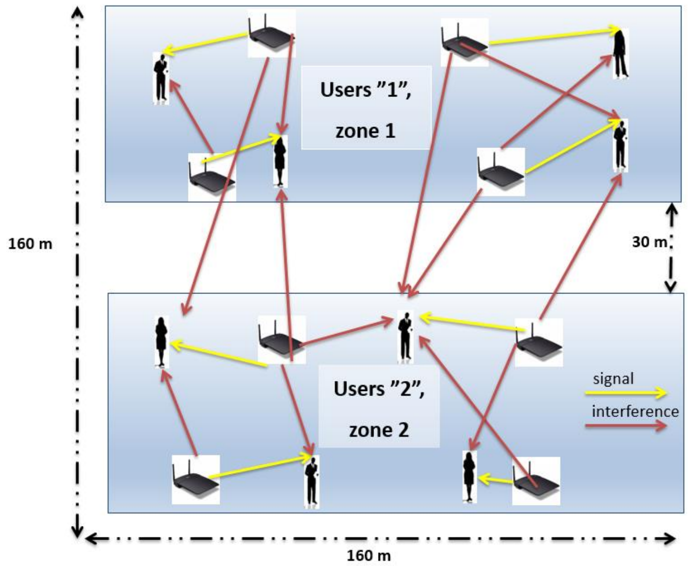


**Figure 14.** Scenario 5 (adapted from Publication 2)

## Results

This section presents the potential gains for the simulated scenarios. For each scenario, different user utility functions are selected, such as represented by Figure 15. The shapes of these functions (e.g., concave versus convex range) describes the criticality of multimedia requirements in terms of SINR (assumed proportional to throughput and perceived QoS) and they are cathegorized into real-time, not real-time and strict real-time.

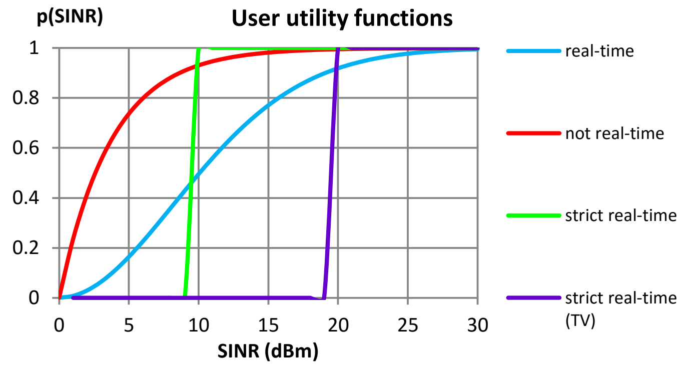


**Figure 15.** User utility functions (adapted from Publication 2)

In Figures Figure 16, 17, 18, 19 and 20, the total benefits are calculated based on individual user benefits for each operator and for all users. The costs of sharing are obtained by calculating the incremental energy costs incurred by the operator when adapting its transmission power. For all analysed scenarios, spectrum transactions result in additional benefits, indicating that the obtained gains are larger than the losses caused by interference. Figure 16 shows that the first scenario achieves its optimal interference level with primary base stations transmitting at 46dBm of power, when primary users have real-time and secondary users have not-real time requirements. The optimal interference depends on the user utility functions, the separation distance between coverage areas and the leasing distance of secondary users. The results of the second scenario (Figure 17) indicate a trade-off between the perceived QoS of each MNO, in which the network having priority (and more users) should transmit with higher transmission power than the secondary network to achieve the optimum. Figure 18 shows that, in the third scenario, when the primary operator is a TV network (with strict real-time requirements), the secondary system should transmit with low power and consequently the overall benefits of this scenario are limited; however, spectrum transaction is still beneficial. In the fourth and fifth scenarios (Figures 19 and 20), the optimum is achieved when both networks are transmitting with relatively high power to optimize their own QoS. Scenario five additionally highlights the importance of internal coordination for achieving the optimal benefits. In short, while the outdoor scenarios (1, 2 and 3) indicate a trade-off in QoS between the involved parties; the indoor scenarios (4 and 5) do not follow such a trend, since the interference is reduced by the walls.

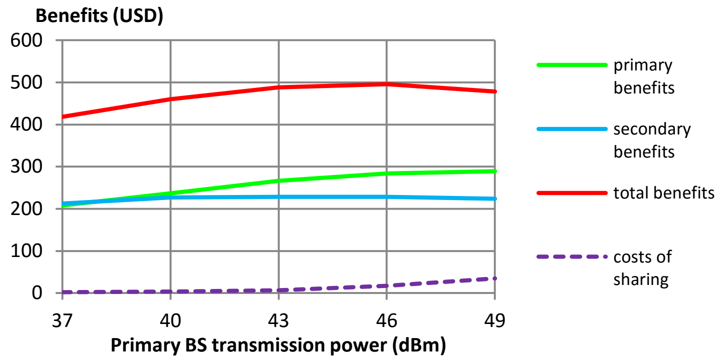


**Figure 16.** Simulation results for scenarios 1: Primary MNO (real time), secondary D2D devices (not real-time secondary) (adapted from Publication 2)

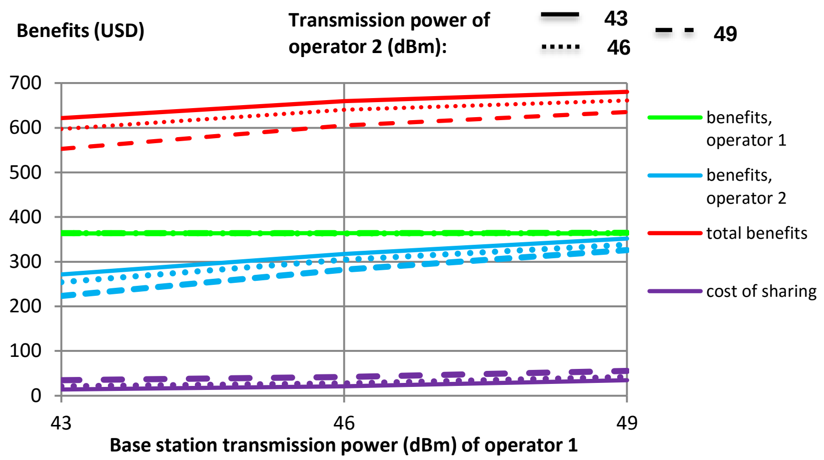


**Figure 17.** Simulation results for scenarios 2: Primary and secondary MNOs, all users require real-time service (adapted from Publication 2)

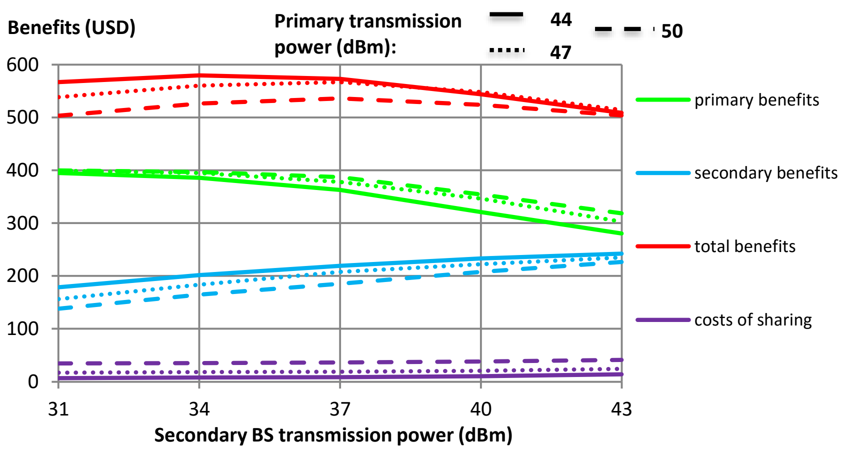


**Figure 18.** Simulation results for scenarios 3. Primary TV operator (strict real-time), and secondary MNO (not real-time) (adapted from Publication 2)

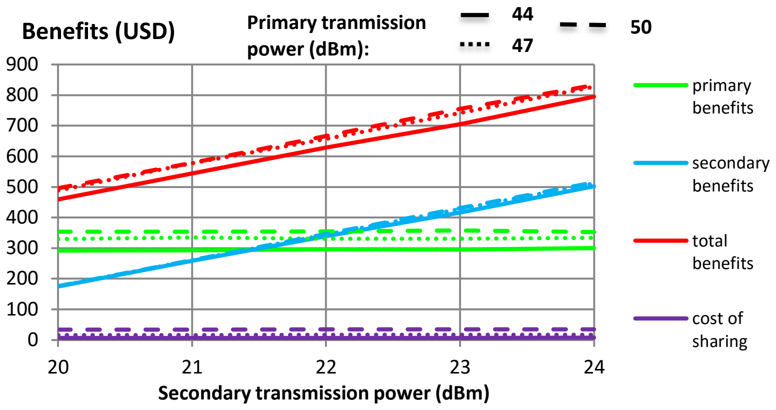


**Figure 19.** Simulation results for scenarios 4. Primary MNO (outdoor) and secondary femto-cell operator (indoor). Both have real-time requirements (adapted from Publication 2)

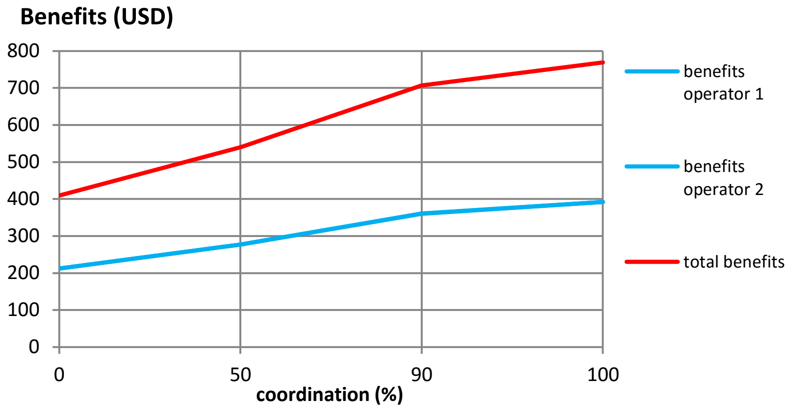


**Figure 20.** Simulation results for scenario 5. Two small cell operators, all users have similar requirements (adapted from Publication 2)

This simulation exercise assesses the benefits of spectrum transactions, which include interference as a tradable characteristic of the spectrum. Thus, it performs a feasibility analysis of realistic spectrum transaction between two operators, based on the state-of-the-art DSA technologies and on the pluralistic licensing concept. The results show that the optimal level of interference is usually above zero; therefore, spectrum transactions should consider the interference that a spectrum holder is able to receive and generate. A spectrum regime needs to provide operators with an economic incentive to accept a certain level of interference to maximize the value of the spectrum. Moreover, spectrum transactions should consider user utility functions. This observation holds for both primary-secondary and co-primary schemes.

In all analysed scenarios, this study indicates that for a given spectrum band, a demand increase will result in additional benefits if voluntary transactions are allowed. Therefore, a scheme which restricts transactions or minimizes interference, such as exclusive licensing, is never optimal. The optimal level of interference will depend on service requirements and user utility functions.

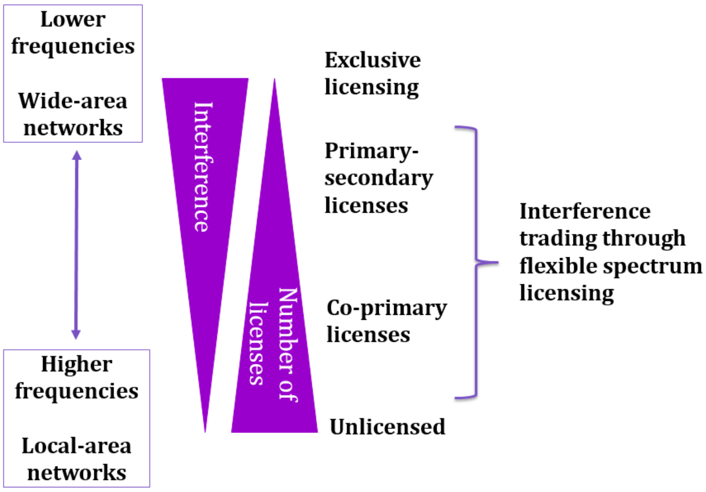


**Figure 21.** Scheme of simulation results: frequencies and type of regime

Figure 21 summarizes the obtained results. In general, spectrum transactions are beneficial when they consider the interference in the transaction. However, those cases which generate the least amount of interference are especially beneficial; in concrete, in indoor-outdoor and indoor transactions. Between exclusively assigned low frequency bands and license-exempt high frequency bands, medium range frequencies may be beneficially traded in a primary-secondary or co-primary fashion. From this middle range, lower frequencies may be more suitable for a primary-secondary scheme, while higher frequencies may be more suitable for co-primary scheme.

The previous observations may be especially interesting for the deployment of future indoor networks, including 5G, small cells and emerging IoT applications, since they require less coordination than wide-area networks. For very high frequencies (i.e. millimetre-waves), the most suitable regime may be the license-exempt, since those frequencies do not require coordination between spectrum holders. For outdoor cellular networks, LSA seems to be the first practical implementation for spectrum trading, being its benefits smaller than those of the indoor scenarios.

## 5.3 Adoption of DSA technologies

The previous sections 5.1 and 5.2 analyse the benefits of spectrum transactions. This section models the adoption of DSA technologies, to understand the requierements for a successful DSA deployment. Since DSA changes the way spectrum is managed, and spectrum assignment is in tight relation with the industry structure, this modelling work performs a top-down analysis based on system dynamics to understand the interaction between technology adoption and industry dynamics. This analysis considers two main elements affecting the adoption of DSA technologies: (i) industry openness, defined as entry and exit barriers, and (ii) spectrum centralization which is the mode spectrum is assigned, its associated usage rights and consequent concentration. As described in sections 2.3 and 2.6, DSA standards may be adopted by operators or by end-users. In addition, DSA technologies compete with network or substitution effect, depending on the type of design a standard is implementing. This section answers to the following research question: How could DSA adoption happen in Internet access markets?

## Model

This work performs a synthesis of previous modelling work, specifically the spectrum management modelling of Sridhar, Casey and Hämmäinen (2013), the industry openness dynamics of Davies, Howell and Mabin (2008), the network effect modelling of Sterman (2000) and the substitution effect formulation of Pistorius and Utterback (1996). Figure 22 presents a system dynamics representation of a competition model with network and substitution effects.

System dynamics employs causal loop diagrams to visualize the relation between variables in a system. Diagrams consist of nodes and edges; nodes represent variables, while edges depict the relationship between variables. The sign and direction of the edges indicate the type of relationship forming a causal link; two nodes change in the same direction if the sign is positive, or they change in opposite direction if the sign is negative. A causal or *feedback loop* is the result of a closed sequence of causal links. The feedback loop is *reinforcing* (denoted as R) if a variation in any variable propagates through the loop and returns to the initial variable with the same direction, further stimulating the initial variation. The feedback loop is *balancing* (denoted as B), if a variation in any variable propagates through the loop and returns to the initial variable in opposite direction, causing the contrary effect.

Figure 22 (a) models the network effect produced by the path dependence of two competing technologies. In this figure, the variable adoption (of user- or operator-centric devices) describes the performance of each type of device. The adoption level positively affects the installed base of these devices; and this higher installed base leads to higher levels of compatibility and hence attracts more adoption of such devices. This in turn increases the market share of these devices, which constitutes a reinforcing network effect (loops R1 and R2). However, an increase in attractiveness of one type of device decreases the share of the other type of device, which slows down the rate of adoption and causes a saturation in the adoption of the other type of device, as depicted by balancing loops B2 and B1.

Figure 22 (b) illustrates the substitution effect, by employing a predator-prey competition model, which is mathematically described by the Lotka-Volterra equations and describes technological substitution (Pistorius & Utterback, 1996). This model exhibits a similar logic than the previous model, but with a different relation between the two competing technologies: the growth of user-centric devices (predators) leads to the substitution of operator-centric devices (prey). Hence, the reinforcing loops R1 and R2 originate the substitution balancing loop B1.

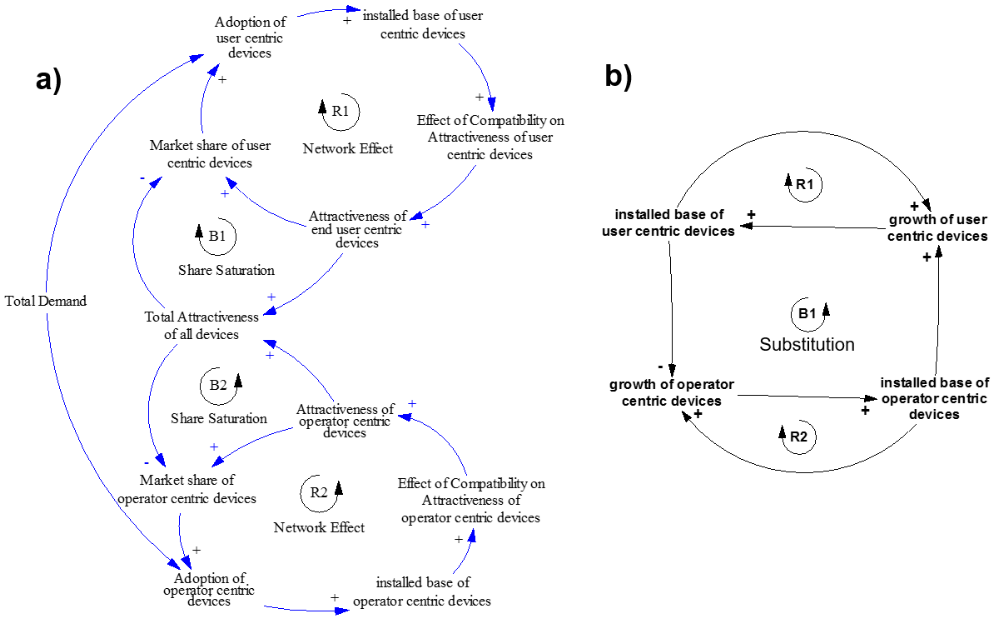


**Figure 22.** System dynamics representation of DSA adoption with network and substitution effects (adapted from Publication 4).

Figure 23 (a) adapts the model on spectrum management developed by Sridhar, Casey and Hämmäinen (2013). This model explains that a centralized spectrum management incentivizes a wholesale spectrum market, thus leading to adoption of operator-centric DSA technologies, depicted as reinforcing loop R3 (wholesale); and at the same time discouraging a user-centric adoption in the retail market. On the other hand, a market driven and decentralized spectrum assignment incentivizes user-centric adoption of DSA technologies in the retail market, depicted as reinforcing loop R4 (retail). In the wholesale loop, high spectrum concentration stimulates operator-centric spectrum sharing and trading that subsequently stimulates high spectrum concentration, without any need for a decentralized spectrum regime. In the retail loop, lower spectrum concentration induces end-users to drive the spectrum market, which in turn promotes user-centric devices to be deployed and thus promoting a decentralized spectrum regime. The reinforcing loops R5 and R6 show that the growth in one type of devices reduces the demand for the other type of devices.

Figure 23 (b) adapts the model describing the industry openness developed by Davies, Howell & Mabin (2008). This model explains that low entry barriers (i.e. open industry) favoured by regulators to stimulate competition can have a negative impact on investments due to a decrease in operator profits. This leads to a reinforcing loop (R7), because a decrease in prices opens the industry further. In a similar manner, increasing entry barriers due to a regulatory effort to improve QoS, provides market participants incentives to invest in operator-centric infrastructure, which decreases industry openness and disincentivizes user-centric DSA technologies, causing the reinforcing loop R8. At the same time, lowering entry barriers (i.e. opening the industry) decreases the willingness to invest in operator-centric infrastructure, making the user-centric proposition attractive for old and new industry actors (reinforcing loops R9 and R10).

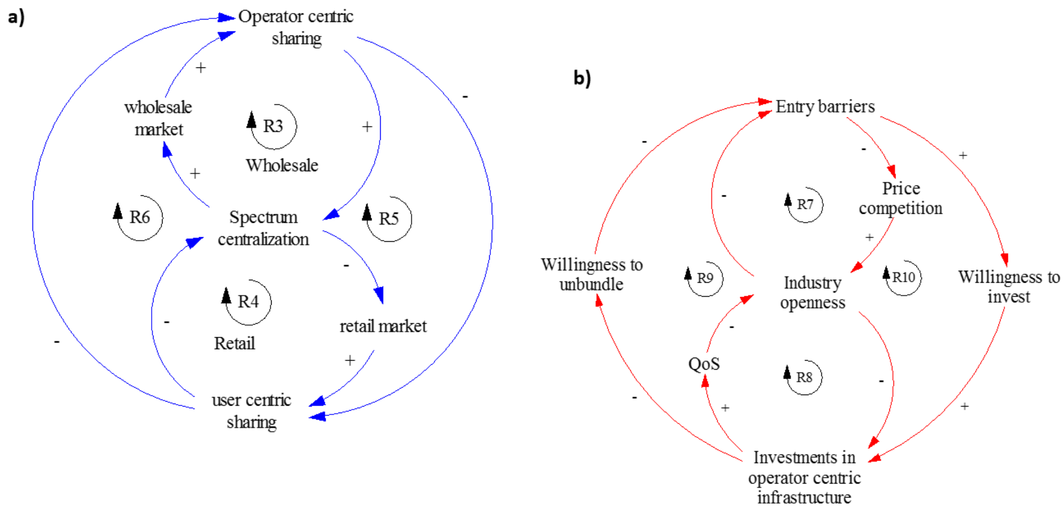


**Figure 23.** System dynamics representation of industry openness and spectrum centralization (adapted from Publication 4).

The integrated models consist of the merging of Figure 22 and Figure 23. See Publication 4 for further details. Thus, spectrum centralization and industry openness affect the adoption of user- and operator-centric technologies for both types of competition; with network and substitution effects. The model assumes a spectrum regime allowing transactions, which may happen at retail or at wholesale levels. If the spectrum regime is centralized, spectrum sharing or trading is performed between operators. If the spectrum regime is decentralized, spectrum transactions are driven by end-users.

## Results

Table 8 summarizes the simulation results of the adoption models with network and substitution effects. With high network effect, the adoption of user-centric devices is only successful under open industry and decentralized spectrum. With substitution effect, user-centric devices are adopted with a decentralized spectrum, regardless the industry openness. In all other cases, operator-centric adoption dominates.

**Table 8.** Summary of the results

| | Spectrum | Industry | Operator-Centric | User-Centric |
|---|---|---|---|---|
| Network Effect | Centralized | Open | √ | |
| | | Closed | √ | |
| | Decentralized | Open | | √ |
| | | Closed | √ | |
| Substitution Effect | Centralized | Open | √ | |
| | | Closed | √ | |
| | Decentralized | Open | | √ |
| | | Closed | | √ |

These observations are relevant to the current discussion on DSA adoption for two reasons. Firstly, most of the countries have a centralized spectrum; and secondly, most of the DSA standards have been developed for end-users. This means that most of the DSA efforts will not be successfully adopted in most countries under current spectrum conditions, as described by Table 9.

Thus, if few operators continue to hold most of the spectrum, an operator-centric adoption of standards such as ETSI RRS LSA, 3GPP CA and open standards like Weightless offering specific IoT integral solutions may dominate. For markets with decentralized spectrum, end-user adoption dominates for open industries, including for standards with modular design, such as 3GPP D2D, ETSI Reconfigurable MD, IEEE 802.11af and 802.11ah, and for standards with integral design, such as ETSI WSD, Weightless, IEEE 802.22 and IEFT PAWS. In closed industries, end-user adoption dominates for modular standards and operator-centric adoption dominates for integral standards.

**Table 9.** Application of the results

| SPECTRUM | INDUSTRY | NETWORK EFFECT | SUBSTITUTION EFFECT |
|---|---|---|---|
| **CENTRALIZED** | **OPEN** | WEIGHTLESS | ETSI RRS LSA, 3GPP CA |
| | **CLOSED** | | |
| **DECENTRALIZED** | **OPEN** | ETSI WSD, WEIGHTLESS, IEEE 802.22, IEFT PAWS | 3GPP D2D, ETSI RRS RE-CONFIGURABLE MD, IEEE 802.11AF, IEEE 802.11AH |
| | **CLOSED** | | |

DSA technologies involve a wide set of standards and solutions with different design and applications. This work aims to understand how these technologies may be adopted by operators or end-users. This work synthesizes the previous literature to explain such adoption. This is a question of interest given the uncertainty that these solutions present in the current market. Thus, this work provides a deeper understanding on the relation between mobile market and DSA technologies than the previous literature.

The standardization efforts of DSA can be divided into: (i) end-user centric with modular design; (ii) end-user centric with integral design; (iii) operator-centric with modular design; and (iv) operator-centric with integral design. Previous Tables Table 8 and Table 9 describe the conditions for a successful adoption for each type of solution. The system dynamics modelling developed herein describes how the industry structure affect the standard suitability and how the adopted standard affects back the industry structure.

In general, operator-centric DSA standards, such as 3GPP CA and ETSI RRS LTA, are therefore expected to dominate in most countries, which present a centralized spectrum. On the other hand, user-centric DSA standards may be adopted in countries with decentralized spectrum. The main reasons for this are the investment incentives and the lock-in of DSA technologies, as described by the system dynamics models. These observations emphasize the need for a more decentralized spectrum management in line with current DSA development, for instance, when assigning spectrum for new infrastructure deployment.

## 5.4 DSA against other alternative mechanisms

Finally, this last modelling work compares DSA with other alternative mechanisms, as described in section 2.9. Previous sections have explored the potential of DSA technologies. However, the techno-economic challenges of DSA may limit the potential benefits, at least initially, to only few cases. This section investigates other alternative solutions for increasing economic efficiency at outdoor and indoor networks. Thus, the following model compares inter-MNO spectrum transactions against two other mechanisms that increase market dynamics at different levels: national roaming which promotes network capacity trading, and end-user multihoming which allows the end-user to rapidly switch from one network to another. While transaction costs affect the industry structure and determine the level of vertical integration, switching costs determine the market concentration and the monopoly power of incumbent firms. This section answers to the following research question: How does DSA compare against other alternative mechanisms for increasing economic efficiency of Internet access markets?

## Model

The following agent-based model analyses the interaction between three MNOs and seventy-two end-users accessing mobile networks (see publication 6 for details on assumptions). Figure 24 depicts the simulation setup for the location of base stations of three MNOs. On the left side, the MNOs have a colocated topology and on the right side a non-colocated topology. In the colocated topology, MNOs have similar network coverages and they cooperate in passive elements (same location of antenna sites). In the non-colocated topology, MNOs show higher network coverage disparities. The colocated topology may describe an outdoor cellular network deployment, while the non-colocated topology may also be seen as a simple indoor deployment based on small-cellular networks. In general, both outdoor and indoor cases are equally represented by the same simplified simulation scheme, being the difference that in the indoor case each base station depicts a local network consisting on several small cells.

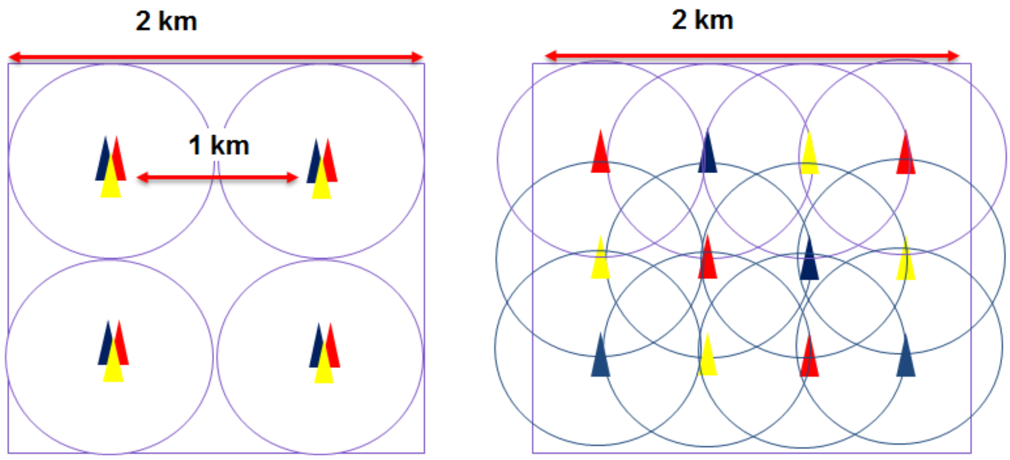


**Figure 24.** Simulation setup. (Left) collocated topology (Right) non-colocated topology (Adopted from Publication 6)

Switching and transaction costs are modelled in the simulation as described as follows. Switching costs are defined by the easiness for the end-user to switch from one MNO to another. Switching happens when the perceived benefits of switching, in present value, exceed the switching costs. Thus, the switching costs are estimated by the end-user based on his/her own experience on QoS failures and on the availability of information. A failure in QoS is defined in terms of signal strength (i.e. out of coverage) and congestion (i.e. not enough capacity). Switching costs are high when the end-user switches MNO only after tolerating many QoS failures. For the simulation, user switches after 10 failures for high switching costs, which roughly represent the switching cost of a manual SIM card replacement. The simulation assumes for this case that the end-user chooses another MNO randomly. When switching costs are at a medium level, then end-users switch MNO after only one failure, for instance through multi-SIM devices. The simulation assumes for this case that the end-user chooses the closest base station. Finally, switching costs are low, when end-users can proactively choose in each access the base station offering the best QoS (i.e. lowest congestion). This phase represents, for instance, the deployment of automated eSIM in which the real-time QoS comparison is based on MPTCP. Such deployment provides the end-user an automated switching decision capability based on previously user-configured settings.

Transaction costs are quantified via the break-even point between scale benefits and transaction costs. Thus, they describe the level of coordination between MNOs and its impact on the related costs items. In national roaming the costs are shown by the number of available roaming agreements for end-users. When transaction costs are high, the inter-MNO book-keeping is performed on a retail level by the involved MNOs and the routing is non optimal (i.e. through the home network), and thus roaming agreements will not be available for end-users. Thus, these high transaction costs are modelled by zero roaming agreements. Transaction costs are medium level if the inter-MNO book-keeping is performed at wholesale level. This situation is modelled as one roaming agreement available to end-users. Transaction costs are low when the inter-MNO book-keeping happens at wholesale level and routing is optimized through the visited network. This requires a higher level of trust and a well-defined trading mechanism. In the simulation, this situation corresponds to a full national roaming.

The transaction cost assumptions for DSA specifically describe a femto-cellular network deployment; however, this can be also extrapolated to outdoor networks (e.g., LSA scenario). Currently, spectrum trading between operators is non-existent for outdoor networks. With the deployment of indoor femto-cellular networks, the base station customer (e.g. home owner) experience a high demand in its network since he/she wants to provide access for an identified group of end-users (e.g. home guests). In such situation, inter-MNO carrier aggregation (CA) enables the femto-cellular customers to obtain additional spectrum. In the simulation, the transaction costs are medium when spectrum trading is managed manually, for instance in time-slots of 3 hours. Transaction costs are low, when spectrum transactions are automated and performed in time-slots of 3 minutes (i.e. the length of one iteration) without direct interaction of the femto-cellular customer. In this DSA scenario, spectrum transactions are performed upon request, mediated by a broker. CA permits to aggregate bandwidth of different sizes, from 1.4 to 20 MHz, and thus provides high flexibility in the amount of traded spectrum. The broker only coordinates transactions and does not own or hold any spectrum. This means that each femto network can temporally increase its capacity by acquiring additional spectrum.

Table 10 summarizes the simulated transaction and switching costs for each mechanism. Note that the level of costs between different mechanisms are not directly comparable, but the cost levels aim to match with the major cost reduction steps as enabled by technology.

**Table 10.** Definition of transaction and switching costs

| | Switching costs | Transaction costs | |
|---|---|---|---|
| | **End-user multihoming** | **National Roaming** | **DSA** |
| | *Number of experienced failures, after which the user switches MNO* | *Number of roaming agreements available for a user* | *Frequency of spectrum trading transactions* |
| **Low** | 0<br>(automated eSIM) | 2<br>(wholesale, optimal routing) | 3 minutes<br>(femtos, automated inter-MNO CA) |
| **Medium** | 1<br>(manual multiSIM) | 1<br>(wholesale, home routing) | 3 hours<br>(femtos, manual inter-MNO CA) |
| **High** | 10<br>(SIM replacement) | 0<br>(retail, home routing) | Never<br>(no femtos) |

## Results

The simulation results of Figures Figure 25, Figure 26, Figure 27 and Figure 28 show that any of the three analysed mechanisms (national roaming, DSA or end-user multihoming) can dynamically improve the allocative efficiency of the mobile market. In other words, a decrease of switching or transaction costs, that is, an increase of competition or cooperation, can result in higher efficiency. The model simplifies the complex reality and the simulation results are rather qualitative than quantitative; however, they describe well the underlying dynamics. In practice, the market efficiency improvement opportunity depends on the quality difference between networks.

While end-user multihoming is the most cost effective mechanism for increasing allocative efficiency, DSA is especially suitable for scenarios with high congestion. National roaming is an alternative choice to end-user multihoming for a regulator willing to promote cooperation between MNOs.

In general, any of these mechanisms can change the current market dynamics. Therefore, the regulator has little incentive to introduce them, if MNOs can maintain a good performance in terms of coverage, congestion and blackouts. Correspondingly, if the market suffers from performance problems, the regulator may consider promoting these mechanisms.

Moreover, the level of colocation of base stations highly affects the efficiency attained by these mechanisms. Thus, colocation decreases the opportunity of these mechanisms, while non-colocation (and their consequent coverage disparity) increases the opportunity. However, in reality, MNOs practice both approaches; they colocate part of their base stations to reduce costs and, at the same time, increase coverage in other areas through a non-colocated topology. Therefore, a balanced combination of cooperation and competition is needed to achieve higher efficiency. This observation is in line with literature suggesting that if cooperation enhances social welfare, the maximum degree of competition may not be efficient (e.g., Canegallo, Ortona, Ottone, Ponzano & Scacciati, 2008). Additionally, the simulation results are relevant for the small cellular networks based on non-colocated topology. Since small cells present coverage and capacity disparities together with challenges for developing a good business case; any of these mechanisms may be very relevant for MNOs in such deployments.

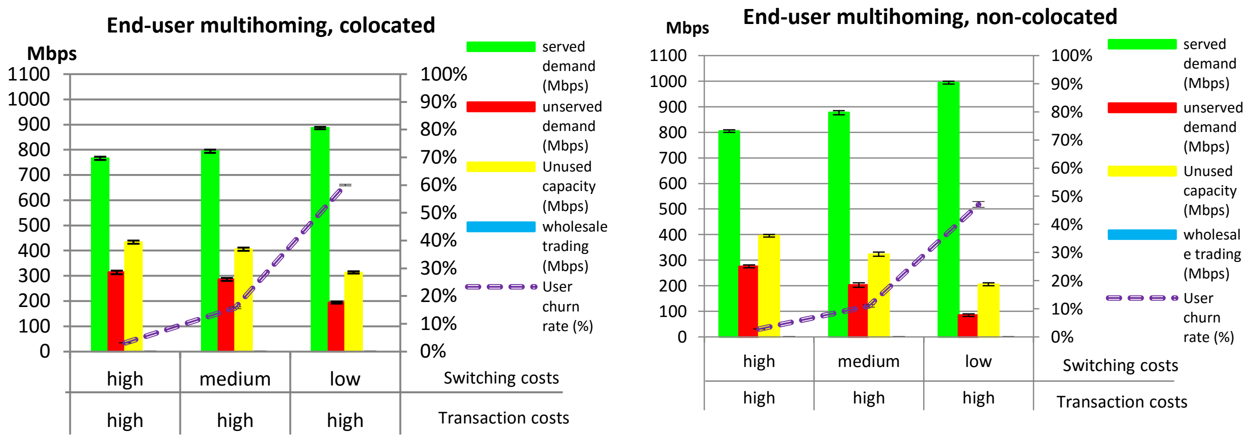


**Figure 25.** Simulation results of end-user multihoming

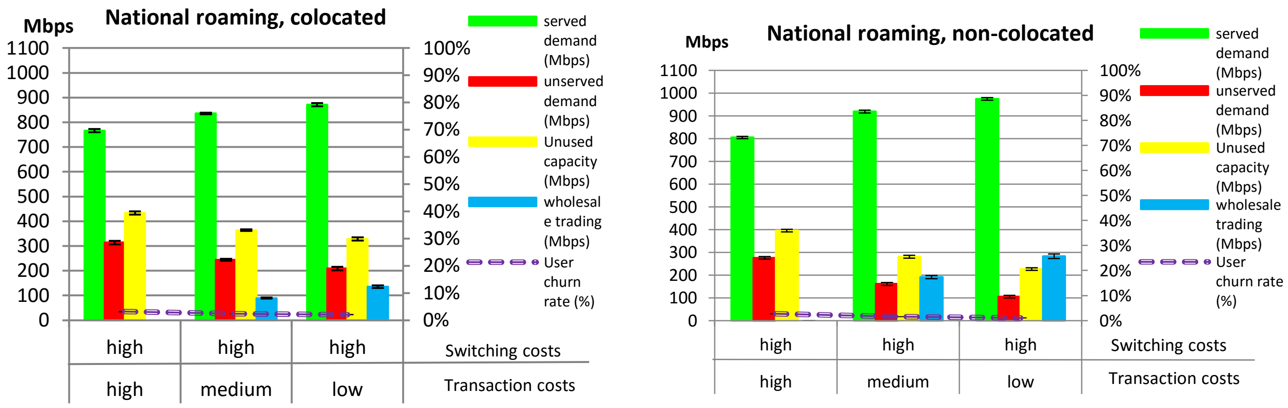


**Figure 26.** Simulation results of national roaming

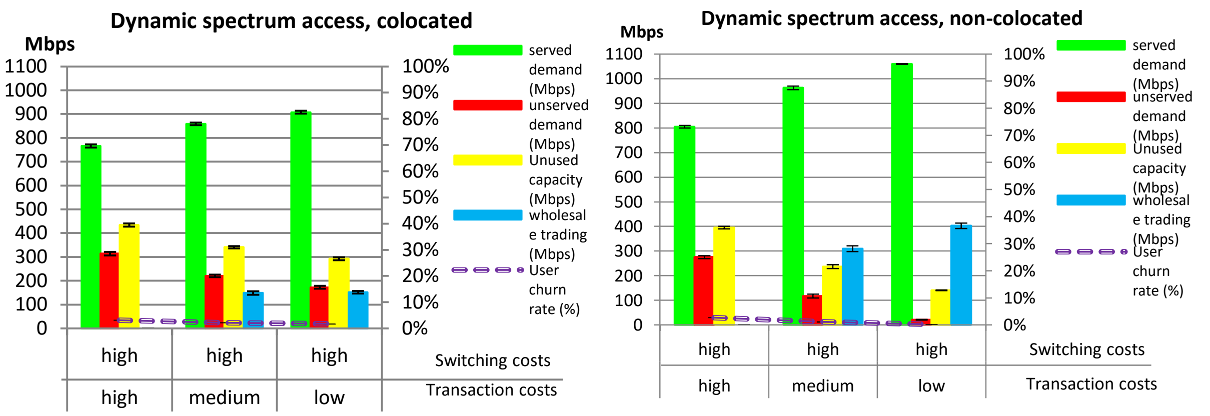


**Figure 27.** Simulation results of DSA

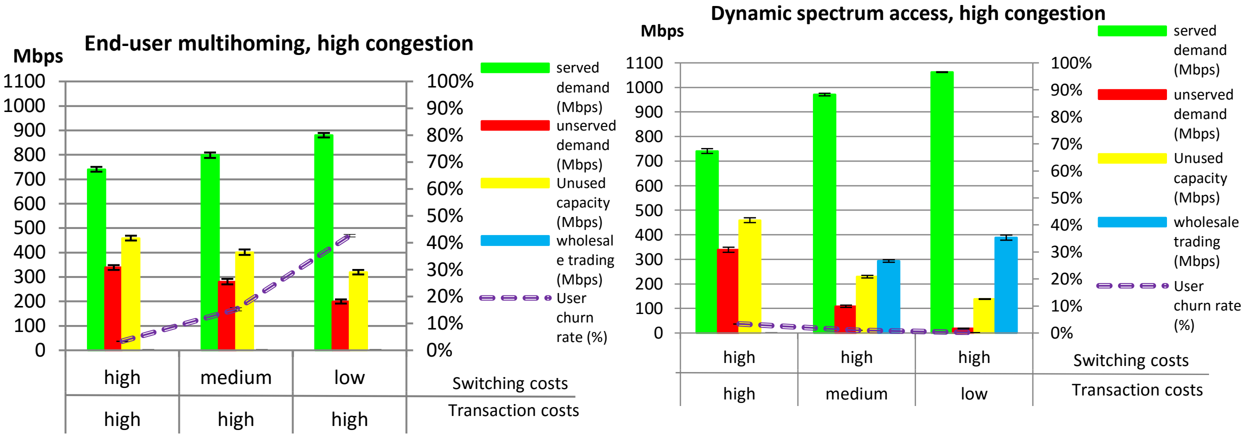


**Figure 28.** Simulation results of end-user multihoming and DSA with high congestion

**Table 11.** Observations

| **Observations** | **DSA** | **National roaming** | **End-user multihoming** |
|---|---|---|---|
| **Simulation performance** | Most efficient in non-colocated topology and high congestion | In par with other mechanisms in colocated topology | Slightly more efficient than national roaming |
| **Main strategic challenge** | Business and technical co-ordination between MNOs | Trust between MNOs | Reluctance of MNOs |
| **Initial use case - indoors** | Extension to femto-cellular national roaming or end-user multihoming via inter-MNO CA | Cooperative femto-cellular deployment | Competitive femto-cellular deployment |
| **Initial use case - outdoors** | - | Coverage support for entrant MNOs. Security network with foreign SIM. | High-availability MVNOs, e.g. authorities, IoT applications |
| **Regulator's means to push mechanisms** | Set quality targets. Include trading in new spectrum licenses. Establish or act as a broker. | Set coverage targets. Include national roaming requirement in new spectrum licenses and regulate roaming prices. | Set coverage (and quality) targets. Push retail competition through unbundling of subscription and device. |

The simulation results indicate that DSA attains highest efficiency with non-colocated network topology (Figure 27) and high congestion (Figure 28). However, deployment of dynamic spectrum trading through DSA technologies may take a longer time since they still face technical challenges. When network topology is colocated and congestion is low, all three mechanisms behave similarly, while when topology is non-colocated end-user multihoming outperforms national roaming. Additionally, when national roaming and end-user multihoming are simulated together, the efficiency is driven by the technology with higher performance and, in general, their effect is not cumulative.

Each mechanism faces its own challenges. MNOs are reluctant to end-user multihoming, since it stimulates retail competition. Moreover, this mechanism avoids MNOs to have visibility over user behaviour and forces to develop new business models based on intense competition and metered pricing. The main challenge of national roaming is the trust required to deploy optimal routing and wholesale capacity trading which turn pricing toward an Internet like model. In the case of DSA, real-time trading requires high coordination, both from a business and technical perspectives. In general, spectrum trading initially seems more feasible for higher frequencies and indoor use cases, since they require less coordination due to shorter propagation range.

The analysed mechanisms are especially promising for indoor deployments, since small cellular networks, such as femto-cells, are typically non-colocated. Thus, national roaming may provide indoor networks a cooperative mechanism and end-user multihoming a competitive one. DSA may provide to national roaming deployment (or end-user multihoming) an extension for additional network efficiency, addressing congestion problems. In outdoor networks, national roaming may continue facilitating new MNO, while end-user multihoming may provide high-availability services, such as those related to public safety and security. Both end-user multihoming and national roaming are suitable mechanisms for a market which suffers from coverage problems.

# 6. Discussion

## 6.1 Opportunities for DSA technologies

The current static spectrum management based on exclusive and license-exempt regimes can be significantly improved by introducing a more flexible spectrum regime allowing transactions, taking carefully into account the generated interference between involved parties. DSA, which gradually decreases transaction costs and improves interference management, provides the basic conditions for the Coasean implications on policy; in other words, it gradually pushes spectrum management towards a property rights regime.

DSA technologies are still under development and cannot yet be seen as a general remedy for market efficiency. From the analysed cases, indoor deployment is most promising for DSA technologies. The coexistence of two or more systems in the same frequency band is much more feasible in indoor areas, or between outdoor and indoor areas, since these scenarios require less coordination (i.e. less effort to decrease transaction costs). However, indoor deployments which include small-cellular networks, IoT and M2M applications, are still under development.

Another interesting observation is that most DSA standards are user-centric, while most countries assign spectrum in a centralized fashion. Therefore, DSA requires spectrum reforms to succeed, especially in higher frequencies intended for new indoor deployments.

Outdoor networks also show room for improvement in allocative efficiency. However, the logic and dynamics of outdoor infrastructure is more in line with other alternative mechanisms, such as national roaming and end-user multi-homing. Only under extreme spectrum scarcity, spectrum trading may be attractive for outdoor deployment. In the case of indoor deployment, higher frequencies facilitate the local reuse of such spectrum bands. Given this, static outdoor deployment should address coverage requirements, whereas indoor and local deployments may focus on congestion. Thus, flexibility in spectrum assignment, being a property right or a flexible licensing regime, provides indoor networks with the ability to respond more dynamically to the changes in demand. Therefore, DSA technologies facilitate new indoor infrastructure deployments rather than more efficient use of the existing wide-area cellular infrastructure.

## 6.2 Indoor versus outdoor spectrum management

This work observes the contrasts between higher and lower frequency bands; and between indoor and outdoor network deployments. Results suggest that DSA technologies are more relevant for indoors and high frequencies due to several reasons. Publication 1 shows that DSA is especially beneficial for serving user traffic variations in local demand. Publications 2 and 3 compare the benefits of different spectrum transaction cases and conclude that indoor transactions bring more benefits than outdoor transactions. Publication 4 highlights the need for spectrum decentralization for a successful user-centric DSA deployment. Such spectrum reforms may be much more feasible in higher frequencies which have not been yet assigned to MNOs. Publication 6 also concludes that indoor deployment presents the highest potential for DSA because of the naturally non-colocated topology. In addition, it claims that DSA may extend the benefits of national roaming or end-user multihoming by solving congestion problems.

Regarding spectrum regime, Publication 1 highlights that under zero transaction costs and well defined usage externalities (i.e. interference), a property rights regime should be optimal. However, since DSA gradually decreases transaction costs and gradually improves the definition of usage rights, a flexible licensing scheme, which includes interference as a tradable characteristic of the spectrum, may be a suitable means for increasing spectrum efficiency in the shorter run.

Additionally, Publication 2 argues that a very high frequency band, such as millimetre waves, should be set license-exempt, since neighbouring networks transmitting in those frequencies generate very little interference. In practice, an exclusive and tradable local license in the millimetre wave frequency band (i.e. above 6 GHz) may have a similar impact as a license-exempt regime, since the venue owner manages the indoor spectrum. In addition, co-primary (indoor) and primary-secondary (outdoor-indoor) regimes are suitable for middle range frequencies (e.g., 3-6 GHz). Finally, exclusive licensing is most suitable for lower frequencies (e.g., below 2 GHz). These three categories may also be mapped to the three tiered sharing framework: dynamic exclusive sharing, hierarchical sharing and open access.

Publication 4 emphasizes the need for spectrum decentralization to facilitate a user-centric DSA adoption. Even though an operator-centric DSA deployment brings some benefits to the end-user, user-centric innovation may be more beneficial, especially at local network deployments, reducing entry barriers and improving the service supply. Thus, this thesis suggests a decentralized spectrum policy for assigning new spectrum, especially in the higher frequency bands. Along this line, the regulator should opt for an ex-ante definition of spectrum trading and sharing rules to increase coordination and decrease transaction costs, especially regarding the interference. Such regulation favours new entrants against an ex-post antitrust approach, which permits incumbents to enjoy their dominant position.

Publication 6 suggests that the three compared mechanisms increase allocative efficiency dynamically. While national roaming and end-user multihoming address especially coverage problems and increase efficiency in the existing infrastructure (shorter term), DSA addresses congestion in new indoor infrastructure (longer term). In the licensed bands, spectrum transactions may temporally increase the utilization level of base stations. However, in practice, this is more challenging since outdoor networks have been deployed for static spectrum and network capacity. In addition, alternative mechanisms, such as national roaming or end-user multihoming, are more suitable for outdoor infrastructure for addressing coverage problems.

## 6.3 User-centric versus operator-centric innovation

This thesis analyzes the relationship between market structure and DSA. So far, NRAs have typically assigned the mobile spectrum to few MNOs, mainly because of large investment requirements. DSA permits NRAs to drive a more decentralized spectrum policy to allow new entrants and new service innovation. The little interest of MNOs towards DSA suggests that user-centric innovation is more likely to come from new actors.

From a regulatory perspective, the main objective is to maximize the value obtained from spectrum. With this purpose, spectrum policy should stimulate both operator-centric innovation (outdoor) and user-centric innovation (indoor).

Therefore, DSA and the other analysed mechanisms such as end-user multihoming, may provide NRAs a tool for evolving from closed to more open innovation systems. NRAs should keep in mind that user-centric focus is applicable to new infrastructure, for instance indoor and emergent services, rather than to the already deployed cellular networks which have so far followed the operator-centric innovation process.

## 6.4 Limitations

This thesis analyses different DSA scenarios at system level, with special focus on the following comparisons: indoor versus outdoor deployments; high versus low frequency bands; and user-centric versus operator-centric innovation. However, the present work does not consider in detailed the emerging IoT services and the possible interaction with fixed networks. In addition, this thesis does not compare different indoor deployments (e.g., small-cellular networks against Wi-Fi), for instance, by doing a cost-benefit analysis for each option. Since this thesis focuses on regulation, it was a strategic choice to leave certain analyses out of scope. In any case, the reader is encouraged to read additional literature (e.g., Kang, 2014) for a comprehensive understanding of the topic.

Finally, this thesis has not included in detail the usage patterns and user behaviour; and therefore the main conclusions are qualitative rather than quantitative.

## 6.5 Future work

Dynamic spectrum management and consequently spectrum regulation are still areas under development. This thesis provides some guidance for future spectrum regulation. Concrete solutions and spectrum regimes will depend on the progress of DSA technologies; for instance, the millimetre wave solutions and more generally on the small-cells or alternative indoor networks, and finally on the emergence of new IoT and M2M services.

Future work may include a more detailed analysis on new services and applications, their related spectrum requirements and concrete policy implications. In fact, DSA can play an important role in emerging services such as smart city applications related to energy, transportation, security applications, etc. Each application may have specific challenges, since each one is related to other industry. For instance, while in general a property rights or flexible licensing regimes may stimulate innovation, some particular emerging services require further analysis on a case-by-case basis.

Regarding the employed methods, this thesis combines agent-based and system dynamics modelling for studying the implications of DSA for regulation. Such combination may be suitable for analysing other disruptive technologies such as those emerging services mentioned above.

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# Publication 1

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# Implications of dynamic spectrum management for regulation

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Interference and property rights.

A B S T R A C T

The Coase theorem suggests that a regulatory scheme, which clearly defines spectrum property rights and allows transactions between participants, induces an optimal spectrum assignment. This paper argues that the conditions required by Coase are gradually achieved by the introduction of Dynamic Spectrum Management (DSM), which enables a dynamic reassignment of spectrum bands at different times and places. DSM reduces the costs associated with spectrum transactions and thus provides an opportunity to enhance efficiency through voluntary transactions. This study analyzes the factors affecting the benefits of a regulatory scheme allowing transactions, compares and quantifies the potential gains associated with different spectrum regimes by employing agent-based simulations and suggests policy implications for spectrum regulation.



## 1. Introduction

The radio spectrum has become increasingly vital for modern communications. In fact, global mobile data traffic is expected to grow 11-fold between 2013 and 2018, reaching 1.4 mobile devices per capita by 2018 (Cisco, 2014). In a context of increasing scarcity, optimizing the assignment of radio spectrum has emerged as an important policy issue (Cave & Webb, 2012; Freyens, 2009; Ting, Wildman, & Bauer, 2005). This debate has led to the development of numerous proposals regarding new regulatory regimes. Currently, the most commonly adopted regulatory approach is the so-called *Command and Control*, which assigns spectrum on an exclusive basis to an operator, through a centralized mechanism, including auctions. Under this regime, the government decides both on the type of use (allocation) and on the operator for the frequencies (assignment) in a centralized fashion and it usually allows no market-based reassignment of the spectrum. Another regime, the *Commons*, allocates part of the spectrum (e.g. the industrial, scientific and medical (ISM) band) on an unlicensed basis for free access. More recently, a *Property Rights* approach has been introduced in some countries, including some with large markets, such as the UK. This regime allows spectrum transactions between operators, market-based reassignment and reallocation of the spectrum (e.g. service neutrality).

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0308-5961/

The effect of market-based regimes on competition and efficiency is debatable, due to the variety of practical implementations. Thus, whilst a property right regime has had low impact on new firms entry in New Zealand and Australia (MED, 2005; ITU, 2003a), it has had a considerable impact in Guatemala (ITU, 2003b).

On grounds of economic efficiency, Coase (1959, 1960) first recognized that well defined property rights help solve externality problems. The application of the Coase theorem to the current spectrum policy debate suggests that, as the spectrum is valued differently by agents, a sufficiently low transaction cost and clearly defined property rights induce transactions which result in an efficient outcome, regardless of the initial spectrum assignment. In turn, if transaction costs are high, the social optimum is attained when a spectrum band is assigned to the agent that values it the most. A central entity (e.g. government) can assign the spectrum if it is aware of these valuations. However, if it lacks this information, it should find a mechanism to make the agents reveal their valuations (e.g. auctions). In any event, a centralized decision leads to inefficient assignment over time if valuations change or if the criteria to assign the spectrum improperly reveal preferences (e.g. *beauty contests*). Moreover, in the case of a suboptimal initial assignment, subsequent transactions can lead to an optimal assignment in a Coasean scheme, because reassignments are mutually beneficial.

A regulation that defines spectrum property rights and enables transactions is limited by the technology, because of the complexity of radio access and interference management. Recently developed radio access capabilities address these issues and, at the same time, several national regulatory authorities (NRA) are currently introducing the option of trading in spectrum licenses.

In particular, the development of Dynamic Spectrum Management (DSM) technologies, such as Cognitive Radio Systems (CRS) (ITU Report ITU-R M.2225, 2011), may constitute a significant step towards facilitating transactions, since they enable spectrum band reassignments at different times and places in a dynamic fashion. In CRS, several deployment scenarios have been identified, such as (i) managing dynamically and jointly the resources of the deployed radio access technologies (RAT) of the mobile network operator, to adapt the network to the dynamic behavior of the traffic and to maximize the capacity; (ii) improving the spectrum efficiency by exploiting the unused spectrum for cooperative spectrum access at a specific location and time; and (iii) accessing spectrum in bands shared with other radio-communication services by identifying unused spectrum resulting from traffic variations by means of CRS capabilities (e.g. use of white spaces).

Thus, DSM offers a great potential by allowing market mechanisms, which detect the value of the spectrum at different times and places. DSM aims to use the spectrum *holes*, which are points in frequency, time and space unoccupied by any transmission. Furthermore, DSM may allow to compare different spectrum valuations in real-time to assign it to the users who value it the most and thus induce further transactions. DSM may not bring any significant effect within a static spectrum regime, which maintains the ownership conditions in time and location. However, a flexible regime may require DSM to reassign the spectrum in a dynamic fashion.

Several authors highlight the benefits of a spectrum regime that includes tradability of rights and higher flexibility in interference management (Cave & Webb, 2012; Freyens, 2009; Ting et al., 2005). Other researchers study how DSM may increase spectrum efficiency (Attar, Ghorashi, Sooriyabandara, & Aghvami, 2008; Crocioni & Franzoni, 2011; Freyens & Yerokhin, 2011; Raychaudhuri, Jing, Seskar, Le, & Evans, 2008), the feasibility of different business scenarios for DSM (Grønsund, Grøndalen, & Lähteenoja, 2013; Sayrac, Uryga, Bocquet, Cordier, & Grimoud, 2013) and the importance of regulation and standardization (Baldini et al., 2013; Durantini & Martino, 2013).

Interference management has been until the date either too restrictive, such as in an exclusive regime which allows no other operators to interfere, or too relaxed, such as in a commons regime in which interference precludes assuring quality of service (QoS). The optimal interference level, which is usually higher than zero and depends on the service requirements, leads to an optimal usage of the spectrum. Diversity in service demand may indicate that a flexible spectrum regime can bring benefits by creating a diversified supply of spectrum, which incentivizes quality differentiation through transactions. Under flexible spectrum regimes, a portion of spectrum could be assigned under different interference levels for different services. This is facilitated by DSM, which permits a precise control of interference parameters, i.e., the quality of the service.

The effects of a regulatory regime, which facilitates transactions, are not yet fully understood in a context of changing spectrum valuations.[1] The purpose of this paper is to analyze the potential of DSM to increase social welfare, when applied under a spectrum regime that considers the dynamic value of the spectrum and implements a spectrum market in a context of clearly defined property rights and zero costs of spectrum transactions. In concrete, this work aims to acquire an approximate value on the social gains of employing DSM under such a regime.

This study defines the spectrum value by its ability to fulfill user requirements, which present volatility in terms of required capacity and quality. In other words, the spectrum value depends on its specific use. The paper employs agent-based modeling (ABM)[2] to simulate the dynamic behavior of ICT agents, both operators and end users. ABM is especially suitable for analyzing the behavior of agents and the collective effect of their interaction. These simulations illustrate and quantify the advantages of a flexible spectrum regime, assuming the conditions of the Coase theorem that are likely achieved by the introduction of DSM, current characteristics of mobile traffic and a competitive market, which includes different type of operators.

[1] One theoretical approach has been performed by Freyens and Jones (2014).

[2] For more information on ABM see Tesfatsion and Judd (2006).

The paper is organized as follows. Section 2 describes the conditions under which a regime with well-defined property rights can lead to an optimal spectrum assignment and the factors which affect the benefits DSM yields in such a regime. Section 3 simulates the social gains associated with free transactions for different spectrum regimes by taking an ABM approach. Section 4 presents the simulation results and Section 5 the main policy implications.

## 2. Factors that make a property rights regime beneficial

There are a number of factors affecting the benefits of a spectrum property rights regime. From the market perspective, the availability of spectrum and the structure of the market determine the participant willingness to perform transactions. In addition, the effective decrease in transaction costs, enabled by technology, and an adequate definition of property rights increase the benefits obtained by spectrum transactions. This section analyzes these factors in a DSM context.

### *2.1. Spectrum scarcity and heterogeneous valuation*

In mobile communications, the necessity to optimize the use of scarce spectrum is becoming evident. Although the development of transmission technologies has provided sufficient capacity in the past, the current rise in demand driven by new services is exceeding the increase in spectrum capacity achieved by technology development. Moreover, ITU-R M.2243 (2011) forecasts that mobile data will undergo on average a four-fold increase for the period 2012–2015, driven by smartphones, tablets and other mobile networked devices.[3] As spectrum becomes scarcer, the assignment mechanisms become increasingly important.

Heterogeneity in spectrum valuation causes spectrum reassignment. Transactions are particularly valuable when user requirements are diverse and the demand from participants varies in quantity and quality over time. The value of the spectrum for a participant is higher during high demand periods than during low demand periods. As peak demand occurs at different times, frequencies and locations for different participants, dynamics transactions permit assigning spectrum to the one most in need at every time, frequency and location, thus reaching an optimal spectrum assignment.

Propagation characteristics of different frequencies affect the suitability of spectrum bands for different radio access technologies. In fact, telecommunication systems transmitting on higher frequencies have usually less transmission coverage and interfere less, ceteris paribus, than those systems transmitting on lower frequencies (transmission power and distances between receivers and transmitters remain the same). Therefore, lower frequencies are preferred by national mobile network operators for building their mobile networks, because they usually allow mobile operators to reach higher coverage at lower costs (see e.g. Lundborg, Reichl, & Ruhle, 2012). Higher frequencies, on the other hand, are preferred by access technologies intended for local access, such as WiFi or Bluetooth.

Concisely, time and location have an influence on valuation, since the demand for different services varies, in some cases widely, across time and geography. Spectrum transactions, made according to these valuations, generate mutual gains.

Fig. 1 shows an example of the efficiency of transactions under heterogeneous valuations. This example depicts two operators requiring spectrum to serve users with different service valuations, leading to decreasing derived demands D1 and D2 for spectrum. The total spectrum available is given by the distance in the horizontal axis (*TS*), and hence, if operator 1 employs *S*1, the maximum spectrum operator 2 can obtain is *TS*–*S*1. Thus, the utilization (and the demand) of spectrum for each operator is indicated in the case of operator 1 from left to right and for operator 2 from right to left.

If spectrum was initially assigned with *So* to operator 1 and *TS*–*So* to operator 2, there will be gains associated with reassignment, when the demand curves of operators are as shown. The marginal valuation (and willingness to pay) of an additional unit of spectrum given to operator 1 ($v1$) will be larger than the marginal valuation of the last unit of spectrum given to operator 2 ($v2$). Thus, a price between $v1$ and $v2$ enables the trading of that unit of spectrum. Eventually, without transaction costs, a price $v^*$ will exhaust all possible gains of trade and produce an efficiency gain equivalent to the shaded triangle in Fig. 1. In this case, an assignment of $S^*$ to operator 1 and consequently, $TS–S^*$ to operator 2, will be socially efficient.

The previous analysis indicates that changes in valuation will generate further transactions and corrections in spectrum assignment.

### *2.2. DSM and transaction costs*

Necessarily, voluntary transactions are mutually beneficial, since the value for the buyer exceeds the cost for the seller. Thus, all potential transactions take place if transaction costs are zero. The larger the transaction costs, the fewer the number of transactions.

Transaction costs, conceived as the costs of *transferring, capturing and protecting* property rights (Allen, 1991; Barzel, 1982), depend both on the technology and on the market mechanism enabling the transaction. DSM is expected to reduce transaction costs. Naturally, DSM has its own costs which can be classified into capital expenditures (CAPEX) and operational expenditures (OPEX). CAPEX are related to the investment in DSM infrastructure (spectrum sharing

[3] ITU estimates average mobile data traffic based on several sources. One of them is Cisco, mentioned in the introduction.

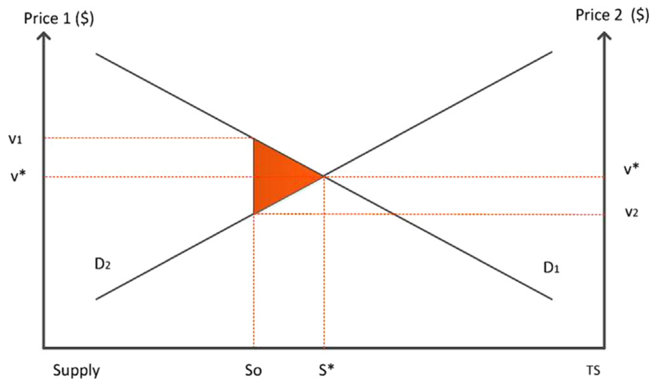


**Fig. 1.** Optimal assignment of the spectrum.

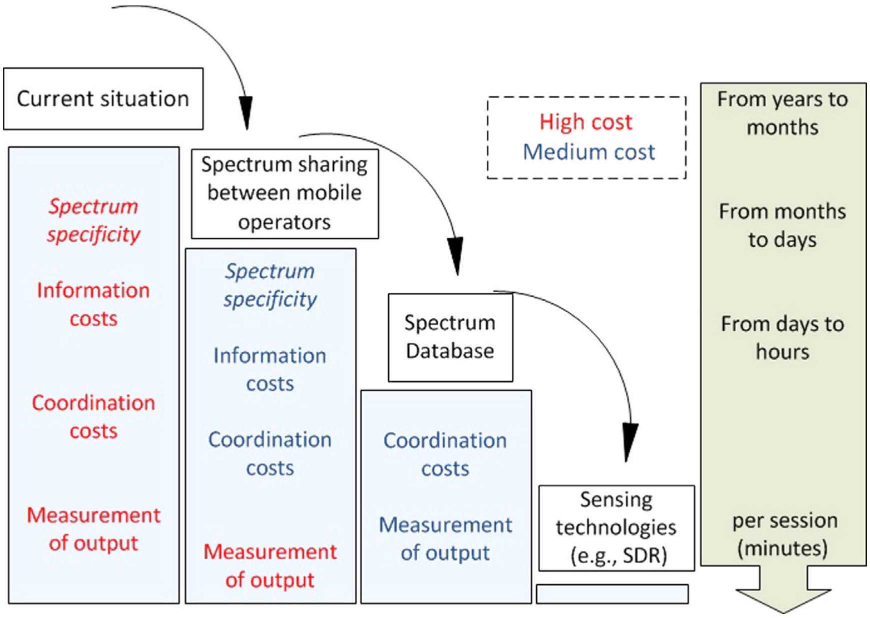


**Fig. 2.** DSM evolution decreases transaction costs (adapted from Suomi et al. (2013)).

technologies of network elements, spectrum database, sensing capabilities in mobile terminals, etc.) and OPEX are related to the operation of the system. Once DSM is in place, the only relevant costs are OPEX, which are relatively small (Suomi, Basaure, & Hämmäinen, 2013). In other words, incurring in CAPEX creates a scenario in which spectrum transactions take place at a very low cost.

Fig. 2 illustrates the different stages in which DSM reduces transaction costs. This figure indicates that a DSM solution based on a *spectrum database*, which manages and authorizes spectrum access, considerably diminishes information and coordination costs, while sensing technologies (such as Software Defined Radio (SDR)[4]) decrease measurement costs and spectrum specificity costs are reduced along with the development of spectrum sharing mechanisms. In addition, low transaction costs make possible shorter spectrum leasing times.

Even though the timing of DSM adoption is uncertain, there is a clear tendency towards decreasing transaction costs. This uncertainty is mainly due to the private incentives to invest in this technology. Whilst there is no clear evidence of the support DSM gets from the industry, some authors suggest that both incumbent and new entrant operators may have suitable business cases to incur in the required CAPEX (Grønsund et al., 2013). Others claim that industries with a lower market concentration may have a better fit (Sridhar, Casey, & Hämmäinen, 2013). In addition, regulators may be willing to support DSM to decrease entry barriers (Basaure & Sridhar, 2013). In any case, the private incentives to invest in this technology will be larger under a regulation scheme allowing spectrum transactions.

[4] For a definition of SDR see ITU-R SM.2152.

### 2.3. Interference and spectrum rights

Interference is part of a spectrum property rights definition. In theory, spectrum users should be aware of the caused and received interference and, unless technology allows measuring and sharing this information, the definition of the spectrum property rights will be precarious. Under clearly defined property rights, operators will produce and accept interference according to some predefined rules. A regime which allows no spectrum transactions presumably sets a conservative level of interference, which produces an inefficient use of resources, as much as another hypothetical regime accepting an excess of interference. The current literature discusses this issue. For example, Cave and Webb (2012) emphasize the benefits of increasing the interference limits, while Crocioni and Franzoni (2011) focus their attention on providing receivers the right incentives to filter out the unwanted emission, rather than protecting them by conservative interference limits.[5] By allowing a more detailed definition of the interference, DSM incentivizes spectrum transactions not only by reselling the whole frequency band but also by selling or buying part of the spectrum band, which further optimizes spectrum usage. In a spectrum transaction, the spectrum holder sells the spectrum usage rights of a frequency band (in time and space) to another participant, under predefined conditions. In this situation, the quality of the spectrum will depend, among other issues, on the interference generated in the same frequency band, originated from: (i) users of other operators in adjacent geographical areas and (ii) users of the same operator.

Until this moment, measuring and defining interference has been challenging. Nevertheless, the state-of-the-art of DSM technologies can already enable a flexible management of the interference. For instance, latest development of spectrum database technology can hold statistical information on the interference and by applying some predefined rules they can accept or reject additional users to access the spectrum. Examples of such rules have been defined in ECC Report 186 (2013) and in FCC 10-174 (2010). In addition, the information held by the spectrum database will improve in accuracy by means of sensing technologies (such as SDR), by detecting the interference and evaluating the access costs in real-time (example of SDR development can be found in ETSI TS 103 095 (2013)). In line with the technology, the latest emerging proposals for flexible spectrum regimes, such as pluralistic licensing (Holland et al., 2012), consider the interference as a tradable characteristic of the spectrum.

Thus, the Coase theorem applies to interference management. When defining spectrum property rights, each license should define the level of interference the spectrum holder is willing to receive (even interference free spectrum). The current improvements in measuring and identifying sources of interference allow each spectrum holder to sell its right to be free of interference, and a Coasean view suggests that they will accept optimum levels of interference. Naturally, allowing transactions of spectrum with interference requires the ability to prove in court the fulfillment of the contract, to identify the sources and specifically, the definition of several parameters,[6] such as base station and terminal transmission powers. When sharing the same spectrum band, this definition includes coverage areas and rules for accessing the spectrum through an authoritative register (e.g., primary–secondary, co-primary sharing, etc.).

### 2.4. Market structure and spectrum transactions

The current experience with property rights regimes suggests that market structure highly affects the resulting benefits for the industry. Moreover, transactions are more likely to take place in a competitive market. A firm with a dominant position in the market, which holds a considerable amount of the spectrum, may be unwilling to sell spectrum, even though the value of that spectrum given by a competitor is higher than its own valuation. This is the case if by selling spectrum, the incumbent losses some of its market power or if the price reduction associated with the larger supply causes losses.

In general terms, a low market concentration increases the probability of having spectrum transactions. The current literature lacks a clear view on the critical amount of mobile operators a market should have to be competitive. One attempt was performed by Caicedo and Weiss (2011), who suggested that a competitive mobile market needs a minimum of five to six interacting spectrum holders.

From another perspective, network investment requirements affect the market structure, since they constitute an important entry barrier. A wide-area network requires high investments and therefore, the frequency bands intended for mobile services are assigned to few operators in an exclusive basis. On the other hand, the commons frequency band enables short-term investments for a high number of independent WLAN networks. In the future however, DSM may allow the entrance of new middle sized operators to the market (Markendahl and Casey, 2012), which compete with nationwide mobile operators on a local basis. These operators would have intermediate investment requirements, which allow new business models.

## 3. Modeling a spectrum market in a DSM context

We develop herein a model to simulate a spectrum market based on different valuations. This model compares the efficiency of different spectrum regimes, considering DSM is in use.

[5] A similar situation is presented by Zivin and Small (2003) in the context of environmental pollution. These authors suggest that the pollution should be considered as part of the configuration of the property rights.

[6] An example of the rules and parameters for a flexible spectrum licensing implementation can be found in Basaure and Holland (2014).

### 3.1. Alternative spectrum regimes

This section describes the spectrum regimes to be analyzed in the simulations, including the widely adopted exclusive and commons regimes, as well as the most relevant emerging spectrum regimes.

The exclusive regime gives a frequency band usage right to one operator for a long period of time (typically 10–15 years). These usage rights can define a concrete technology and service or they can set them as neutral. Recently, there has been a trend to relax the restrictions of an exclusive regime by allowing license trading, while still maintaining the condition of exclusivity of the frequency band.[7] From the operator perspective, the exclusive regime gives certainty for wide-area investments and therefore, it may be more suitable for lower frequencies, since they have better propagation characteristics to reach nationwide coverage at lower costs. An exclusive regime may, in addition, allow operators to practice several cooperative mechanisms (e.g., spectrum aggregation, roaming agreements, infrastructure sharing, etc.), while making it difficult to sell a part of the spectrum through transactions.

The commons regime permits a free access to the spectrum for any device able to communicate in that frequency band. This regime lacks any quality assurance and until this moment, it has been mainly used for wireless internet access in the ISM band. The commons regime is better suited for those cases without either scarcity or negative externalities. For instance, local-area networks adopting higher frequency bands are able to maintain a low level of interference. A commons regime allows terminals intended for a specific use to access the spectrum of a different service if they are capable of transmitting in that access technology (e.g. cellular phones accessing WLAN networks).

The use of DSM technologies has the potential of decreasing transaction costs and of accurately managing the interference parameters, when trading spectrum. This means, for example, that part of a spectrum band can be dynamically traded (in time and place) between operators. Since DSM involves spectrum transactions and more detailed interference management, new spectrum regime proposals have recently emerged. These regimes consider the coexistence of different types of users in the same frequency band, while offering them a predictable quality by managing the interference *ex-ante*. Two important approaches include Licensed Shared Access (LSA) and Light Licensing, which authorize spectrum holders to adapt their interference level until a certain extent, providing more flexibility than the exclusive and commons regimes respectively. In addition, Pluralistic Licensing presents a novel mechanism to include the interference as a tradable characteristic of the spectrum.

The LSA allows license holders to accept secondary usage of their spare spectrum with a predictable quality for involved parties (EC COM, 2012, 478). LSA was originally developed by the industry (Qualcomm and Nokia) with the name of Authorized Shared Access (ASA). ASA was initially intended as a means for mobile operators to obtain additional spectrum from another type of spectrum owner. Later, the European Commission extended this concept to include other cases with the name of LSA. More generally, LSA introduces a means to perform spectrum transactions with predictable interference levels.

Light licensing (ECC Report 132, 2009) refers to a regime that allows a common usage of a frequency band, with a guaranteed quality of service. Compared to an exclusive licensing regime, light licensing requires a simplified issuing procedure. In contrast with an unlicensed regime, it requires a registration mechanism in exchange to obtain a higher level of quality. Light licensing permits a coordinated sharing mechanism, in which different types of users are supported (RSPG11-392, 2011), enabling spectrum transactions between parties. Light licensing with individual authorization may also referred to as *private commons*, with the conditions for its usage being more restricted than in a public commons.

Finally, the *pluralistic licensing* regime (Holland et al., 2012) enables the spectrum holder to accept a secondary access to the spectrum, under the condition that the interference produced by this access is defined by parameters and rules that are known to the primary spectrum holder at the moment of obtaining the license.[8] These afore-mentioned parameters and rules can be implemented as a fixed pre-committed amount of interference or as a known formula with changing values and a defined revenue mechanism. Thus, the operator can define its interference tolerance according to its users' profiles. The pluralistic licensing regime additionally introduces a trade-off between the level of interference and the spectrum license fee to be paid by the spectrum holder. The purpose of this reduced fee in exchange to tolerance to interference is to incentivize the spectrum holder to sell part of its spectrum, accepting as many other users as possible to a certain frequency band. Hence, this regime authorizes spectrum transactions with several levels of service assurances for the coexisting types of users. From this perspective, this regime facilitates flexibility in interference management, providing incentives to the spectrum holder to adapt its interference tolerance according to its own needs.

Table 1 summarizes the selected spectrum regimes for the simulations.

### 3.2. The spectrum market model

The model simulates the interaction between users and operators in a spectrum market enabling transactions, which matches supply and demand at different locations. Simulations are performed by employing an ABM tool (Repast Symphony 2.0).

[7] More details on the condition for the exclusive bands intended for mobile services in Europe can be found in ECO Report 03 (2012).

[8] The literature usually employs the term *primary* to refer to the spectrum holder and the term *secondary* to refer to the operator buying spectrum from the spectrum holder. These terms usually imply that the secondary user should not interfere with the primary or that the primary user has a priority access to the spectrum. This analysis avoids these terms to emphasize the existence of different types of users and their access rights are defined case-by-case.

**Table 1**
Spectrum regimes: description and interference characteristics.

| Spectrum regime | Description | Interference | Fee | Enables transactions? |
|---|---|---|---|---|
| Exclusive | It assigns a frequency band for exclusive use to mobile operators during several years, enabling certainty for investment. | Low | High | No |
| Licensed shared access (LSA) | Mechanism to provide a secondary access of a spectrum band, with a guaranteed quality of service. Initially intended for mobile operators as a mean to obtain additional spectrum (ASA). | Low–medium | Medium–low | Yes |
| Pluralistic licensing | Allows a trade-off between interference tolerance and spectrum fee for spectrum holders. It provides higher flexibility in interference management. | Defined by incentive mechanisms | From low to high | Yes |
| Light licensing | A restricted version of commons regime, which allows a common usage of a frequency band, limiting by the number of users or by registration. | High–Medium | Low | Yes |
| Commons | Unlicensed regime allows free access to the spectrum, currently adopted in the ISM band by wireless access technologies. | High | Free | No |

Users generate traffic according to a demand profile. For simplicity, the model assumes that each user generates one type of service and changes his/her location and amount of traffic according to the time of the day. In addition, two types of operators are assumed: wide-area operators, which cover the entire simulated area and local-area operators, which cover one specific area (house, office or public place). All operators serve first their own users' demands with their available spectrum. After that, they sell their spare spectrum in the market. If they lack spectrum capacity, they buy it from other participants in the market. This analysis focuses on the users of wide-area operators. From this perspective, the model considers that wide-area operators can obtain additional spectrum capacity from local-area operators and from other wide-area operators. A centralized entity continuously publishes information on spectrum availability and requirements from each operator, providing the required information for spectrum transactions.

In the model, operators can continuously learn from the demand information to react by adapting their interference level. When increasing the interference tolerance, the capacity of the spectrum increases, while its quality of service decreases. Each operator can decide on its own interference profile, considering the quantity and quality of the available spectrum to maximize its profits.

The simulation is run iteratively; every cycle simulates all transactions that have taken place in a market clearing process, which is assumed to occur every one hour. Fig. 3 describes one cycle, in which operators decide on adapting their interference profile at the end of each simulation cycle, whenever the spectrum regime authorizes it.

### 3.3. *Assumptions for the simulations*

The model simulates a competitive market which allows spectrum transactions between three similar mobile network operators and four local operators per area (home, office or public area).[9] This setup emphasizes diversification of operators and enables all types of beneficial transactions, because the industry has adopted DSM and achieved zero cost of spectrum transactions. Since the spectrum capacity is provisioned locally, the level of competition is determined by the number of service providers at each location.

The simulation setup is summarized in Fig. 4. Spectrum transactions are performed through a centralized entity, which publishes trading information each hour, 24 times a day. To access the spectrum, the users of the buying operator request permission from a local spectrum database, which grants access under predefined conditions of interference. End users demand spectrum capacity in three different places: home, office and public area. The model assumes 20 types of services and the demand for each type of service depends on the scenario. The default scenario distributes all service types equally distributed. In addition, a *higher QoS demand scenario* defines a case, in which the service demand for higher QoS requirements (1 and 2) is larger than the demand for lower QoS requirements (3 and 4). Mobile network operators serve the entire area without distinction, while each local-area operator only serves one sector. Users generate a service demand according to a traffic pattern obtained from measurements performed in Helsinki (Figs. 4 and 5).

The model includes a trade-off between QoS and capacity offered by a certain spectrum band. Specifically, given an interference constraint at the spectrum seller, an increase in usage of the spectrum buyer decreases in average the quality of the sold spectrum, but at the same time it increases the total level of spectrum capacity (see an example in Appendix B). Therefore, for certain amount of spectrum offered in the spectrum market, a lower QoS will be compensated for with higher capacity.

From a network perspective, the end-to-end network quality can be measured by means of latency or *round trip time* (RTT). However, this analysis employs the level of interference to refer to the QoS experienced by the end user. The

[9] Many authors think that the interaction between wide-area and local-area operators is a promising scenario for spectrum transactions (e.g. Markendahl & Casey, 2012). In fact, globally nearly 45% of the mobile data was offloaded onto the fixed network through Wi-Fi or femto-cell in 2013 (Cisco, 2014).

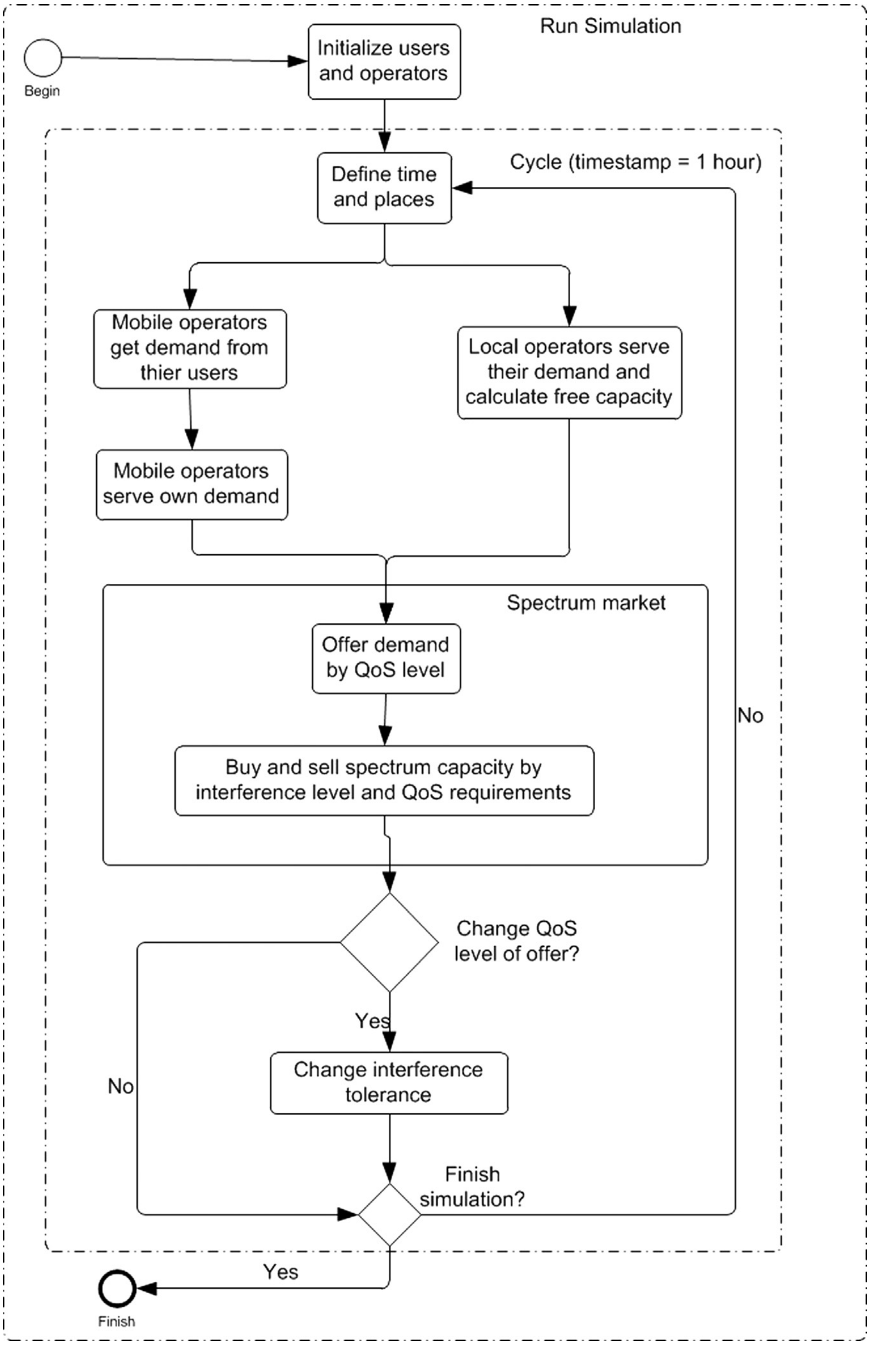


**Fig. 3.** A simulation cycle for a dynamic spectrum market.

interference determines the signal-to-interference-and-noise ratio and its variation over time, which corresponds to a certain level of QoS. When the operator decides on an interference tolerance level, it guarantees a certain QoS for its users.

The mobile networks of the model present differences in the QoS offer. In addition, user demand varies not only in time, but also spatially. In concrete, this model employs the demand profile suggested in Figs. 7 and 8, which show the latency measurements at different times and places performed in the city of Helsinki. Fig. 7 shows the city divided into small squares. In each square, the color indicates the operator providing the best QoS, with each color corresponding to a particular network. Fig. 8 provides some snapshots of mobile networks' QoS measurements during different times of the day, indicating that, at similar time and place dimensions, mobile networks differ in QoS. These observations corroborate that competing mobile networks vary in time and place in terms of provided QoS.

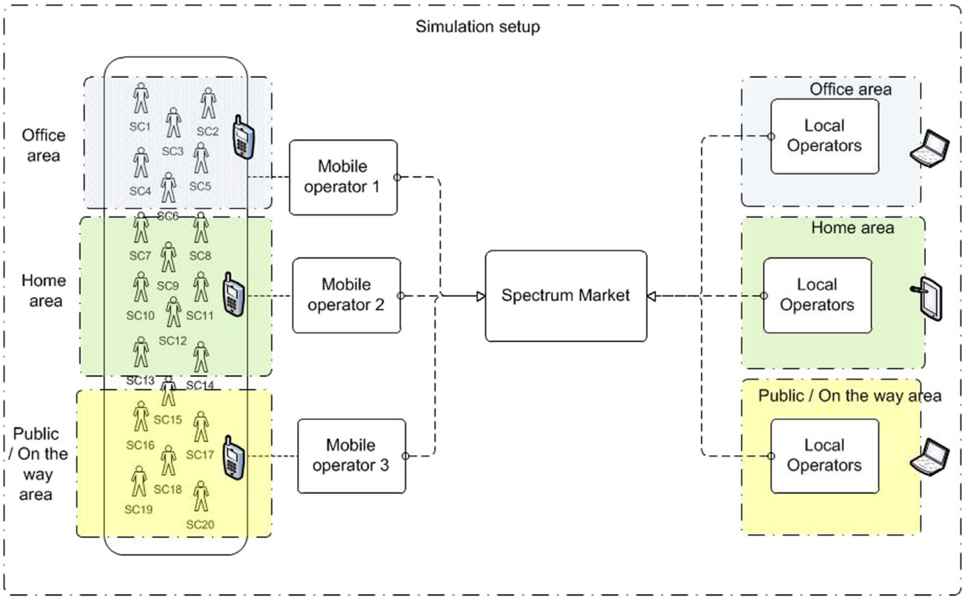


**Fig. 4.** Simulation setup; users, operators and their location.

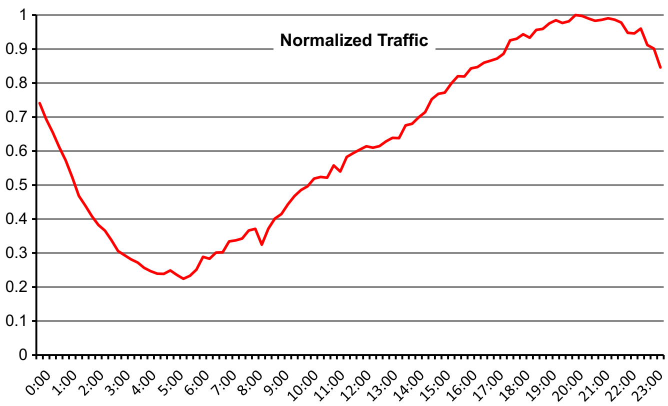


**Fig. 5.** Merged normalized daily traffic of Finnish mobile networks (Finley, 2012).

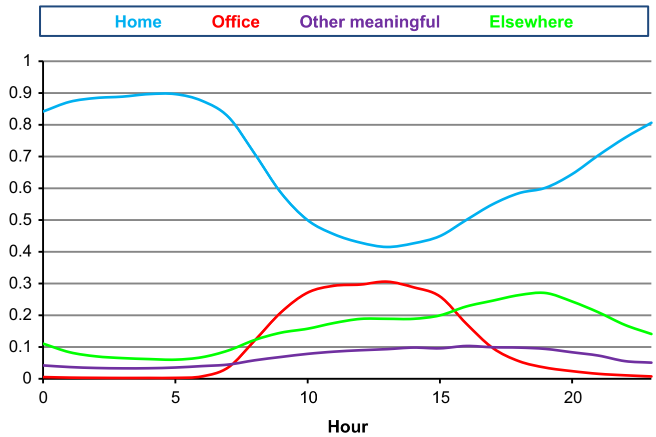


**Fig. 6.** Place distribution of traffic (Karikoski & Soikkeli, 2013).

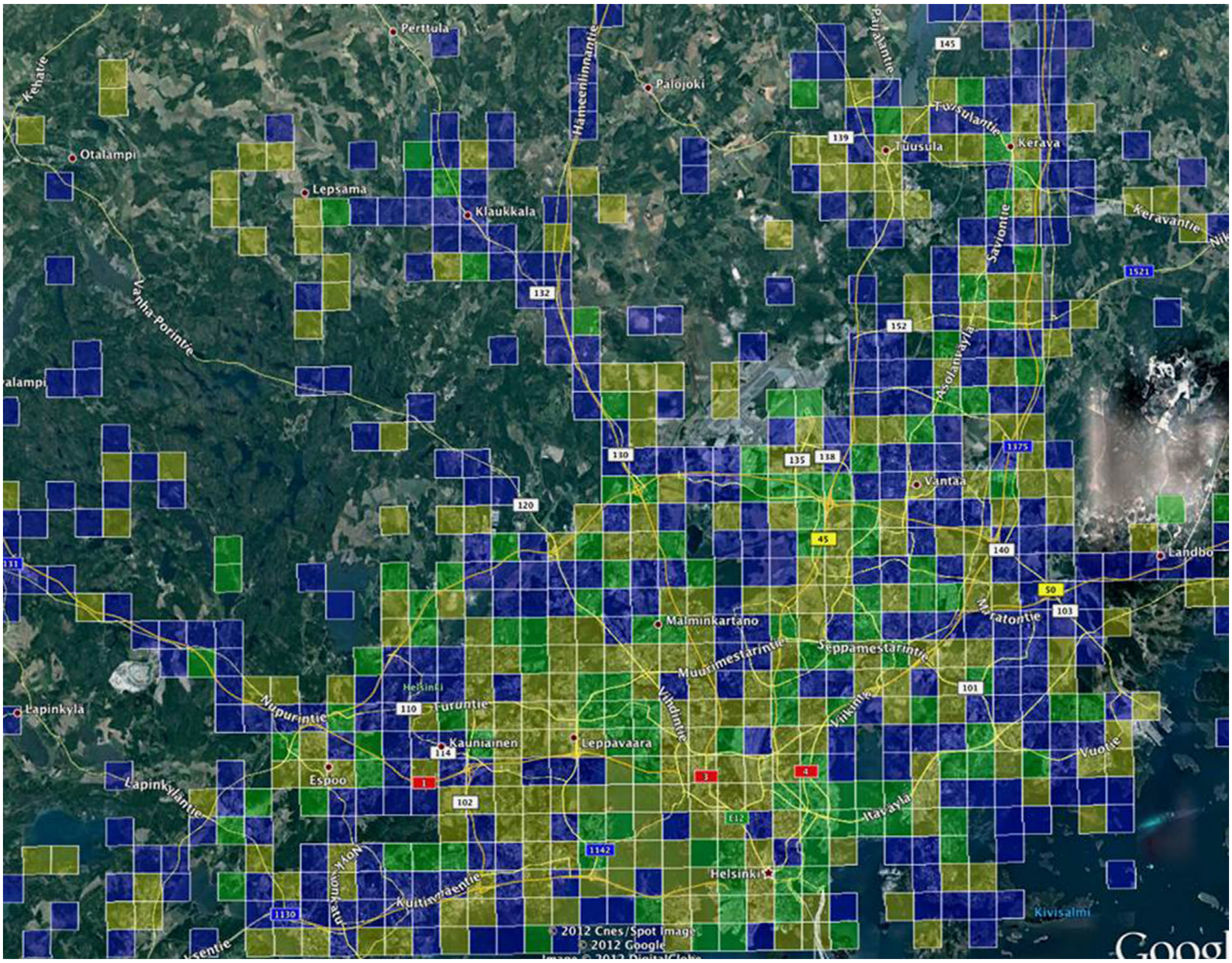


**Fig. 7.** Describes which network is offering, in average, the best QoS at each location based on latency measurements in Helsinki (from Netradar database).

The value of the service is defined by its capacity and quality requirements, i.e. a service with higher requirements is more valuable than another with lower requirements. The simulation utilizes a classification of services developed by ITU (first in ITU-R M.1079-2 (2003) and later in ITU-R M.1768-1 (2013)). This classification (depicted in Table 2) defines service classes (SC1-20) by a capacity requirement (service type) and a quality requirement (traffic class). A traffic class determines the maximum allowed interference.

The simulation calculates the traded capacity for each QoS class, assuming that one unit (i.e. bit per second) of traded capacity of QoS class 1 has higher value than another unit of traded capacity of QoS class 2; and so on:

$$\text{Unit Value(QoS1)} > \text{Unit Value(QoS2)} > \text{Unit Value(QoS3)} > \text{Unit Value(QoS4)} \quad (1)$$

Note that the spectrum valuation depends on the user demand. For instance, if a user requires QoS class 2, a spectrum of QoS class 3 or 4 has very low or zero value to that user. On the contrary, a spectrum of QoS classes 2 and 1 has the same value to a user requiring QoS class 2. This means that the value of the spectrum is defined by its usage and consequently transaction prices reflect the marginal valuation of each service. Thus, the value of a certain frequency band will depend on the ability to fulfill the service requirements, both in terms of capacity and QoS.

Presently, most data services are so-called *best effort* and guarantee no QoS. The classification in Table 2 encourages service diversification, which exclusive and commons spectrum regimes do not necessarily support. The simulation assumes a diversified service demand based on latest forecasts which show an increasing demand for new services, such as Machine-to Machine (M2M) and Internet of Things (IoT). These new service areas can play a key role in a DSM context (EC COM, 2012, 478) and they are very diverse in quality and capacity requirements.

Finally, the model supposes a spectral efficiency in accordance with the latest radio access technologies. Mobile operators provide a capacity of 100 Mbps per cell, while local operators provide 60 Mbps at each access point. At each simulation cycle, spectrum capacity is sold (in bps) at each location in which spectrum is available.

Based on the spectrum regimes described in Section 3.1, Table 3 introduces the simulation scenarios. The first scenario describes the current situation of mobile operators, which allows mobile offloading in WLAN networks to decrease the traffic load of cellular

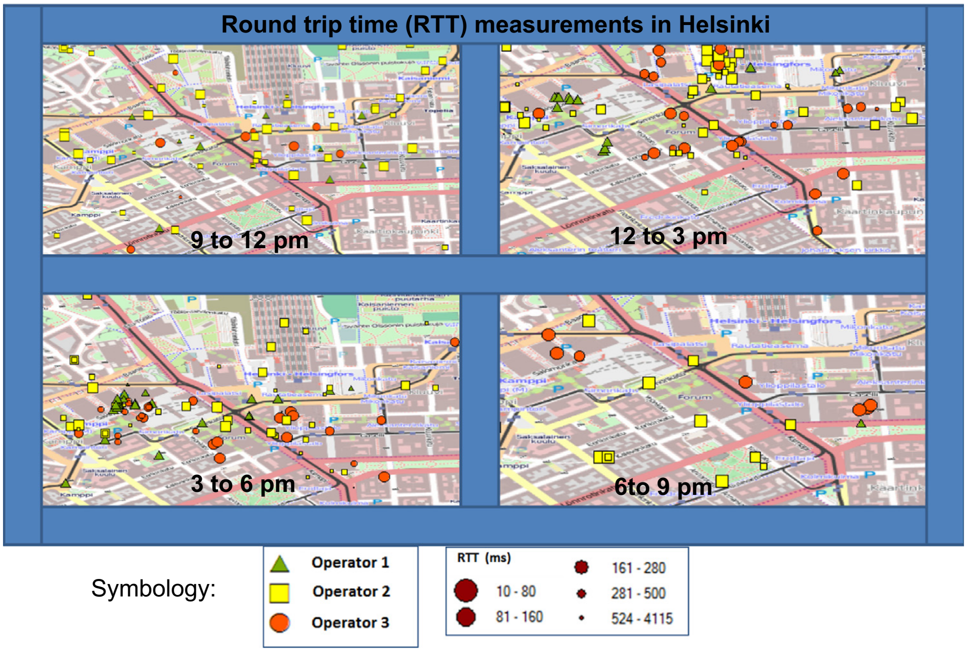


**Fig. 8.** Measurements during different times of the day. Colors and shape represent different operator networks. The size of the symbols is proportional to the latency (RTT in ms) (from Netradar database). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

**Table 2**
Service categorization adopted for the simulations.

| | Service categorization | | | |
|---|---|---|---|---|
| **Traffic class (QoS requirement)** | **Conversational (QoS 1)** | **Streaming (QoS 2)** | **Interactive (QoS 3)** | **Background (QoS 4)** |
| **Service type (capacity requirement)** | | | | |
| **Super-high multimedia (e.g., premium service)** | SC1 | SC6 | SC11 | SC16 |
| **High multimedia (e.g., video streaming)** | SC2 | SC7 | SC12 | SC17 |
| **Medium multimedia (e.g., internet browsing)** | SC3 | SC8 | SC13 | SC18 |
| **Low rate data and low multimedia (e.g., messaging services)** | SC4 | SC9 | SC14 | SC19 |
| **Very low rate data (e.g., machine-to-machine services)** | SC5 | SC10 | SC15 | SC20 |

access radio. This scenario consists therefore of a combination of exclusive and commons regimes. In this case, spectrum transactions are not allowed, and the spectrum capacity from local-area network is accessed by end users opportunistically, without a flexible management of the interference. The second scenario simulates a cooperation scenario, in which spectrum capacity is shared between mobile operators based on an exclusive regime basis. This may occur by allowing network operators to join their licenses for a common access (Anchora, Mezzavilla, Badia, & Zorzi, 2012) or through any type of operator cooperation mechanism, such as national roaming agreements, virtual operator agreements or network infrastructure sharing (Markendahl, 2011). In addition, mobile users offload their traffic to local-area networks based on a commons regime. This scenario assumes that all mobile operators cooperate and that the interference characteristics correspond to the exclusive and commons regimes. For the remaining scenarios (LSA, pluralistic and light licensing) spectrum is traded in a spectrum market by means of DSM technologies, such as a spectrum database and end user sensing capabilities, and users assess the spectrum if it fulfills their service requirements. Additionally, the *adaptive* pluralistic licensing regime assumes that each operator can modify its interference level over time according to some predefined rules, while in the *fixed* pluralistic regime all operators remain with the same interference level throughout the simulation.

The simulation assumptions are summarized in Appendix A.

## 4. Results

The simulation results are depicted graphically in Figs. 9–11. These graphs show the average amount of traded spectrum capacity (or shared in some cases) per QoS class in different spectrum regimes. The results illustrate both the total amount of traded spectrum capacity and the traded amount per each QoS class (average values of an area). The spectrum valuation

**Table 3**
Summary of simulated scenarios with its main characteristics.

| Scenario for simulation | Transactions allowed? | QoS offered in the market | Adapt interference in time? |
|---|---|---|---|
| Mobile offloading based on opportunistic use of commons | No | QoS 4 | No |
| Operator cooperation based on exclusive and commons regimes | No | QoS 1 (exclusive) and QoS 4 (commons) | No |
| Spectrum market based on LSA licensing | Yes | QoS 1(from mobile operators) and QoS 2 (from local operators) | No |
| Spectrum market based on light licensing | Yes | QoS 1 (from mobile operators) and QoS 3 (from local operators) | No |
| Spectrum market based on pluralistic licensing, fixed interference | Yes | QoS 1 (from mobile operators) and QoS 1 to 4 (from local operators) | No |
| Spectrum market based on pluralistic licensing, adaptive interference | Yes | QoS 1 to 4 (from mobile and local operators) | Yes |

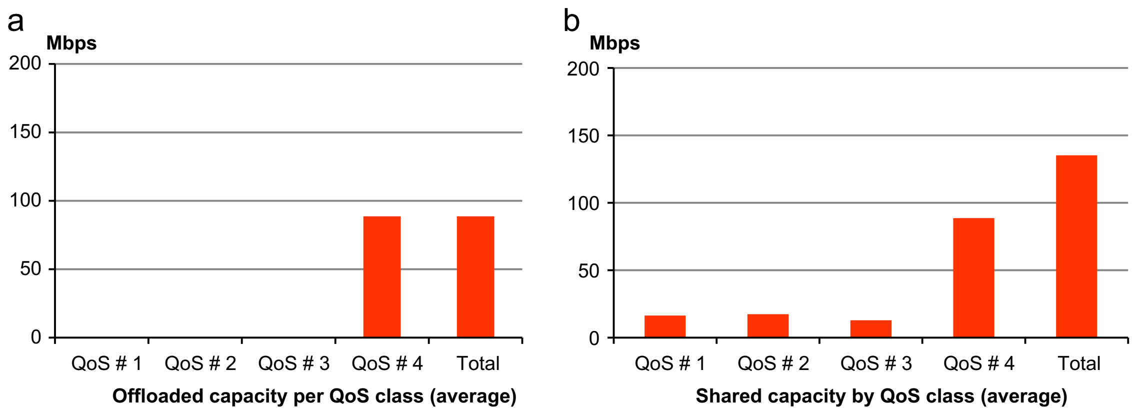


**Fig. 9.** Base scenario. Shared spectrum capacity for each QoS class (average values in Mbps).

for each graph corresponds to the sum of the values of each traded unit of spectrum capacity, with each unit obtaining a value proportional to its achieved QoS (as described in Eq. (1)).

Fig. 9 illustrates the case of a cooperation scenario under exclusive and commons regimes. Fig. 9(a) evidences that mobile offloading is a useful means for mobile operators to fulfill their traffic requirements. In addition, Fig. 9(b) shows the impact of inter-operator spectrum sharing, which increases the spectrum usage with higher QoS. Note that, in practice, this scenario may demand a revenue sharing mechanism.

The next simulation consists of a spectrum market adopting light licensing and LSA regimes. LSA and light licensing enable local-area operators to sell spectrum to mobile operators according to the QoS level described in Table 3. Mobile operators can also buy from other mobile operators. The results depicted in Fig. 10 reveal that both regimes achieve a higher value than the commons and exclusive regimes. LSA enables mobile operators to better serve their demand requirements by obtaining additional capacity for the service with higher QoS requirements. Light licensing brings further capacity to spectrum transactions. Nevertheless, the benefits based on light licensing transactions are reduced if the demand for higher QoS rises over time (Fig. 10(c)).

The last exercise consists of simulating a spectrum market based on a pluralistic regime. In this regime, each operator chooses the interference level that it is willing to accept based on the available market information on service requirements. When allowing pluralistic licensing, operators can adapt their supply by changing the interference level and consequently the offered QoS. The simulation assumes that each local-area operator provides spectrum capacity with different QoS levels in a *pluralistic licensing regime with fixed interference* (Fig. 11(a) and (c)). In a *pluralistic licensing regime with adaptive interference*, each local operator can modify its interference level over time, according to the demand information (Fig. 11(b) and (d)). Fig. 11 evidences that pluralistic licensing maximizes the value of the spectrum as compared with the other analyzed regimes, since it increases both the total capacity utilization and the value of transactions derived from each QoS class. In fact, Fig. 11(b) shows a two-fold increase in the first three QoS levels as compared with an operator cooperation scenario based on commons and exclusive regimes (Fig. 9(b)).

Fig. 11(c) and (d) illustrates the performed transactions of a scenario with higher QoS demand, as explained in Section 3.3. These graphs indicate that pluralistic licensing maximizes the volume and the value of transactions when the interference level is adapted over time according to the demand.

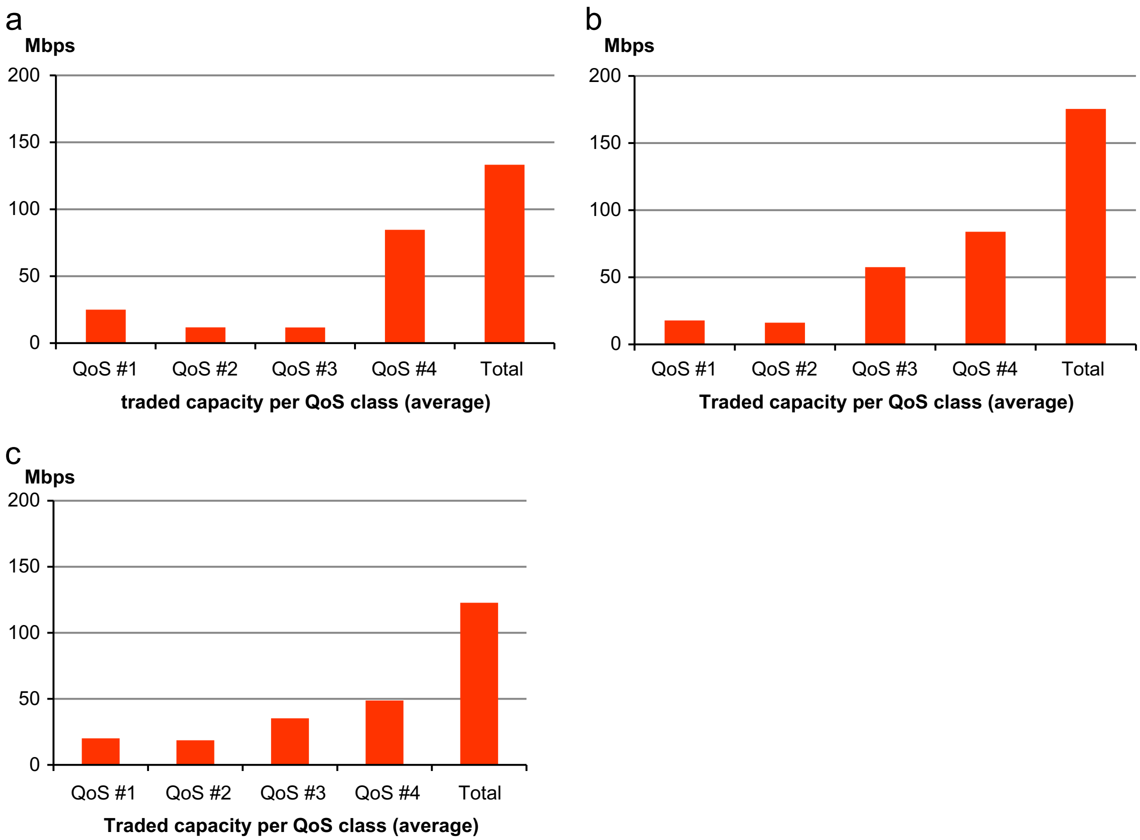


**Fig. 10.** LSA and light licensing scenarios. Traded spectrum capacity for each QoS class (average values in Mbps).

The simulation results show that social welfare becomes more optimal with interference management based on user requirements and valuations. By allowing different types of QoS on the supply side and matching supply with demand, the number of voluntary transactions is maximized.

To obtain a broad idea of the social gains associated with higher flexibility, the values of traded services are adopted as marginal valuation. Prices for a broadband connection range on average from 22 USD to 161 USD per month (OECD, 2011) and assuming that these prices reflect the experienced quality of the service class, an average price for a monthly subscription per service class would be the following: QoS 4 connection costs 22 USD/month, QoS 3 costs 56 USD/month, QoS 2 costs 91 USD/month and QoS 1 costs 126 USD/month. Considering these prices, a pluralistic licensing scenario (Fig. 12) doubles the total value of the spectrum (with an increase of 116%) as compared with an operator cooperation scenario (spectrum sharing) based on exclusive and commons regimes. LSA and light licensing regimes increase the value of the spectrum by 7% and 39%, respectively.

## 5. Conclusions and discussion

The simulations of different regulatory schemes show significant potential gains with a flexible spectrum regime allowing transactions. While service valuations have been different and time-changing for a relatively long period, recent technological advances radically change the possibility to detect these valuations and to trade spectrum. In particular, DSM can effectively decrease transaction costs if property rights are defined on a detailed level. Thus, DSM facilitates detecting and trading spectrum on a real-time basis and establishing interference parameters as a tradable characteristic of the spectrum, consequently improving the definition of spectrum rights.

Reduction in transaction costs together with clearly defined spectrum property rights provide the basic conditions for the Coasean implications on policy. Even though the performed simulations simplify the reality, the magnitude of the potential gains is significant, implying that the benefits are robust to the assumptions. The gains rely on the nature of the service demand, highly changing with location and time. This creates diversity and volatility in service valuations, which further increase when the spectrum is scarce, for instance, in an area with high population density. Therefore, the widely adopted exclusive and commons regimes offer considerable room for improvement.

Pluralistic licensing, which has been recently introduced by Holland et al. (2012), offers a means to address the increasing sophistication required by contracts to enable spectrum transactions. This regime introduces the idea of a trade-off

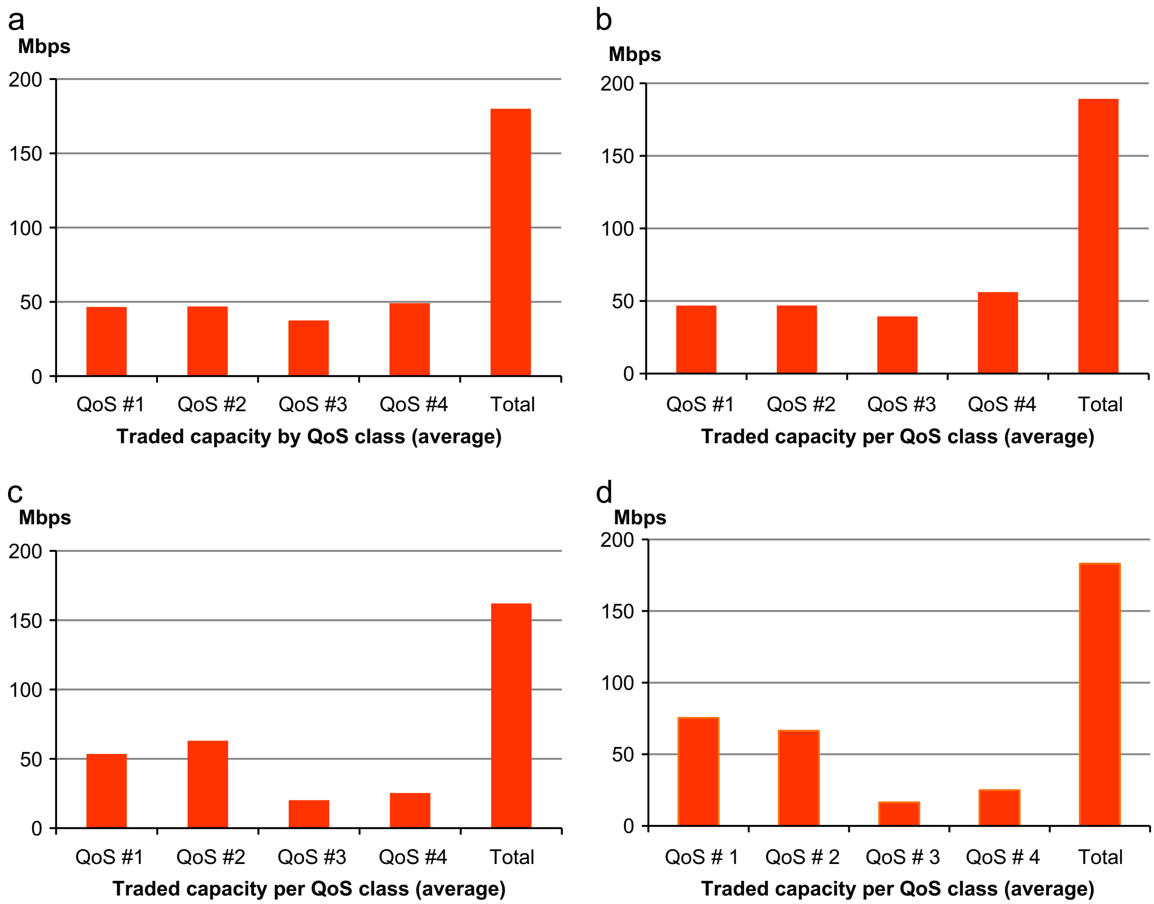


**Fig. 11.** Pluralistic licensing scenario. Traded spectrum capacity for each QoS class (average values in Mbps).

mechanism between interference and license fee to achieve an optimal spectrum usage. From a Coasean perspective, transactions should take place between market participants, i.e. through private contracts between operators, rather than being mediated by the regulator. Thus, each spectrum owner can accept to be interfered by others at an agreed price. For instance, if the demand for higher QoS rises over time for an operator, it can provide the required QoS for example, by increasing its transmission power and compensating to the adjacent operators for the interference caused. Alternatively, local licenses may be bought and sold to adapt the supply to the demand. In general, a flexible spectrum regime should permit to modify the interference levels over time by adapting the contract conditions.

In practice, a flexible spectrum regime such as pluralistic licensing can already be applied employing emerging DSM technologies. The state-of-the-art of this technology, for instance a spectrum database, considerably decreases transaction costs and maintains information on interference. Still, the current technology lacks the capability of managing interference in the most demanding cases. Nevertheless, regulators can define mechanisms which reduce transaction costs related to negotiations and availability of information for several cases. For instance, the latest developments in defining spectrum database rules help pursue this goal. Previous attempts at implementing spectrum property rights (e.g. Australia or New Zealand) and flexible spectrum regimes (e.g. SUR in UK) have failed to decrease transaction costs, because they have not considered concrete technical solutions and usage cases.

Furthermore, the results in this paper suggest that flexible spectrum regimes are particularly promising for a possible interaction between wide-area and local-area operators. Along this line, this study emphasizes that a wide-area/local-area scenario greatly benefits from a more detailed definition of the interference, which guarantees a sufficient level of quality. Currently, the inexistence of medium-to-large local-area networks makes this idea challenging. Under a scenario of increasing demand, regulators are willing to allocate additional spectrum for mobile services. In such a case, spectrum assignments based on exclusive and commons regimes make the emergence of new business models difficult. Thus, regulators should assign flexible spectrum licenses on a local basis to non-incumbent operators to incentivize the emergence of larger local-area operators, which encourages innovation to the industry. Additionally, the standardization of DSM technologies plays an important role in achieving the feasibility of new business models, since the emergence of a single standard considerably diminishes transaction costs.

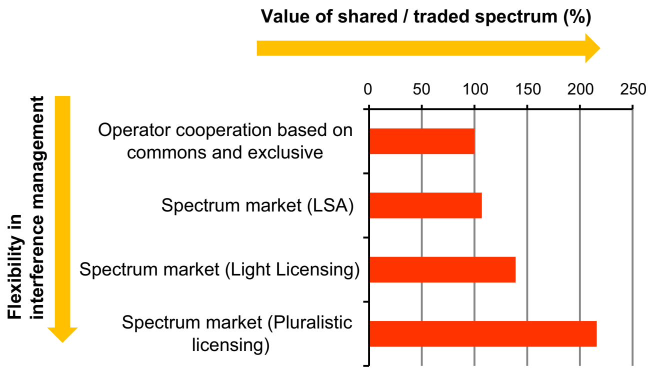


**Fig. 12.** Value of the spectrum for an equally distributed service scenario. The value increases alongside flexibility in interference management.

Finally, this study emphasizes a further role for regulation in a DSM scenario. Private incentives to invest in DSM technologies require a new regulatory regime. However, even under the existence of such a regime, the private incentives to invest may prove insufficient. For instance, a highly concentrated industry offers low incentives to implement DSM. On the contrary, if the industry presents a larger number of actors, the benefits of transactions become greater. This suggests that regulators should understand the effect of their current market structure on the diffusion of DSM.

## Acknowledgments

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## Appendix A. Model assumptions

| **Model assumptions (Summary)** | |
|---|---|
| **Number of wide-area operators** | 3, Capacity per site of 100 Mbps |
| **Number of local-area operators** | 4 per location (home, office and public place). Capacity per site of 60 Mbps |
| **Average traffic of local-area** | 6 Mbps per site |
| **User types (or service class)** | 20 User types, classified from SC1 to SC20 (according to classification of ITU-R M.1768-1), Table 2 |
| **Service types** | Very low rate (1 Mbps), low data rate and low multimedia (5 Mbps), medium multimedia (10 Mbps),<br>high multimedia (30 Mbps), super high multimedia (50 Mbps) |
| **Traffic classes** | Conversional (QoS #1), streaming (QoS #2), interactive (QoS #3), background (QoS #4) |
| **Spectral efficiency of the users at buying operator** | QoS # 4: ratio1; QoS # 3: ratio 1,15; QoS # 2: ratio 1,3; QoS # 1: ratio 1,5 |
| **Probability of location** | See Fig. 6 |
| **Traffic capacity demand** | See Fig. 5 |
| **Simulation length** | 300 cycles (h) |

| **Interference characteristics of spectrum regimes** | | |
|---|---|---|
| **Regime** | QoS offered by mobile operators | QoS offered by local operators |
| **Exclusive and commons regimes** | QoS # 1 | QoS # 4 |
| **Licensed Shared Access (LSA)** | QoS #1 | QoS #2 |
| **Light Licensing** | QoS #1 | QoS #3 |
| **Pluralistic Licensing, fixed interference** | QoS #1 | QoS # 1, 2, 3 or 4 (fixed) |
| **Pluralistic Licensing, adaptive interference** | QoS # 1, 2, 3 and 4 (changes according to demand information) | QoS # 1, 2, 3 and 4 (changes according to demand information) |

| Learning algorithm for pluralistic licensing (adaptive interference) | |
|---|---|
| **Condition** | **Behavior** |
| If the unattended demand of QoS class $N >$ spectrum capacity of local operator, AND the unattended demand of QoS class $(N+1$ or $N-1) <$ last trade/2 | Change interference profile of local operator from $(N+1$ or $N-1)$ to $N$. |
| If the unserved demand of QoS class $N >$ spectrum capacity of mobile operator, AND the unserved demand of QoS class $(N+1$ or $N-1) <$ last trade/2 | Change interference profile of mobile operator from $(N+1$ or $N-1)$ to $N$. |

## Appendix B. Interference and capacity requirements

Based on similar calculations than that performed by Basaure & Holland (2014), this work estimates the effect of a change in spectrum usage on the received quality of the signal (signal-to-interference-and-noise ratio, SINR) and on the total capacity. This example assumes that the experienced SINR is proportional to the experienced capacity (in bits/s/Hz). The table below shows a gradual change in number of users from the buying operator (from 6.9 to 10.2), with similar interference restriction at the selling side. As a result, the users at the buying operator experience a total increase in capacity with a decrease in experienced quality. In this example, an increase of 15% in spectrum capacity corresponds approximately to a decrease of 0.3 dB in average and an increase of 0.6 dB in standard deviation in SINR values respectively (about 5 Mbps of throughput according to (3GPP TR 25.814)).

| Selling operator | | | Buying operator | | | | |
|---|---|---|---|---|---|---|---|
| Number of users | SINR (dB, average value) | SINR (dB, standard deviation) | Number of users | SINR (dB, average value) | SINR (dB, standard deviation) | Total capacity (Mbps) | Ratio |
| 16.37 | 12.77 | 3.55 | 6.90 | 6.24 | 6.67 | 137.94 | 1 |
| 16.41 | 12.64 | 3.79 | 8.88 | 5.81 | 7.57 | 165.54 | 1.20 |
| 16.24 | 12.60 | 3.78 | 10.20 | 5.74 | 8.24 | 187.69 | 1.36 |
| 16.23 | 12.49 | 3.85 | 12.22 | 5.36 | 8.58 | 209.96 | 1,52 |

For the purpose of this study, the following ratios are employed for each QoS class. Note that these ratios are approximations, since they depend on many variables. For instance, the signal orthogonality of the interacting terminals highly impacts the results. Here it is approximated by a factor of 10%.

| QoS class | Capacity ratio |
|---|---|
| QoS # 1 | 1 |
| QoS # 2 | 1.15 |
| QoS # 3 | 1.3 |
| QoS # 4 | 1.5 |

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# Publication 2

**Basaure, A., Holland, O. (2015). Optimizing spectrum value through flexible spectrum licensing. IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN), 130-141, DOI: 10.1109/DySPAN.2015.7343897**

# Optimizing Spectrum Value Through Flexible Spectrum Licensing

Arturo Basaure[1] and Oliver Holland[2]

*Abstract*— **Latest developments in radio access are radically changing the management of the spectrum for mobile services, progressing from exclusive licensing with static conditions towards more flexible licensing schemes, which allow a dynamic spectrum assignment. In this context, spectrum transactions between participating actors can generate mutual benefits. However, the fact that these transactions typically generate interference between users requires a clear definition of that interference and any associated benefit. This paper analyzes realistic cases of spectrum transactions between two operators, considering different service requirements and generated interference in the context of flexible spectrum licensing. The simulated transactions suggest that the optimal level of interference is usually above zero, and given a fixed spectrum bandwidth, an increase in demand results in additional gains in a scheme, which allows voluntary transactions with flexible interference respect to a scheme. This in turn restricts or minimizes interference. Finally, this paper provides guidelines for achieving the most beneficial type of spectrum transaction. The main contribution of this paper is to provide a concrete scheme in which interference is traded within a transaction to optimize the value of the spectrum.**

*Key words*—**Agent-based modeling, flexible spectrum licensing, measuring and pricing interference, primary-secondary and co-primary sharing, spectrum transactions, user utility function.**

## I. INTRODUCTION[3]

Spectrum management is one of the main challenges facing mobile and wireless communications, especially in the context of systems evolution and ever-increasing traffic demand. Ongoing improvements in radio access capability facilitate the assignment of spectrum licenses with more flexible conditions, which in turn can improve aggregate capacity through spectrum trading. However, spectrum holders (specifically, mobile operators) are usually not supportive of spectrum trading. Thus, the understanding of the incentives of the spectrum seller (primary operator) and the spectrum buyer (secondary or co-primary operator) in a spectrum transaction plays an important role in deploying successful new spectrum regimes.

In recent years, spectrum auctions have achieved very different outcomes [2]. Given this, the possibility of trading spectrum more dynamically over time has been suggested as a means to more accurately quantify the value of the spectrum. Since spectrum has different values to different entities at different times and places, spectrum transactions should generate mutual gains. In step with such transactions, a spectrum market has the role of matching supply with demand, and thus reaching an optimal spectrum allocation, which is dynamic in nature over time. However, spectrum trading usually generates interference to spectrum users, and therefore transactions need to consider this negative externality. Therefore, the ability to measure interference will determine how prices can reflect user utility and internalize the produced negative externality.

This paper explores license flexibility as a means to realize spectrum transactions, thereby also achieving a valuation of the caused interference and an optimization in spectrum usage. The work performed herein can be seen as in line with an assessment of the pluralistic licensing concept [3] or any other flexible spectrum regime allowing spectrum transactions. Previous related work has been theoretical. With the purpose of understanding the real implications of interference flexibility in spectrum regimes, this study carries out realistic simulations of bilateral spectrum transactions together with a sensitivity analysis that provides useful guidelines for optimizing the spectrum value, considering the interference as a tradable characteristic of the spectrum and assuming the deployment of state-of-the-art Dynamic Spectrum Access (DSA) technologies.

The current literature has increased its understanding on the value of the spectrum; however, it typically does not recognize the economic impact of interference as its main negative externality. Very often interference is considered as a constraint to be minimized rather than an externality to be optimized. The analysis of concrete spectrum transaction situations, which may be deployed with the existing state-of-the-art technologies, might improve the understanding of the effects of spectrum transactions on the spectrum value and social welfare.

Given the above, this paper performs a feasibility study of bilateral spectrum transactions in a flexible spectrum licensing regime, and assesses the conditions under which the spectrum value is maximized in such transactions.

The paper is structured as follows. Section II provides a review on related literature. Section III presents the model for assessing spectrum value. Section IV describes the simulation results, whereas section V estimates the total value of accessing the spectrum based on these results. Finally, section VI concludes the paper.

## II. LITERATURE REVIEW

The idea of spectrum trading has been frequently proposed in the literature in recent years. However, often the analyzed scenarios are more hypothetical than practical and they lack

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[3] This work is an extension of [1].

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concrete implications for the current mobile industry, remaining as an interesting theoretical exercise.

For instance, the existing literature presents several models of auction mechanisms and game theoretical analysis of spectrum dynamic allocation. The work of [4] suggests game theoretical model for sharing spectrum between two cells, which include interference mitigation. Other work proposes an optimal auction mechanism for maximizing the revenue of the primary operator while providing access to a secondary operator [5]. In this work, interference is taken as a constraint parameter within the auction design.

Some other authors focus on market design. For instance, reference [6] characterizes the implementation of a spectrum market in general terms, performing a classification of the spectrum trading architectures. In reference [7], the authors perform a dynamic spectrum trading scheme based on market equilibrium to assess the price given the demand of the secondary operator and the supply of the primary operator. In a more hypothetical fashion, reference [8] performs a modeling exercise with mobile users dynamically accessing different networks on a per-session basis. The authors propose a flexible access paradigm, in which multiple users with different requirements access the network. In this same line, another work attempts to value spectrum according to the experienced *quality of service* (QoS) can be found in [9], which analyses theoretical quality-price contracts between a primary operator and multiple secondary users.

In general, the literature presents two opposing market types, namely *reservation* and *spot markets*. While a reservation market is static and performed through long-term contracts, a spot market is much more dynamic and user driven, usually based on real-time spot pricing. From this perspective, spectrum trading may evolve towards a spot market along with the development of the technology. Analogically, in energy markets the fluctuations of different sources of energy, especially in the case of renewable energy sources, limit the benefits of market based mechanisms [10][4]. Spot markets seem to fit better for a low-risk scenario with low fluctuations. These markets have been widely investigated in the literature, for example by [11], [12] and [13]. A study on the impact of reservation markets can be found in [14].

For the purpose of this paper, real-time markets based on auctions and spot prices are not yet realistic, since those transactions involve further development of the technology and may create uncertainty in the market. For instance, reference [15] compares the economic value of spectrum under three different trading mechanisms: direct trading, auction and brokerage, suggesting that direct trading optimize social welfare, considering current technical, economical and policy factors. In fact, more complex trading mechanism may not yet achieve the optimal benefits due to implementation costs.

Together with emerging literature, several new spectrum regimes have been proposed to incentivize spectrum transactions in recent years. *Licensed Shared Access* (LSA) is a licensing regime which permits the spectrum holder to lease its spectrum to additional users with a guaranteed quality of service, through a legal contract providing certainty and financial compensation [16]. *Light licensing* provides a collective access of the spectrum, given as an individual or a general authorization, assuring a certain quality of service by requesting a registration mechanism or other means of coordination [17]. While LSA has come from industry and initially focused on getting additional spectrum to mobile operators, light licensing has a longer background history with several existing applications and have been finally formalized by the European Commission in 2009 and suggested as a means of sharing spectrum between different actors [18]. Finally, *pluralistic licensing* proposes a flexible licensing mechanism which allows the spectrum holder to adapt its interference tolerance in exchange for an economic compensation based on well-known and predictable interference conditions [3]. This regime considers explicitly the interference in the license price. In fact, pluralistic licensing requires the primary operator to agree interference parameters and rules at the point of obtaining the license. Such a license incentivizes the operator to accept secondary users through a reduced license fee or additional revenue mechanism, whereby the secondary spectrum access will be based on cognitive radio (CR) capabilities to avoid causing harmful interference to the primary or to otherwise keep interference within known parameters.

Besides market design, interference is a main concern of several studies. A number of authors consider interference as a technical constraint, and commonly from the primary operator perspective. For example, reference [19] analyzes spectrum sharing between a primary and a secondary system in the so-called gray spaces, to make more efficient use of the already allocated spectrum, given an interference limit of the primary system. The work in [20] designs of subdivision of spectrum, which operators should be able to buy, sell, divide and combine. This work suggests that neighbors in adjacent regions should be able to negotiate the costs and benefits of interference mitigation mechanisms. In reference [21], authors analyze the optimal conditions for leasing spectrum from the perspective of the perceived QoS by the secondary operators for a long term spectrum leasing market. The work in [22] proposes a pricing scheme by formulating an optimization problem of the primary operator revenues, considering as trade-offs the caused interference and spatial constraints. The same authors study the conditions of profitability for trading spectrum through a private commons regime in [23].

A number of authors have suggested that interference should be treated as an externality to be optimized and not just as a technical constraint. A first step towards this vision claims that the focus should not be only in the transmitter, but also in the receiver [24], [25]. Finally, some authors have emphasized the role of the interference in spectrum trading. However, this idea has remained typically vague and untested, especially on how to connect technical parameters of interference to economic value of the spectrum. For instance, another work presents the concept of interference rights defining a spectrum market which considers interference as tradable, and thus it should be determined by private operators involved in the transactions without the intervention of the regulator [26]. In the same line, reference [27] describes interference as a tradable characteristic, which enable a differentiated service supply to optimize social welfare. Despite these efforts, the economic perspective of the

[4] For example, wind energy depends on weather conditions, which represents an additional uncertainty for energy supply and consequently a source of volatility for spot prices.

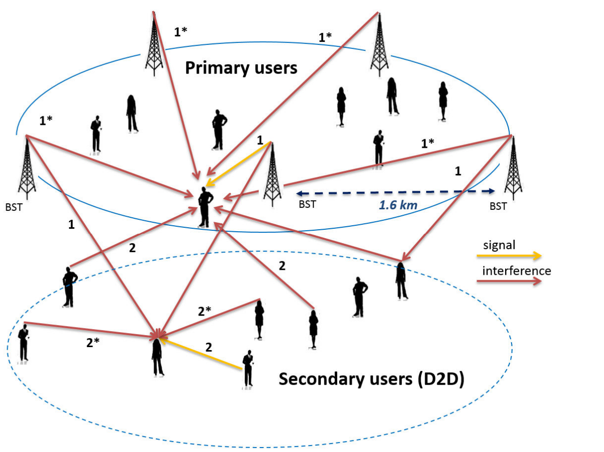
interference has been often understudied. For instance, while a number of authors have been suggesting new means of assessing the spectrum value (e.g., [28] and [29]) the interference has been missing in these proposals.

This study simulates realistic spectrum transactions in a long term set-up between two operators. The purpose of this study is to propose a transaction scheme, in which interference is traded as a flexible characteristic of the spectrum, to maximize spectrum value in such transactions. This paper is not intended for determining the conditions for competition or addressing any other issue related to market design. It rather provides a new understanding of the interference as a dynamic trading characteristic and claim that such transactions can be already implemented with state-of-the-art technology.

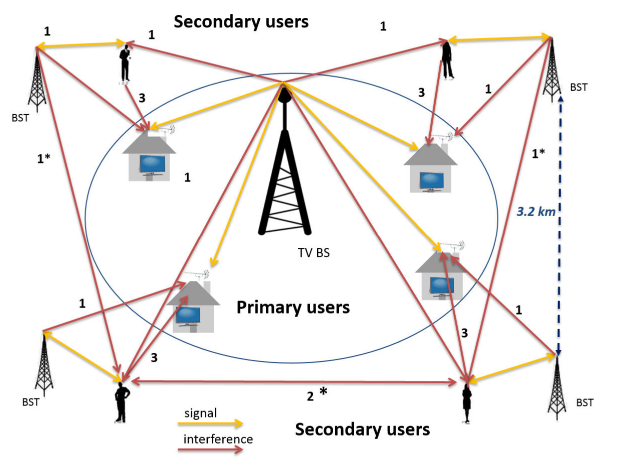
## III. A MODEL FOR ASSESSING THE SPECTRUM VALUE WITH INTERFERENCE

This section develops a model which simulates the interference experienced by the involved users, to analyze the main parameters impacting the experienced QoS.

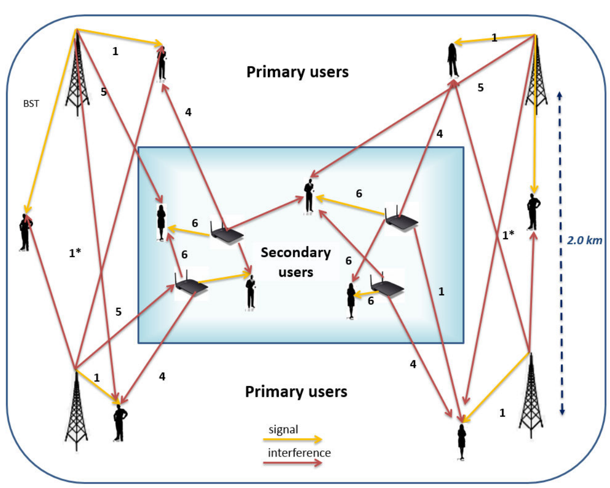
To date, interference measurement has been extremely challenging; nevertheless, the understanding and aspects of such management are constantly improving along with the development of DSA technologies, such as *Cognitive Radio Systems* (CRS) and *Software Defined Radio* (SDR). Although several sensing techniques have been developed [30], the current state-of-the-art presents important challenges, such as the sensing time and delay, cooperation and energy efficiency, tracking mobile users and channel impairment [31]. Notwithstanding, secondary spectrum access can be presently based on an authoritative register (here referred as to *spectrum database*), from which users request permission for access to the spectrum. This database has predefined rules based on non-real-time interference measurements or predictions. For instance, an example of such rules and requirements for a spectrum database can be found in [32], [33] and [34]. Such a spectrum database holds the geographical information on



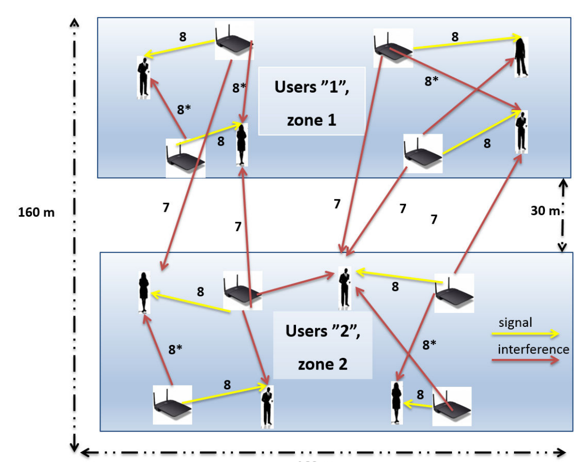

a) 1st scenario: cellular network – D2D spectrum sharing




b) 2nd scenario: cellular network accessing TV white spaces




c) 3rd scenario: macro-femto cellular spectrum sharing




d) 4th scenario: indoor local area spectrum sharing

Figure 1: Graphical representation of simulation scenarios (transmitted signal is depicted in yellow and interference in red): a) Cellular- D2D sharing scenario b) TVWS sharing scenario c) macro and femto-cell sharing scenario, d) co-primary indoor scenario. Numbers indicate the employed path loss model: 1) COST Hata model, 2) ITU-R P.1411 end-to-end [41], 3) End user-TV antenna model [42], 4) COST 231 for building penetration (LOS), 5) COST 231 for building penetration (NLOS), 6) ITU-R indoor propagation model, 7) In building propagation model for mm-waves [43] with wall penetration loss 8) In building propagation model for mm-waves, *: Orthogonal signal.

TABLE I: SIMULATION ASSUMPTIONS

| Parameters | Scenario 1: Cellular-D2D | Scenario 2: TV / cellular | Scenario 3: Macro/ femto cellular (outdoor-indoor) | Scenario 4: co-primary indoor pico/femto cellular |
|---|---|---|---|---|
| Cellular BS spacing (km) | 1.6 | 3.2 | 3.2 | NA |
| Secondary leasing distance (m) | 100, 200 or 300 | 50 | 50 | NA |
| Separation between coverage areas (m) | 700 | 500 | NA | 30 m |
| Transmission frequency (center) | 700 MHz | 700 MHz | 2.3 GHz | 60 GHz |
| Primary BS transmission power (dBm) | 37-49 | 44-50 | 44-50 | 18-24 |
| Number of primary BSs | 5 | 1 | 4 | 8 |
| Secondary (co-primary)BS transmission power (dBm) | NA | 31-43 | 20-24 | 18-24 |
| Number of secondary (co-primary) BSs | NA | 4 | 8 | 8 |
| Primary terminals transmission power (dBm) | 21 | NA | 21 | 21 |
| Secondary (co-primary) terminals transmission power (dBm) | 20 | 21 | 21 | 21 |
| Antenna gain, Tx/Rx (dB) | BST: 10; end user: 0 | BST & TV antenna: 10; end user: 0 | BST: 10; end user: 1 | 2.1 |
| Path loss model from Cellular base station to terminal | Cost 231 Hata model for urban area (large city) | Cost 231 Hata model for urban area (large city) | Cost 231 Hata model for building penetration with non-light-of-sight (NLOS) | NA |
| Path loss model from local access point or terminal or to terminal | ITU-R P.1411 end-to-end model [41] | End user-TV antenna model [42] | ITU-R indoor propagation model | In bulding propagation model for mm-waves [43] |
| Noise power | -105 dBm / 0.032 pW | -105 dBm / 0.032 pW | -105 dBm / 0.032 pW | -105 dBm / 0.032 pW |
| Shadowing standard deviation | 6 | 6 | 6 | 6 |
| BS effective height, primary case | 30 m | 50m | 30m | 1.5 m |
| BS effective height, secondary case | NA | 30m | 1.5m | 1.5 m |
| Primary node effective height | 1.5 m | 10 m | 1.5m | 1.5 m |
| Secondary node effective height | 1.5 m | 1.5m | 1.5m | 1.5 m |
| Coordination level at primary system (%) | 90 | 0 | 90 | 0-100 |
| Coordination level at secondary system (%) | 90 | 90 | 0 | 0-100 |

primary services, propagation and other aspects, possessing the capability to calculate interference predictions for a prospective spectrum access. This will improve accuracy with the further development of these technologies.

This study models a spectrum sharing scheme based on primary-secondary and co-primary coexistence, in which the primary and secondary services have different requirements, while co-primary have similar requirements. The analysis herein is intended to be a reflection of [3], as a method of facilitating and compensating for flexibility in spectrum use, permitted by the primary spectrum owner, although may be more generally extrapolated to other schemes allowing transactions such as the above mentioned. In specific, this work assumes that the technical characteristics and geographical coverage of the primary systems are known or calculated by a spectrum database. The secondary device requests permission from this database, which allows the secondary user to transmit if his/her location is within a predefined area (here referred as to *coverage area*) and, in some cases, if he/she has not moved more than a pre-defined distance (here referred as to *leasing distance*), since the last authorization from the database. Thus, while primary users are always allowed to transmit within their coverage area, secondary users can transmit only if their access request is accepted and with restricted conditions of mobility. A secondary user can be additionally equipped with more advanced sensing capabilities or any other means to obtain real time information on primary location and thus diminish even more harmful interference. The model supposes that the secondary awareness will be based on the authorization given by a spectrum database, without involving real-time awareness, which further improves the performance of the system.

The main challenge for enabling such spectrum transactions is the accuracy of interference measurements. Once this is properly addressed, the economic value coming from a spectrum transaction can be transferred through a brokerage system or directly from the secondary users.

This paper develops a simulation model to understand the interference characteristics for primary, co-primary and secondary users transmitting in the same frequency. These scenarios represent a wide range of spectrum transactions cases involving different spectrum bands and systems and they are intended to cover the most representative cases of interest from a deployment perspective. They may be linked, for instance, with each level of the US three tiered authorization framework. The first scenario represents an urban area in which the primary system consists of 5 adjacent cells of an LTE-type cellular network. The secondary users are a set of mobile terminals or other spectrum users implementing device-to-device (D2D) communication[5], which do not require base stations or any other specific network infrastructure and have a different coverage area than the primary (Figure 1(a)). The first scenario focuses on the performance of the primary users being served by the base station of the center cell of a set of 5 adjacent cells at the edge of coverage of the primary system. This base station is surrounded on one side by other primary base stations and on the other side by the secondary users. The secondary users transmit in the same frequency band in a limited area located outside the 5 adjacent cells. The second scenario describes a case, in which cellular mobile devices access the 700 MHz band in an area adjacent to the TV coverage, by requesting permission from an authoritative register. The objective is to analyze those frequencies of the 700 MHz band that might be shared between

[5] D2D communication refers herein to direct terminal-to-terminal communication, excluding any communication supported partially or totally by cellular network infrastructure.

cellular systems and TV provisioning in some regions [35]. This scenario is a reflection of the ETSI standard for white space devices [36]. Figure 1(b) gives a graphical representation of this scenario, in which a TV repeater is located in the middle of the simulated residential primary coverage area, while cellular base stations acting as secondary spectrum users are located in the surroundings of the coverage area. Cellular devices access the TV white spaces after checking with a spectrum database, which authorizes the secondary access by following access rules such as those defined by [33][6]. Authorization is provided based on the locations of the secondary devices and an estimation of the interference caused to the primary, given a minimum requirement of experienced SINR by the primary within a certain confidence level. The third scenario represents a coexistence scenario between a macro cellular network serving outdoor mobile devices (acting as the primary user), and femto-cell serving mobile devices at an indoor environment (secondary users), both in the 2.3 GHz band (Figure 1 (c)). The coverage area is delimited by the outdoor-indoor interface, where secondary users request access permission from a similar authoritative database as in the other scenarios. The fourth scenario, depicted in Figure 1 (d), analyses two adjacent indoor areas (e.g., two buildings separated by a street), each one deploying a local area network by means of pico or femto cellular networks, transmitting in the 60GHz band. Each area is managed by a local operator and enjoy equal priority than the other adjacent local operators (i.e. co-primary operators).

The simulation is performed by employing *agent based modeling* (ABM). ABM is especially suitable for modeling the behavior of agents (such as end mobile users) to observe the collective effect of their interaction [37].

Table 1 describes the simulation assumptions for the technical and location-related parameters. For all scenarios, the database holds information on the interference the primary is able to receive, which depends on the transmission power of the primary base station. The permission is granted to the secondary if the additional interference is within predefined limits. In practice, interference figures are described as distributions, which might vary over time.

At each simulation cycle, all users move at a constant speed[7] (following a random walk algorithm[8]). After the primary system attends the user demand, secondary users request access from the spectrum database. Permission to transmit and receive is provided to the secondary with a mobility restriction (coverage area and *leasing* distance). If the user moves a distance above the *leasing* distance, he/she should request again for accessing the spectrum. Finally, all users require a minimum amount of signal-to-interference-and-noise ratio (SINR) to be considered as active users. Otherwise, they are *out of range*.

In specific, the model analyzes the interference behavior of the transmission link, which is being employed by the primary and the secondary users. In the first and third scenario, the model assumes the downlink of frequency division duplex (FDD) system, while in the second scenario it assumes a time division duplex (TDD) system, since it refers to a TV broadcasting network. Figure 1 illustrates the signal and the interference with different colors for every scenario (yellow and red, respectively). To assess the overall externality caused by interference, the model quantifies the received signal and interference at each user terminal by employing a suitable path loss model. The COST 231 Hata propagation model for urban areas (large city) [40] is adopted for determining the signal and interference transmitted from cellular base station for all scenarios. The propagation model of ITU Recommendation P.1411 [41] is adopted for determining the terminal to terminal communication of the first scenario, using a 99% of error rate probability. In the second scenario, the end user TV antenna model [42] describes the propagation of signals from the mobile secondary users to the TV antenna receivers of the second scenario. In the third scenario, COST Hata model includes building penetration for both light-of-sight (from femto-base station to primary user) and not light-of-sight (from base station to secondary user). Finally, the transmission inside building is described by the ITU-R indoor propagation model at the 2.5 GHz band and by the indoor model developed by [43] for the 60GHz band.

One important issue to consider when modelling interference is the level of coordination between terminals and base stations of the same network. While cellular base stations achieve a high level of coordination between different base stations and mobile users, systems using random access protocols like Wi-Fi usually lack any kind of coordination. For instance, [44] claims that in indoor environment, uncoordinated systems are more suitable for high density areas and lower throughput requirements, while coordinated ones are more suitable for lower density areas and higher throughput requirements. The main reason for this being that cellular technologies require high coordination costs to avoid interference.

This study assumes that cellular base stations interfere very little with other mobile end users of the same network since transmissions are orthogonal (90% of coordination), while femto-cellular base stations and Wi-Fi like technology interfere with other end-user terminals. The third scenario assumes for indoor environment with high building concentration, in which walls protect users from interference coming from other femto-cell base stations for the third scenario. The fourth scenario compares different levels of coordination, assuming different network deployments (e.g., femto- versus pico-cellular networks). For the first scenario, this model supposes a high level of coordination between secondary D2D (device-to-device) end user terminals, assuming a high level of orthogonality, or 90% of coordination.

## IV. Simulation Results

This section presents the simulation results for different sharing scenarios, which will be employed by the next section to assess the value of the spectrum.

These simulations consist of a sensitivity analysis of the main parameters affecting the experienced QoS to analyze the performance of the spectrum usage in terms of total amount of users *in range* and their experienced SINR. For the first scenario, these parameters are the primary base station transmission power and the secondary leasing distance. For the

[6] Note that in this study performs a sensitivity analysis of the secondary transmission power, which requires communication between involved parties; however, this is not part of the referred access rules.

[7] In one simulation cycle, each user moves 50 meters in 20 seconds (i.e. at a constant speed of 15km/h).

[8] A random walk algorithm is suitable for analyzing the general performance of a system ([38], [39]), which is the objective of this exercise.

second and third scenarios, the parameters are the primary and secondary base station transmission power.

For the first scenario, simulations gradually adjust the transmission power of the primary base station from 37 dBm to 49 dBm (from 5 to 80 W) to analyze the impact on SINR and on the number of active users. Additionally, they adjust the leasing distance by +100m and +200m (from the initial value of 100m). Figure 2 illustrates the simulation results for the first scenario. Figure 2 (a) depicts the cumulative distribution functions of the experienced SINR by primary users when varying the primary base station transmission power. The total number of users does not vary much with the transmission power; however, it increases by rising the leasing distance (Figure 2 (b)) at the primary expenses. In fact, the experienced SINR by the primary user suffers a small drop in its average value (Figure 2 (c)) and a larger rise in standard deviation, which can be understood as a higher interference uncertainty. This behavior evidences a trade-off between the secondary mobility and the primary QoS. However, this situation may change with the improvement of secondary sensing capabilities. From the secondary perspective, their coordination will determine the achieved performance. For instance, Figure 2 (d) shows a decrease in experienced SINR with an increase in the number of users, when secondary cause interference to each other with an orthogonality factor of 10%.

In the second and third scenario, the simulations adjust the transmission power of the primary and secondary base stations to analyze the mutual impact of raising the interference from one side to the other. In the second scenario, the TV repeater located in the middle of the simulation area has similar power levels than a conventional cellular base station and for this purposes it changes gradually from 44 to 50 dBm. On the secondary side, the cellular base stations changes gradually from 31 to 43 dBm. This scenario assumes that TV receivers require a higher minimum SINR than mobile receivers to permit the secondary user to transmit. Figure 3 (a) (b) shows the simulation results for this scenario. Figure 3 (a) illustrates the average SINR values of primary and secondary users for different transmission power combinations. As expected, primary values are higher, since they demand a high threshold value. In the third scenario, the transmission power of the primary base station is adjusted gradually from 44 to 50 dBm, while the transmission power of the indoor femto-cellular base station is adjusted from 20 to 24 dBm depending on the number secondary users. Figure 3 (c) indicated that a change in the macro-cellular base station lightly affect the SINR of the indoor users, while femto-cellular base station affect even less the SINR of outdoor users. Figure 3(c) shows additionally that an increase in secondary transmission power permits an increase in secondary users (Figure 3 (d)).

The fourth scenario continues the analysis started by the third scenario by studying the mutual impact of two adjacent indoor areas transmitting at a very high frequency (in the so-called millimeter-waves, at 60GHz). The results show that the experienced quality depends much more on the internal coordination of the network (Figure 4 (b)) than in the interference coming from an adjacent network (Figure 4 (a)). Figure 4(a) illustrates that at a lower transmission power the interference coming from the network at the neighbor building is low, and when the transmission power is increased this interference is almost unexciting. Figure 4(b) shows that for a case of dense network deployment and constant number of users, local network without coordination (such as femto-cellular network) achieves an average SINR of 10 dB, while a network with high coordination (such as pico-cellular network

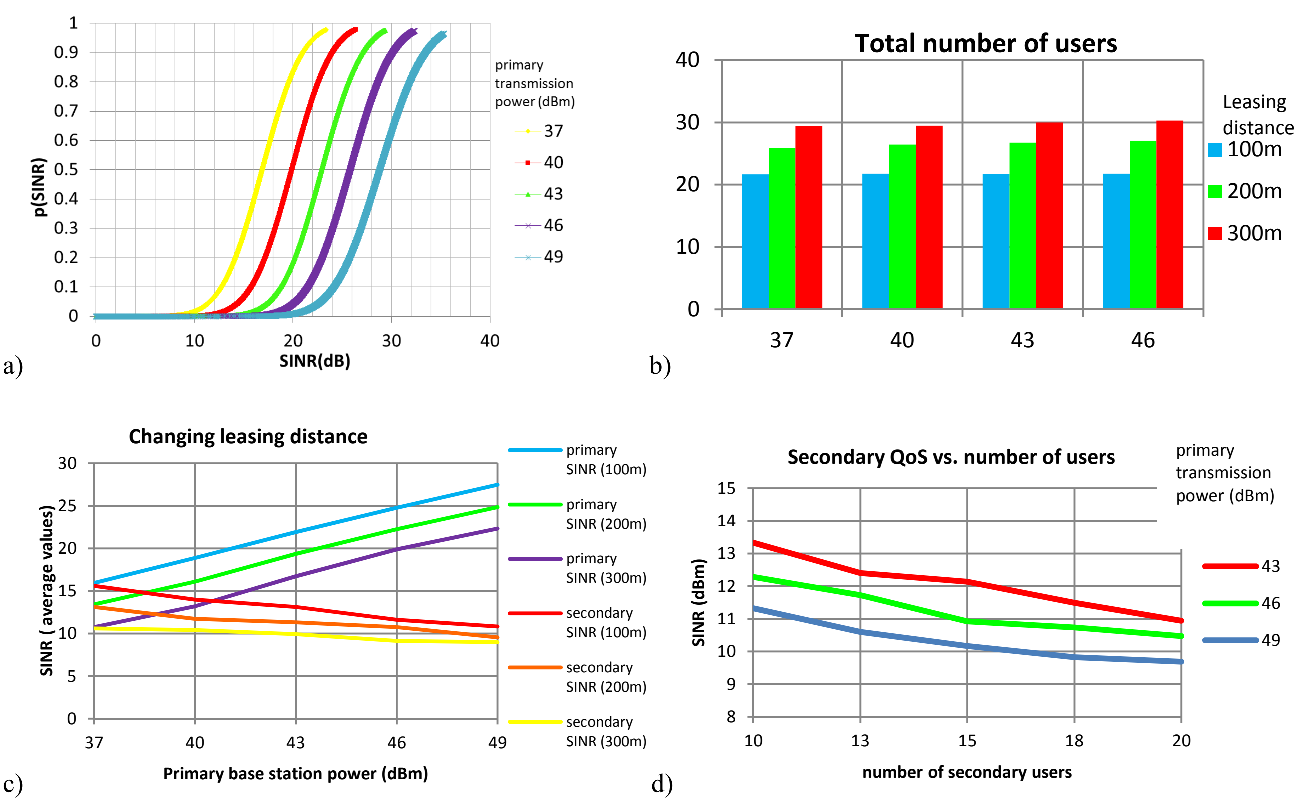



Figure 2: (a) Cumulative distribution function (CDF) for the experienced SINR by primary users. (b) Total number of users for different leasing distances. (c) Sensitivity analysis of SINR for different leasing distances (100, 200 and 300m) (d) Secondary SINR against the number of secondary users.

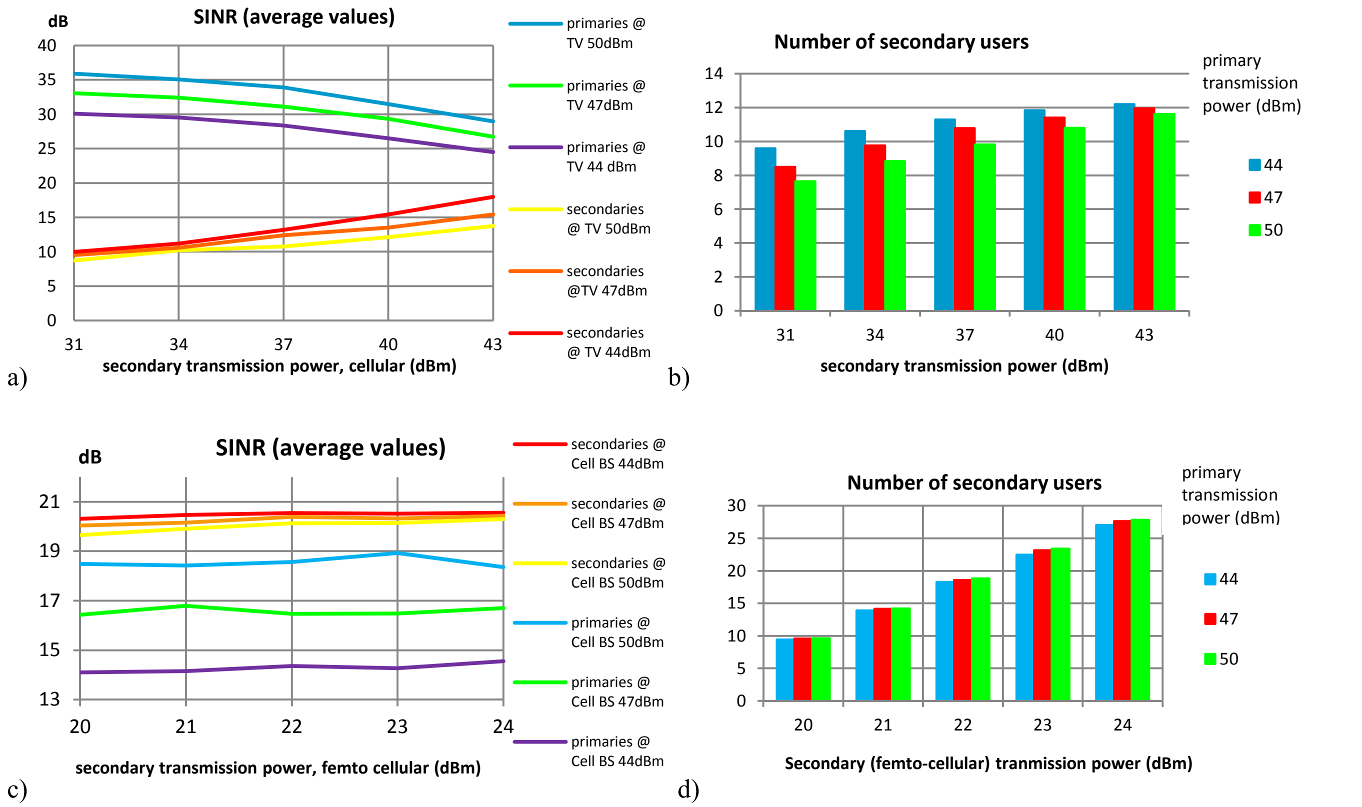



Figure 3: Average value of SINR for primary and secondary users against transmission power (a) second scenario (c) third scenario. Total number of secondary users against transmission powers for (b) second scenario (d) third scenario.

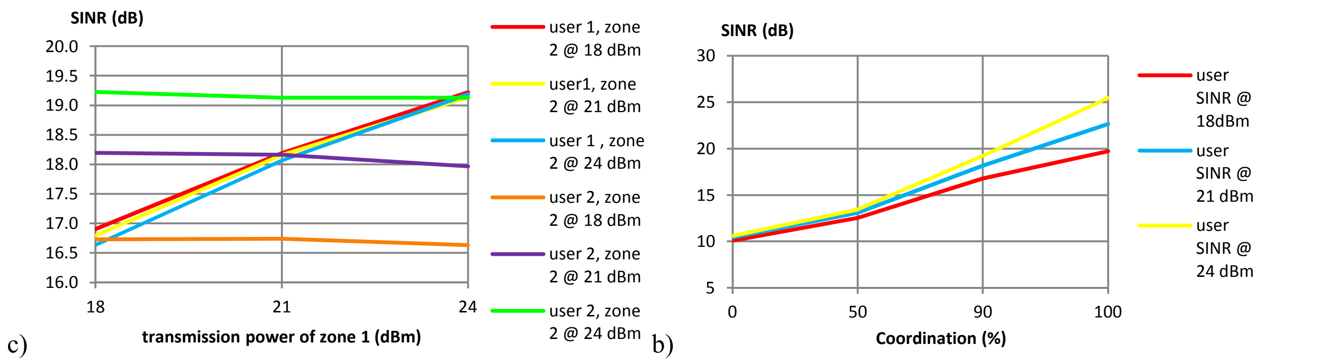



Figure 4: (a) Average value of SINR for a constant number of users at zones 1 and 2 against transmission power for the fourth scenario (b) average SINR for all users against level of internal coordination

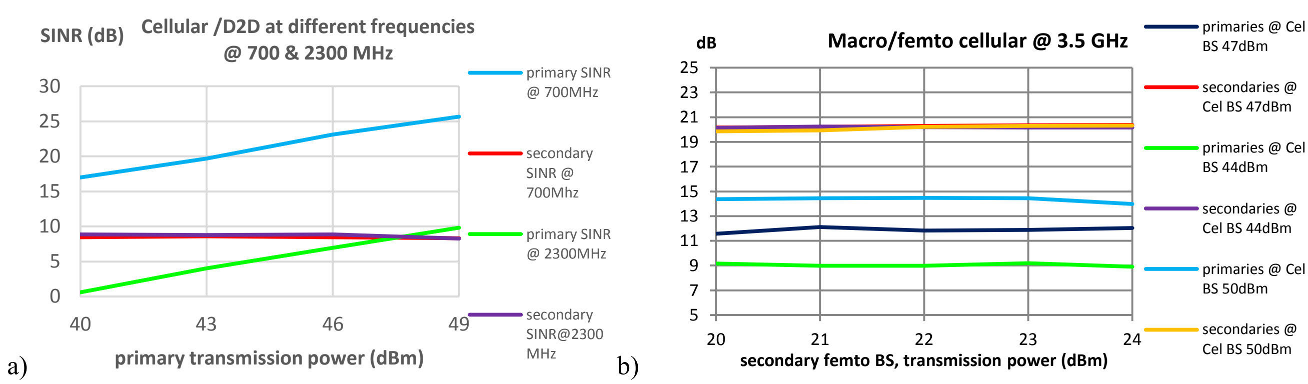



Figure 5: Sensibility analysis of the transmission frequency for the first (a) and the third (b) scenarios.

with 90% of coordination) may achieve as high as 19 dB. A theoretical maximum of 25 dB is achieved with 100% of coordination.

Finally, the last simulation exercise performs a sensitivity analysis of the transmission frequencies for selected scenarios. Figure 5 (a) depicts the effect of the frequency of transmission on the overall system performance for the first scenario, while Figure 5 (b) performs a similar analysis for the third scenario. Figure 5 (a) evidences that a higher frequency achieves a lower performance for the primary users, while a lower frequency achieves a higher performance for the primary user (with same level of transmission power). However the change in frequency is indifferent for the secondary system. This may indicate that lower frequencies are more suitable for a sharing scheme with a primary operator, which possesses higher service requirements (cellular network, TV network) than a secondary operator. On the contrary, higher frequencies may be suitable for spectrum sharing consisting on devices with similar service requirements. Figure 5 (b) evidences that outdoor mobile devices experience a drop in SINR with higher frequencies (see Figure 3 (c) to compare with the base result), while indoor mobile devices lightly improve their performance (in terms of variation), because they receive less interference from the primary system. In general, Figure 5(b) evidences that the higher the frequency, the less interference is generated between different types of users. Therefore, it may be more appropriate to establish a co-primary regime rather than a primary-secondary regime, to avoid costs of coordination and the primary user requires no protection or priority.

## V. Spectrum Value Estimations Based on User Utility Functions

This section evaluates the total value obtained from spectrum usage in different spectrum transactions scenarios in a context of flexible licensing regime, by employing the sensitivity analysis of the previous section.

Under a primary-secondary scheme, the primary system decides on the level of interference it wants to generate by adjusting its transmission power and thus deciding on the level of SINR experienced by the primary and secondary users. Additionally, if operators are able to coordinate, both primary and secondary base stations may find the transmission power, which optimize the overall value given to the spectrum.

From a user perspective, mobile services of different networks are typically different in nature and consequently they should require different QoS. To address this issue, this work employs a classification of services which consider the criticality of real-time communication to measure the value of the experienced SINR. The utility functions are defined as follows [45]:

$$u_{\text{not real-time}} = 1 - e^{k_0 \text{SINR}/SINR_{max}} \quad , \tag{1}$$

where $k_0$ determines the shape of the curve and $SINR_{max}$ is the maximum value of SINR.

$$u_{\text{real-time}} = 1 - e^{-k_1 SINR^2/(k_2+SINR)} \quad , \tag{2}$$

where $k_1$ and $k_2$ are constants determining the shape of the curve.

$$u_{\text{strict real-time}} = \begin{cases} 1, \ if \ \text{SINR} \geq SINR_{threshold} \\ 0, \ if \ SINR < SINR_{threshold} \end{cases} , \tag{3}$$

where $SINR_{threshold}$ is the value describing the minimum required SINR for that service.

This referred work [45] developed a categorization of utility functions given the criticality for multimedia service in terms of throughput. The shape of these functions (e.g., concave versus convex range) is the key aspect describing the behavior of the system as a whole, and similar utility functions have been developed by other authors (e.g., [46]). In this analysis, the same categorization is applied for the signal quality (SINR), assuming that in average the level of SINR is proportional to the perceived QoS. Thus, the utility function describes the value given by the user for accessing the network with a certain QoS. For instance, broadcasting services typically require a minimum of SINR ratio; bellow this critical point the signal cannot be received. Therefore TV services are strict real-time together with some other highly interactive data services requiring strict real-time interaction. On the contrary, many data services, such as messaging, are not real-time critical and require a lower level of SINR. Real-time services, such as those based on multimedia, require a higher level of SINR. $SINR_{max}$ is assumed to be 30 dB, based on the simulation results (maximum achieved value at Figure 2 (a)). For the strict real-time case, the threshold value for SINR ($SINR_{threshold}$) is 10 dB for scenario 1 (which approximately corresponds to a throughput of 35 Mbps based on [47]) and 20 dB for scenario 2 (TV requirement). The constants $k_0$, $k_1$ and $k_2$ define the shape of the utility function curves. Herein, these constant are set as 8, 0.75 and 100 respectively and the resulting graphical representation is shown in Figure 6.

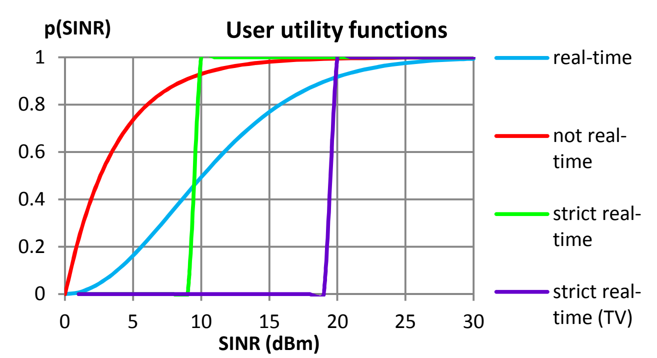



Figure 6: user utility functions for accessing spectrum for different types of usage: not real-time, real-time and strict real-time (with threshold values of 10 and 20 dB)

To estimate the value of the spectrum, the resulting formula should calculate the total benefits of all users by summing their utility functions, given a scenario of spectrum transaction and caused interference. The utility function will be determined by the type of service a user is accessing. Note that the price charged from the user should be less or equal than the utility function.

The total benefits can be expressed as:

$$TB = B^p + B^s - C^{sh}, \tag{4}$$

where TB is the total benefits, $B^p$ is the benefits of primary users, $B^s$ is the benefits of the secondary user, and $C^{sh}$ is the cost of sharing.

To assess the total benefits (TB), the formula assumes that price p charged to the user equals its utility function, and therefore can be formulated as:

$$TB = p_{max} \sum_{i=0}^{N} u(SINR_i) + p_{max} \sum_{i=0}^{M} u(SINR_i) - C^{sh}$$
$$= p_{max}\, N\, u(SINR_{av}) + p_{max}\, M\, u(SINR_{av}) - C^{sh}, \qquad (5)$$

where N is the number of primary users, M is the number of secondary users, $SINR_{av}$ is the average perceived SINR and $p_{max}$ is the price the user is willing to pay when u(SINR) = 1.

Note that by assuming that price equals the user utility function, the formula represents the total social benefit rather than the sum of operator revenues, since it includes the sum of utility functions of all users. As stated, this model assumes that primary and secondary utility functions are different in nature, depending on the type of service.

The costs of sharing are defined as the incremental energy costs the involved operators incur when adjusting its transmission power to meet their required QoS. These energy costs are obtained by applying the formula [48]:

$$P_{in} = N_{trx}\left(P_o + \Delta_p\, P_{out}\right) r^2,\ 0 < P_{out} \le P_{max}, \qquad (6)$$

where $N_{trx} = 6$, $P_o = 130$ W, $\Delta_p = 3$ [9]

The final expression for total benefits is obtained by replacing the utility functions (1), (2) and (3), and costs (6) equation into the total benefits equation (5). In general, the optimal benefits conditions are achieved by setting the derivative of the equation to zero (δP/δ(SINR) = 0). Nonetheless, this paper focuses on analyzing the resulting benefits for different scenarios rather than on formulating a final expression.

Figure 7 illustrates the benefit analysis for the first scenario, in which primary are cellular users and secondary are D2D users. A probable scenario for such a combination is that primaries are real-time users while secondary users are not real-time. The results also consider other combinations of utility functions, to illustrate how the type of utility function impacts on the results. Total benefits are represented by a red line; primary and secondary benefits ($B^p$, $B^s$) and cost of sharing ($C^{sh}$) are represented by green, blue and violet lines respectively. These results indicate that the optimal transmission power varies depending on the utility function of the users. Results are calculated in USD, assuming a 20 USD monthly ARPU for a customer reaching u(SINR) = 1.

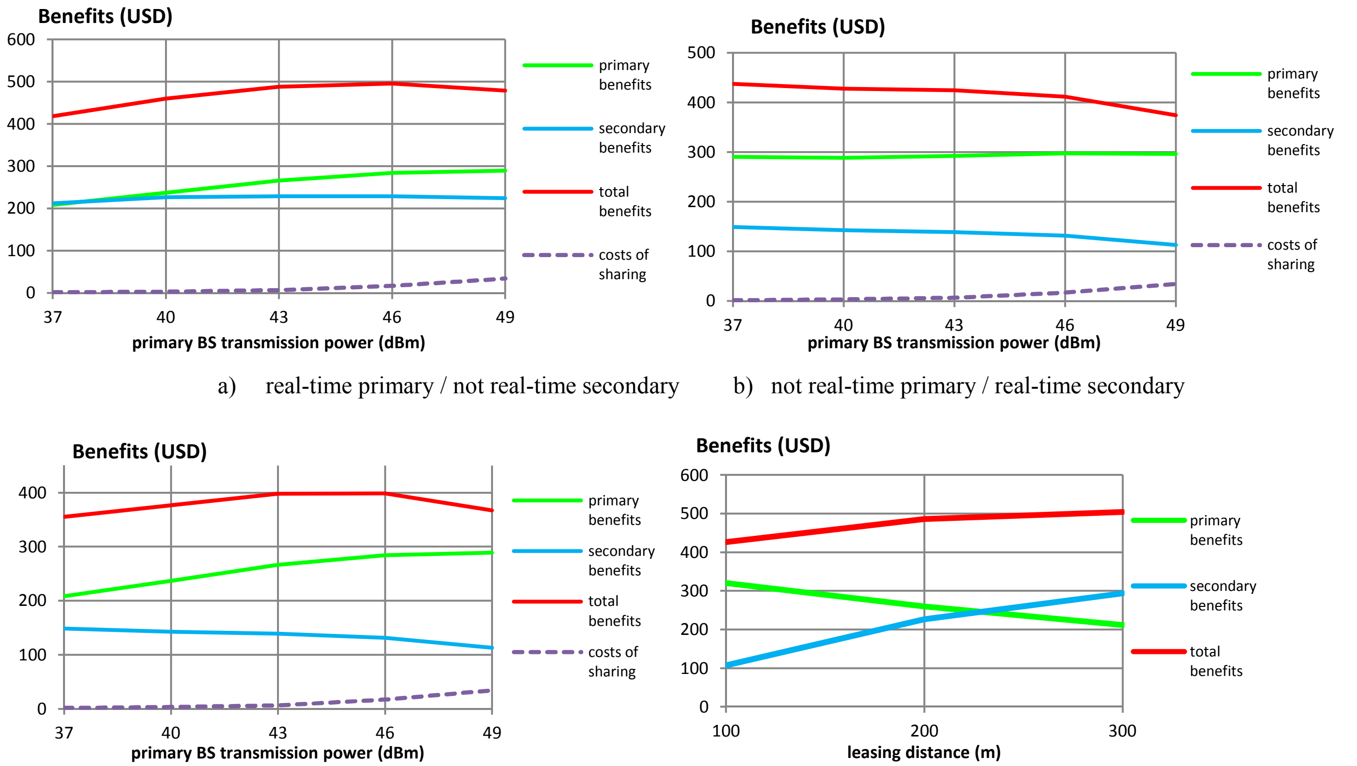
When primary and secondary users present the same utility function (Figure 7 (c)), the optimal transmission power approaches an equilibrium value, which should provide every user the same SINR level, under equal number of primary and secondary users. In this case, this value equals 43dBm, which favors the primary users, since they are more than secondary users. If the primary user requires a real-time service and the secondary user a not real-time service, the optimal transmission power would be higher than 43dBm (46 dBm in Figure 7 (a)). Consequently, if the secondary users require a real-time service and the primary users a not real-time service, the optimal transmission power would be lower than 43dBm (37 dBm in Figure 7 (b)). Finally, Figure 7 (d) depicts the benefits resulting from the sensitivity analysis of leasing distance, assuming a strict real-time requirement for primary users (being $SINR_{threshold}$ 10dB) and a not real-time requirement for secondary users. This result evidences that the obtained benefits increase by allowing additional interference to the primaries through a larger secondary leasing distance, even for the case, in which primaries are strict real-time users. In this case, primary users may be willing to receive higher interference in exchange for lower prices, while secondary may pay more for transmitting with higher mobility conditions.

Figure 8 illustrate the benefit estimations for the second (a), third (b) and fourth (c) (d) scenarios. In the second scenario (Figure 8 (a)), primary receivers (TV roof antennas) present a strict real-time utility function, being their threshold value ($SINR_{threshold}$) 20 dBm. Figure 8 (a) assumes the secondary utility function as being real-time; however, a not real-time utility function for secondary users changes very little the results in this case. Cost of sharing is calculated by using formula (6), as stated before. The second scenario evidences that the gains associated with spectrum transactions are smaller when the primary user requires strict real-time access. In this case, the optimum benefits are attained at relatively low level of primary and secondary transmission powers. In any case, spectrum transactions generate additional benefits for this scenario as well. Figure 8 (b) illustrates that maximum level of benefits are naturally attained when the number of indoor users is maximized (see Figure 3 (d)), while the outdoor transmission power has very little effect on the total benefits. Figure 8 (b) assumes that both primary and secondary users possess the same utility function (even both real-time or both not real-time), since they both are cellular users. Also in this case, the type of utility function changes very little the benefit results. The results of scenario 3 contrast with those of scenario 2. For instance, by observing Figures 8 and 3, one can deduct that the benefits of scenario 2 are driven by the quality of primary access, while the benefits of scenario 3 are driven by the number of secondary users.

Finally, the fourth scenario illustrate that the total benefits depends very little on the transmission power Figure 8 (c), given a certain number of fixed users at both buildings. They rather depend on the internal coordination of local networks. While coordinated local networks, such as pico-cellular, are more expensive to deploy than uncoordinated networks, the benefits are much higher in this scenario, since these calculation do not include capital expenditures. From a regulatory perspective, the amount of coordination each network possess is a private decision of local operators, given the density of access points at each indoor area. In any case, this private decision should optimize the attained benefits minus the capital costs of coordination deployment. Also in this scenario, the optimal interference is above zero and thus the optimal coordination should be >0% and <100%, depending on the density of users.

The results of the third and fourth scenarios especially differs from the ones from the first and second scenarios; since the interference caused from one operator to another is considerably low, and thus the benefits of measuring and trading such interference are meaningless. This is especially true for the fourth scenario. In this case, a co-primary regime without interference trading is the most suitable scheme due to its simplicity. Such local licensing provides the incentives for each spectrum holder to make the optimal decision on how much coordination they need to acquire.

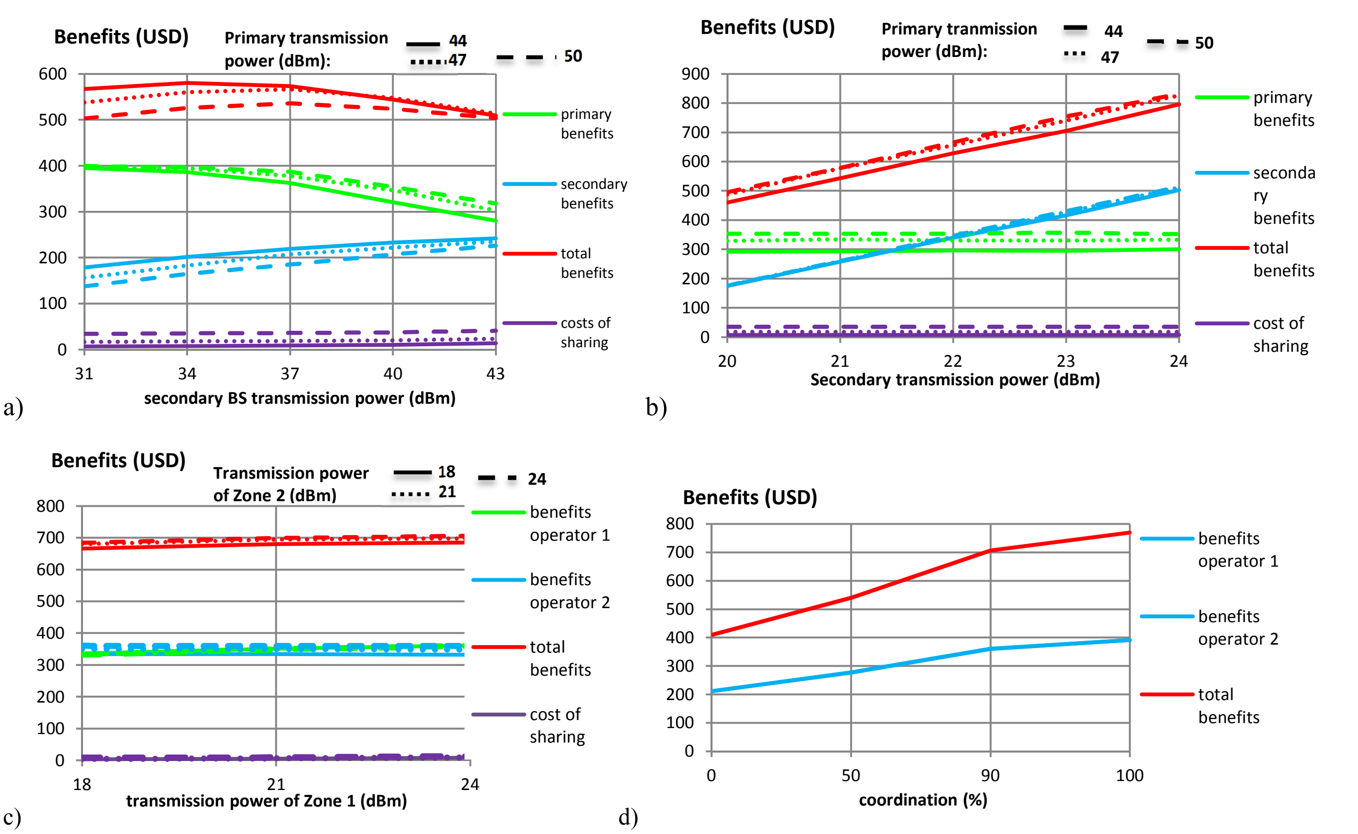
[9] $N_{trx}$ denotes the number of transmitters in a cell; Po is the linear model parameter to represent power consumption at the zero RF output power; and $\Delta_p$ is the slope of the load dependent power consumption.




a) real-time primary / not real-time secondary  b) not real-time primary / real-time secondary

c) real-time primary and secondary  d) strict real-time primary / not real-time secondary

Figure 7: Total benefits obtained from accessing the spectrum. Sensitivity analysis of primary transmission power with constant leasing distance ((a), (b) and (c)) and of leasing distance (d) with constant primary transmission power.




a) b) c) d)

Figure 8: Total benefits for accessing the spectrum. Sensitivity analysis of primary and secondary transmission power for (a) second scenario, (b) third scenario and (c) fourth scenario. (d) Total benefits for the fourth scenario against internal coordination.

## VI. Conclusions

This paper has assessed the benefits of a flexible spectrum regime allowing transactions which include interference as a tradable characteristic of the spectrum. The simulated transactions have reflected the flexibility provided by a spectrum regime which permits several operators to access the same frequency band. Results have shown that the optimal level of interference is usually above zero; therefore, spectrum trading and licensing should involve a trade-off decision regarding the amount of interference a spectrum holder is able to receive and generate. In this context, a spectrum transaction should effectively consider the measuring and pricing of the interference together with assessed user utility functions. Thus, interference can be dynamically adapted in time to continuously maximize the value of the spectrum.

A flexible spectrum regime should provide operators with an economic incentive to endure and accept a certain level of interference. An optimal spectrum transaction should in this case reflect the utility functions of all involved users. In those scenarios with a primary-secondary structure, the primary spectrum holder makes the decision on the optimal level of interference, and therefore revenues coming from secondary users should be transferred as additional profits to the primary operator. Alternatively, in a co-primary scenario, if the spectrum is managed by a third party who provides access to operators, the license or access fee should directly reflect the user utility function, which requires the spectrum access provider to balance the transmission powers of all those involved.

In general, with a given spectrum band, an increase in demand will result in additional gains in a scheme which allows voluntary transactions, as compared with a scheme which restricts transactions or minimizes interference (e.g., exclusive licensing). Additionally, an increase in interference coming from the secondary or co-primary user, may result in additional profits for the spectrum holder until an optimal point is reached, even though it generates a drop in their experienced SINR. However, if users experience a strict real-time utility function, the obtained gains are reduced.

This study has suggested that a flexible spectrum regime should consider the user utility function and the frequency band as the main factors which determine the benefits of spectrum transactions. In practice, the user utility function—based on real traffic demands—may be volatile and difficult to estimate. Nevertheless, an approximation at user group level may achieve a good result, especially in a context in which services are different in nature. This analysis has indicated that a spectrum trading mechanism, which reveals the user valuations, is the most beneficial. Moreover, fee compensation by administrative means has the disadvantage of being far more static for realizing the value of the spectrum. For instance, a brokerage mechanism managed by a third party, which might be the spectrum holder or might not, can enable operators to reveal their users valuations and react by adapting their transmission powers dynamically.

Finally, this study has evidenced the existing differences between use cases and, in particular, the requirements for trading different frequencies. While lower frequencies are most appropriate for wide area operators and thus they require stricter rules to avoid harmful interference for the primary operator, higher frequencies are most appropriate for local operators, which usually transmit over a shorter range. Therefore, lower frequencies require a primary-secondary type of scheme, while higher frequencies are suitable for a co-primary sharing scenario. Following this logic, exclusive licensing may fit better with very low frequencies and a commons regime may fit better with very high frequencies, as depicted in Figure 9. In addition, the number of spectrum owners or licensees per band can increase with frequency. This study has claimed that the majority of the frequencies located in the middle range can be shared in a primary-secondary scheme or co-primary scheme, based on a flexible spectrum licensing such as pluralistic licensing. By trading interference with the license, the value of such spectrum is optimized. Further, under the absence of interference, for the higher frequencies, an unlicensed regime may be the most appropriate. Under an excess of (harmful) interference, for the lowest frequencies, exclusive licensing may be the most appropriate.

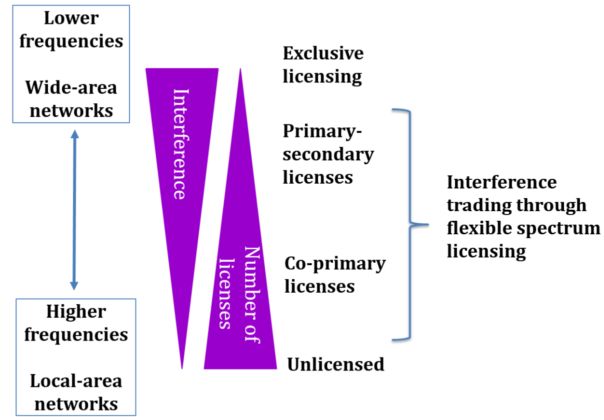


Figure 9: General framework for license classification by type of frequency

## Acknowledgment

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# Publication 3

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# Spectrum and License Flexibility for 5G Networks

*Adrian Kliks, Oliver Holland, Arturo Basaure, and Marja Matinmikko*

## Abstract

Spectrum sharing is a key solution facilitating availability of the necessary spectrum for 5G wireless networks. This article addresses the problem of flexible spectrum sharing by the application of adaptive licensing among interested stakeholders. In particular, it acts as a proponent of "pluralistic licensing" and verifies it in three simulation scenarios that are of strong interest from the perspective of 5G networks. The concluding analysis offers discussion of the potential benefits offered to spectrum holders and other interested players through the application of the pluralistic licensing concept.

## Introduction

Forecasts for global mobile data traffic anticipate continued strong growth [1]. While substantial technological developments are expected to improve system capabilities of fifth generation (5G) networks, additional spectrum flexibility is needed to accommodate the predicted traffic growth of mobile/wireless communications and other services.

Spectrum regulation has traditionally relied on the two extremes of exclusive use and licence-exempt access. The primary means of spectrum management thus far has been through the exclusive or "command and control" approach, which can eliminate harmful interference to licensed users to ensure reliable communications. Such approaches have proven to work very well in supporting a range of services, including ubiquitous voice connectivity in public land mobile, early generations of data services (e.g., 2G/3G/3.5G), high-quality broadcast services, and guaranteed access for critical services (military, air traffic control, emergency services, etc.).

At the other extreme, licence-exempt operation using industrial, scientific, and medical (ISM) bands has led to a rapid, and largely unforeseen, surge in wireless devices and systems including Wi-Fi, Bluetooth, and others. The ISM bands have indeed proven to be a hotbed of innovation as well as an entry point for "free" wireless communications. However, the resulting rich eco-system is built on just one caveat, that is, low transmit power on the premise of limited propagation, which hampers the scope of wireless services. For cellular networks, ISM bands have not been attractive due to the associated uncontrolled interference environment resulting in unpredictable quality of service (QoS).

In this article, we discuss the idea of flexible licensing, which will provide new spectrum opportunities for 5G systems and deliver new opportunities for spectrum holders to make additional profit gains by reusing portions of locally unused spectrum.This article discusses the various concepts of spectrum sharing presented from the perspective of their potential application in 5G networks. We then continue with the discussion of the benefits of the adoption of the "pluralistic licensing" (PL) concept contrasted with other spectrum sharing approaches, such as the two already mentioned extremes, and the novel concept of licensed shared access [2, 3]. The three conducted simulations are described showing the rational profits that can be achieved by spectrum holders. Finally, concluding remarks are provided.

## Spectrum Sharing Strategies for 5G Networks

The density and variety of wireless services and users have dramatically increased over the past decade. The two extreme regulatory approaches of exclusive use and license-exempt access can no longer offer appropriate characteristics to satisfy future demand for wireless services, which need to balance interference tolerance, service prioritization, cost, and market suitability. 5G networks require a significant amount of new spectrum to respond to growing traffic demand, and spectrum sharing through flexible spectrum licensing is a key means to accomplish this. As we argue in this article, flexible licensing can both ensure the necessary QoS for primary and secondary spectrum users, and allow the necessary degree of sharing to alleviate future 5G capacity demand, reflected in ways such as an increase in the realized monetary value of the spectrum.

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## Light Licensing and Licensed Shared Access

Flexible spectrum licensing could better respond to future needs by allowing spectrum that is not used by one network in certain locations to be opportunistically used to the benefit of other 5G operators (e.g., for a fee). Two initial "compromise" regulatory solutions that are at least partially moving toward such flexibility are light licensing [4] and licenced shared access (LSA) [5]. The light licensing concept can ease the burden of coordination, registration, licensing, and interference consideration when making new frequency assignments, or in coordinating sharing between primary and secondary users. It usually implies setting license fees that just cover administrative costs, and is used in cases where there is a need to coordinate with an incumbent user or in a private commons approach where individuals and licensed users set the conditions for license-exempt access. The light licensing model tends to be used mainly for systems with no or limited interference potential, which could be further authorized by a simple automated check-in to an online light licensing tool to manage the interference spatially. Therefore, this approach is not at all suitable for scalable and longer-range high-transmission-power services.

The LSA approach is a relatively new industry-driven concept where additional licensed users are authorized to access incumbent (primary) users' spare spectrum within their licensed bands but under tight controls to prevent any disruption. It was originally intended to support business cases for the mobile broadband, where it is both economically and technically feasible. It is notable that the EC's Radio Spectrum Policy Group (RSPG) has acknowledged LSA in [6], asserting that indeed an LSA licensee might be granted the right to utilize under-used spectrum without interfering with the incumbent user. The objective of LSA is to grant additional spectrum rights of use in specific bands on a shared basis, allowing predictable QoS for all rights holders [5].

Through the aforementioned efforts and other initiatives, regulators across the globe have started to promote spectrum sharing [7, 8]. They have acknowledged that any such expanded sharing would require new regulatory paradigms, such as spectrum sharing contracts and shared spectrum access rights, to ensure the legal certainty and rules, as well as the obligations of the interacting spectrum users.

## Pluralistic Licensing: The Core Concept

The PL concept was proposed by us in [9] as a novel approach, in line with a wide range of spectrum sharing contracts and shared spectrum access rights as discussed above. PL is an innovative means to improve spectrum licensing, which is fair to both primary and secondary users and takes into account the requirements of both parties. The concept is described as "the award of licenses under the assumption that opportunistic secondary spectrum access will be allowed, and that interference may be caused to the primary with parameters and rules that are known to the primary at the point of obtaining the license" [9]. The general assumption is that the primary will choose from a range of offered PLs, each with a different fee structure, and each specifying alternative opportunistic access rules that can be mapped to associated interference characteristics. The locus of control, therefore, remains firmly with the primary, whereby the primary might trade off the form and degree of opportunistic access for a reduced licensing fee or another incentive.

Under the PL concept, primary users who obtain the license, which might be on a very short-term or longer-term basis or even geographical (e.g., per-transmitter), are allowed to access the spectrum at will. A coordination mechanism among primary assignments would nevertheless be needed in cases where there are multiple primaries coexisting. Secondary users must use a "cognitive" mechanism to access the band, whereby the detail of the cognitive mechanism (the use and configuration of a spectrum sensing approach and/or a geolocation database, etc.), as well as its radio characteristics, depends on the context within which the band is chosen to operate. This context might include the expected types of primary services(s) in the band (perhaps also expected secondary services(s)), an assessment of an appropriate "burden" on the primaries in terms of acceptance of a slightly higher probability or net amount of interference while still achieving adequate performance, the degree to which the primary and secondary should negotiate, or even in some foreseeable cases the degree to which the primary should be expected to take proactive measures such as the transmission of beacons. Of course, such a context defines the extent to which the secondary must avoid interfering with the primary, and hence the associated rules on the secondary. Crucially, in this sense, PL can be the practical form of implementing the *spectrum sharing contracts* already envisaged by regulators [8].

## Benefits Achieved through Flexible Licensing

There are numerous benefits of the concept of PL, which are directly tangible to 5G networks and other players in the market. First, particularly in green-field scenarios, there is no need for the secondary systems to cope with the inefficiencies of legacy primary systems, as can be an issue in other spectrum sharing realms such as TV white space. In obtaining the license, the "primary" 5G operators will implicitly accept (and even decide); hence, the rules of the band will be designed and manufactured with better technical capabilities to cope with those rules—in return for an incentive such as a reduced license fee. For instance, the operators holding such licenses might deploy systems that can better reject adjacent channel interference, or enhance their adaptive rate and error correction mechanisms when the opportunistic secondary spectrum access might imply a higher probability of an interference limit being violated or a higher variance in the experienced interference to the other 5G network. Furthermore, such a concept might be applied to other primary services, with the 5G network effectively being the opportunistic spectrum user of that service's spectrum.

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A further, more general benefit of the concept is that it satisfies the need for spectrum sharing between more established users and incumbents, generally giving the 5G network guaranteed spectrum access with a given QoS, while still allowing free access when/where the spectrum is not used by that network.

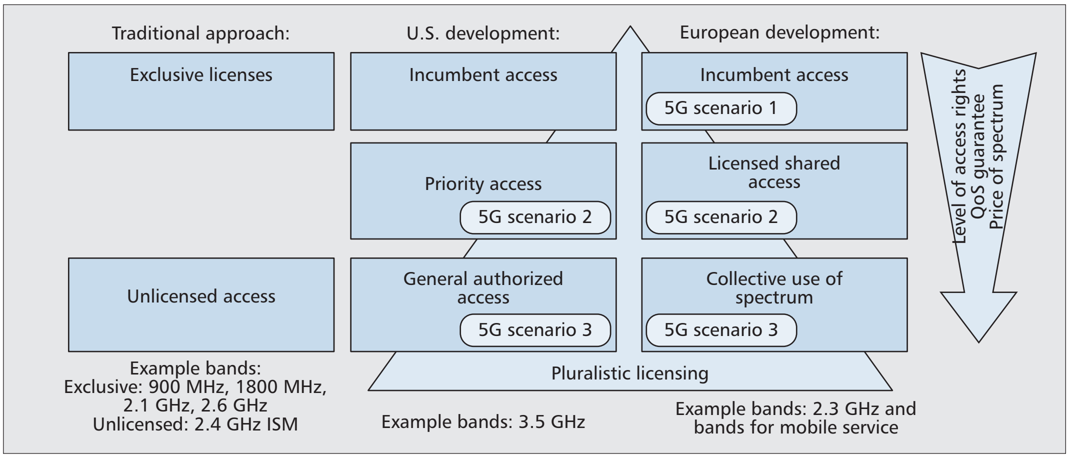


**Figure 1.** Pluralistic licensing in the context of spectrum sharing approaches for 5G.

A further, more general, benefit of the concept is that it satisfies the need for spectrum sharing between more established users and incumbents, generally giving the 5G network guaranteed spectrum access with a given QoS, while still allowing free access when/where the spectrum is not used by that network. This concept can be used to strike a good balance between operators needing to pay more for quality in some locations, and perhaps less in others in return for allowing forms of opportunistic access. Indeed, it is even shown later in this article that this context might even be used to very significantly *increase* profit for the operator.

An additional benefit is that the concept very likely implies significantly improved performance, such as in terms of spectrum usage efficiency. This is very compelling for the 5G operator in scenarios in which the operator might have an agreement with particular systems, and be able to extract revenue for the opportunistic access and increased efficiency of its spectrum usage. A further benefit of the concept is high scalability to progressive deployment in more spectrum bands. This realization is very much in line with 5G networks, which are increasingly likely to be designed and built on large chunks of highly distributed spectrum.

## Application to Opportunistic Access and Spectrum Sharing in 5G Networks

PL is seen as applicable to almost any spectrum licensing scenario, and indeed is viewed by the authors as one possible panacea to the problem of licensing while allowing spectrum sharing in an agreeable and fair way for all concerned. For application to 5G networks, the primary (network operator) will generally have a good understanding of the effects each possible form of secondary access is likely to have. This will, of course, depend on the type of secondary system and associated characteristics such as mobility and transmission patterns of the radio interface (MAC/PHY, bandwidth, and frequency), as well as possibly higher-layer characteristics. It will intrinsically also be linked to the configuration of the network that the primary is deploying and its associated requirements. The latter can be controlled by the primary network operator, but the former must be predicted and mitigated through the choice of PL and associated characteristics.

Aside from such technical considerations, economic considerations can also be expanded upon. The traditional exclusive licenses have strengthened the dominating role of the big operators, as only they can afford to buy licenses from costly auctions. The recent technology development in cellular networks is prepared for spectrum sharing including many supporting features, such as self-organizing networks (SONs), carrier aggregation, and hierarchical cell layers, which can already share spectrum. By allowing local temporary licenses with agreed conditions through the PL approach, operators may adjust their spectrum assets more dynamically to respond to actual needs, and new entrants might get access to spectrum resources, facilitating the more optimal realization of resources right up to the level of dynamic aggregation of tailored spectrum opportunities matching the QoS demands of higher-layer traffic.

The evolution of the spectrum sharing regulatory framework is focusing on three general levels of access rights: primary access, secondary access, and collective use [7, 8]. While in the past cellular networks were solely deployed on exclusively licensed bands, 5G networks are expected to operate on different types of spectrum bands to meet the growing demand. Following the generic spectrum sharing framework, the PL approach could be applied to 5G networks in several scenarios, as depicted in Fig. 1, allowing the operators to acquire different types of spectrum assets according to their preferences and needs.

In the first scenario, the 5G networks could obtain primary access rights to a given spectrum band similar to the traditional exclusive licensing, but it could also admit secondary access/licensed shared access and general authorized access/collective spectrum use rights to other users to access its band with predetermined conditions and rules, and benefit from it. In fact, the regulator could endorse this sharing approach by collecting lower spectrum fees from 5G network operators that allow access to their bands. Moreover, by using the PL concept to allow secondary access/licensed shared access, a 5G operator could collect fees from secondary users. The first scenario could be applicable to the potential new

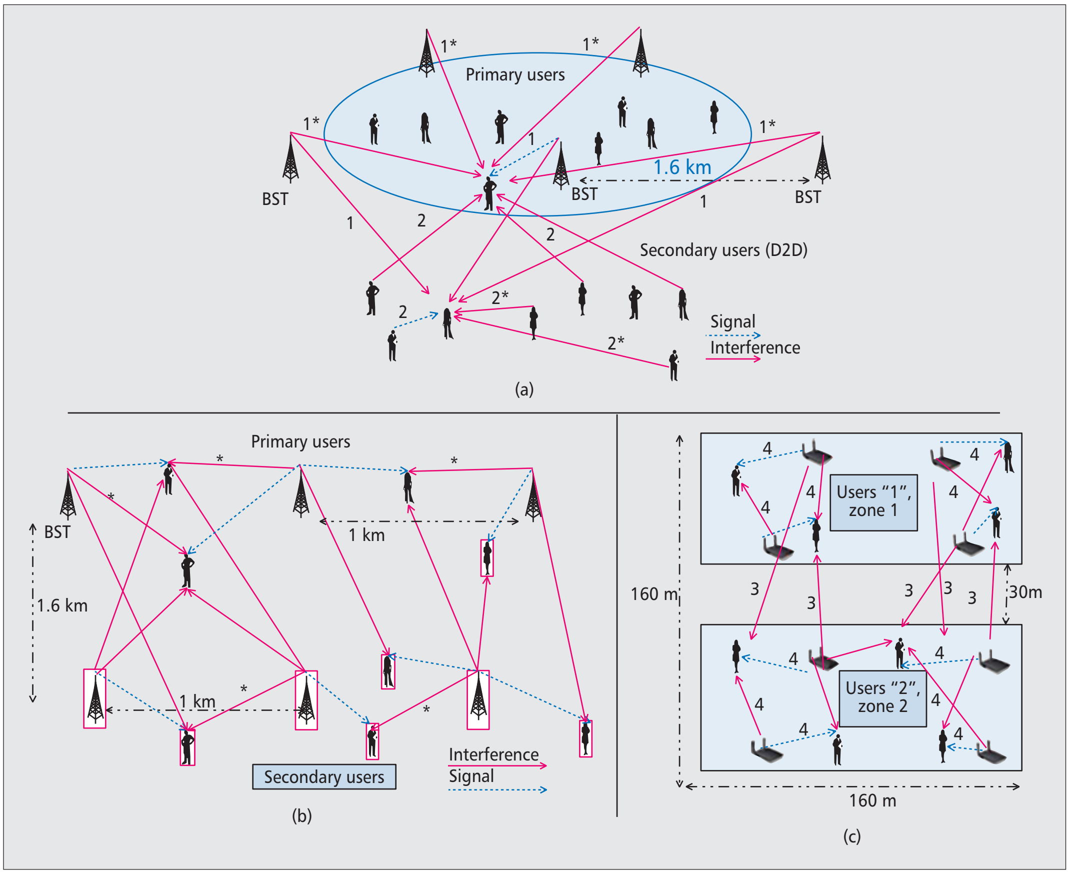


**Figure 2.** Three considered scenarios: a) FDD downlink transmission with D2D communication; the numbers above the arrows define the type of path loss models used: 1. COST Hata model, 2. ITU-R P.1411 end; b) cross-operator spectrum sharing; c) indoor-indoor co-primary sharing with the following path loss model: 3. In-building propagation model of [11, Eq. 5] with wall penetration loss: 4. In building propagation model path loss model.

*By allowing local temporary licenses with agreed conditions through the PL approach, operators might adjust their spectrum assets more dynamically to respond to the actual needs, and new entrants might get access to spectrum resources, facilitating the more-optimal realization of resources.*

spectrum bands with primary allocation to mobile that would be cleared from other use.

In the second scenario, the 5G network would get secondary access/licensed shared access rights to a given spectrum band using the PL approach, which would determine the rules and conditions that guarantee the primary users remain free from harmful interference but at the same time offer sufficient QoS for the 5G network. In this scenario, the 5G networks could gain access to spectrum resources with reduced costs compared to the traditional exclusive licenses by acquiring a local and temporary license depending on its needs. It could gain access to new spectrum bands that with traditional regulatory approach are not available as they are primarily allocated to other use but whose actual occupancy may remain low. Offering PLs with fair conditions to both primary access and secondary/licensed shared access users would open up a considerable amount of new spectrum for 5G networks with QoS conditions resembling exclusive licensing but with lower costs.

In the third scenario, the next generation network could exploit general authorized access/collective spectrum use rights to access spectrum bands that are allowed to be used by multiple users simultaneously according to a set of predefined rules with little or no cost. While these bands would not necessarily offer high QoS over a large geographical area, they could be used for short-range mobile data offloading as is currently done using the unlicensed access mode with Wi-Fi.

## Simulation Scenarios for Spectrum Sharing Incentivization

In order to illustrate the benefits of the application of spectrum sharing strategies based on the PL approach, a set of simulation experiments has been carried out with the use of agent-based modeling. Three scenarios have been identified that are of high interest from the perspective of the spectrum holder in the context of 5G spectrum sharing. In the first scenario, short-range transmissions between two devices (e.g., the device to device, D2D, case) are considered, as realized through PL in the same frequency band as the nearby cellular network using a database or spectrum sensing.

In the second scenario, the coexistence of two networks in close geographical proximity is analyzed assuming one of the operators would like to share the spectrum assigned originally to another operator (primary user), applying the concept of flexible PL.

The final simulation scenario provides an

| Assumptions | | | |
|---|---|---|---|
| Scenario (primary/secondary)<br>Parameters | Scenario 1 | Scenario 2 | Scenario 3 |
| Cellular BS spacing | 1.6 km | 3.2 km | NA |
| Secondary leasing distance | 100, 200, and 300 m | 100 m | NA |
| Separation between coverage areas | 700 m | 400 m | 30 m |
| BS transmission center frequency | 2.6 GHz | 2.6 GHz | 60 GHz |
| Primary BS transmission power | From 40 to 52 dBm | From 43 to 49 dBm | From 18 to 24 dBm |
| Secondary BS transmission power | NA | from 43 to 49 dBm | from 18 to 24 dBm |
| Primary terminals transmission power | 21 dBm | 21 dBm | 21 dBm |
| Secondary terminals transmission power | 20 dBm | 21 dBm | 21 dBm |
| Antenna gain | BST (10 dB) | BST (10 dB) | 2.1 dB |
| Path loss model from base station to terminal | Cost 231 Hata model | Cost 231 Hata model | Anderson and Rappaport [11, Eq. 5] |
| Path loss model from terminal to terminal | ITU-R P.1411 end-to-end model | NA | NA |
| Noise power | –105 dBm or 0.032 pW (in 8 MHz channel) | –105 dBm or 0.032 pW | –105 dBm or 0.032 pW |
| Shadowing standard deviation | 6 | 6 | 6 |
| BS effective height, primary case | 30 m | 30 m | 1.5 m |
| BS effective height, secondary case | NA | 30 m | 1.5 m |
| Primary node effective height | 1.5 m | 1.5 m | 1.5 m |
| Secondary node effective height | NA | 1.5 m | 1.5 m |

**Table 1.** System setup for the considered simulation scenarios.

indoor-indoor analysis, where two sets of users located inside nearby buildings operate in the same frequency ranges, causing potential interference. All these scenarios are presented in graphic form in Fig. 2, whereas their corresponding configuration details are summarized in Table 1.

## Scenario 1: PL Enhancing D2D Communications

In the first case, we consider the coexistence of a five-cell-wide section of a cellular network (treated as the primary) with direct D2D transmissions realized in the relatively small region outside the coverage area of the primary (please also see [10]). Two approaches for granting spectrum access for secondary users are considered: first, where secondary users query dedicated databases asking for transmit permission, and second, where spectrum sensing is applied. In order to minimize the number of queries sent by the secondary (D2D) devices, each granted user is obliged to send new requests to the database only when it leaves the so-called leasing region. It is assumed that the overall environmental and system parameters will not differ strongly within the small region; thus, the replies to the queries sent from any location inside that region will be almost the same. Referring to Table 1, three radii of leasing region have been considered: 100 m, 200 m, and 300 m. Moreover, in order to assess the performance of spectrum sensing, one additional leasing region of size 10 m was also applied.

In order to present the potential benefits of the PL, we analyze the averaged SINRs observed by the primary and secondary users as a function of transmit power and size of the leasing region. The achieved results are presented in Fig. 3, divided into four parts. In Fig. 3a the cumulative distribution function of the SINR observed by the primary users inside the coverage area against different primary user transmission powers is presented. In Fig. 3b, the average SINRs observed by the primary and secondary users are plotted as a function of primary base station transmit power for different radii of the leasing region. The increase of the leasing radius results in SINR degradation of both types of networks

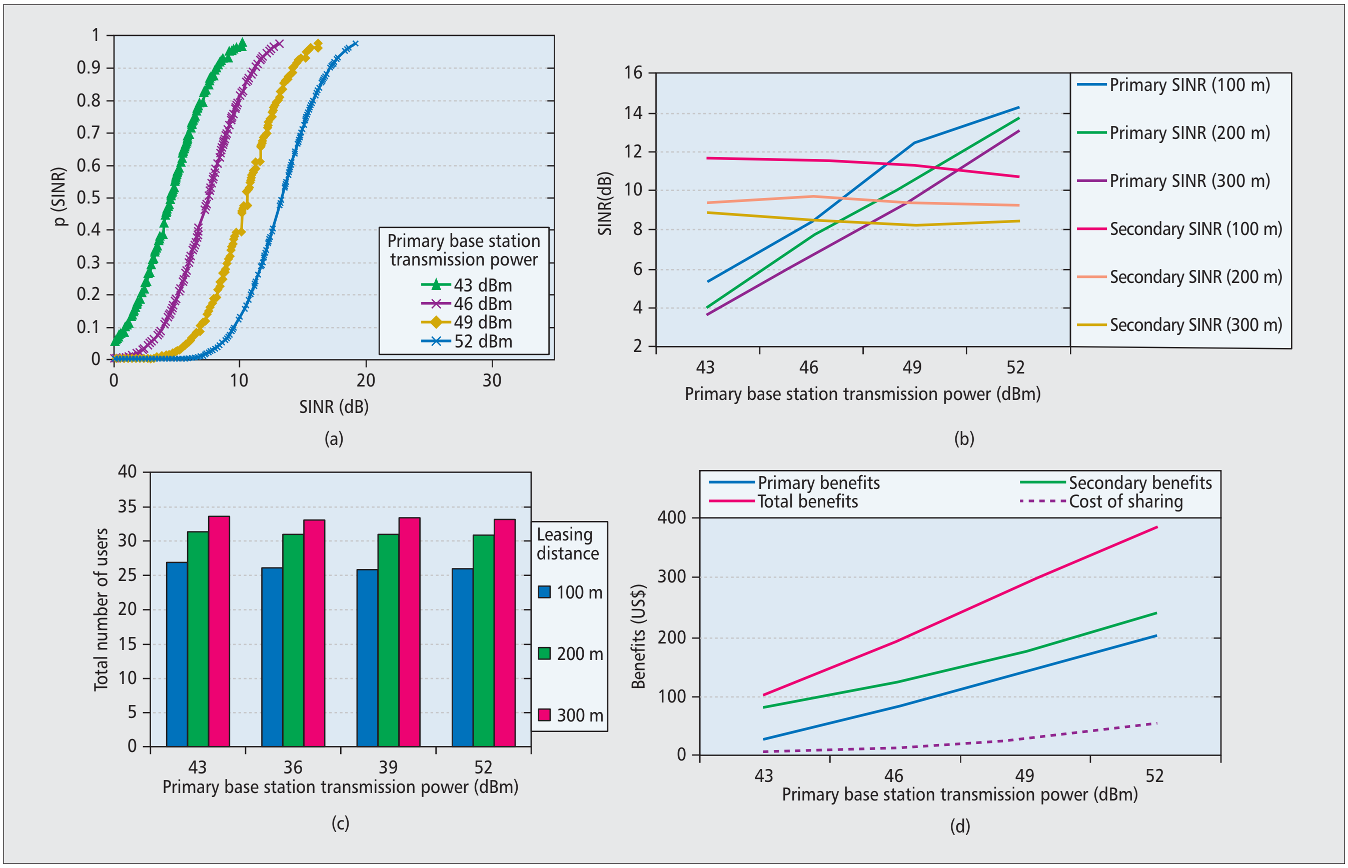


**Figure 3.** Results achieved for the first scenario: a) cumulative distribution function of the average SINR; b) averaged SINR observed by the primary and secondary users as the function of the leasing distance and transmit power; c) average number of supported users; d) financial benefits.

since the lower the frequency of sending queries by the secondary users, the higher interference generated to the network. Moreover, increasing transmission power leads to a very significant increase in SINR for the secondary and a slight degradation for the primary, meaning that the average link performance among the primary/secondary users is improved. In Fig. 3c, the average number of users that can be served is presented: more users can be served when the leasing distance is increased through the flexibility allowed by PL. Interestingly, this number does not depend on the maximum transmit power. It should be noted that the transmit power of the secondary D2D users is constant (20 dBm). In this case, the amount of interference produced by the secondary users is increased by adjusting the "leasing distance" (Fig. 3b, 3c), or the distance secondary users are able to move before they should request access from the spectrum database again. As shown in Fig. 3, if the distance is higher, the number of secondary users is increased at primary SINR expenses. Finally, Fig. 3d gives the profit achieved by the primary and secondary users, as well as the total profit taken from the spectrum, based on the same assumptions of traffic utility functions used in [10]. It is clear here that an increase in profit can be achieved for the spectrum as a whole by allowing an increase in the secondary transmission power through PL, whereby there is a minor impact on the primary's profit that can easily be compensated by the secondary with the secondary still making a good profit. Moreover, it is noted here that both the primary and secondary users challenge "real-time" utility functions, underpinning a high level of reliability for the D2D and cellular deployments sharing the spectrum.

## Scenario 2: Coexistence of Two Cellular Networks

In the second scenario, the coexistence of two separate cellular networks located in close geographical proximity is simulated, where one of the operators (secondary user) would like to share the spectrum assigned originally to another operator (primary user), applying the concept of flexible PL (Fig. 2). Based on the setup presented in the third column of Table 1, we concentrate on measurements of the observed average SINR as a function of the maximum allowed transmit power. Downlink transmission with the FDD scheme has been simulated. Based on observed results shown in Fig. 4, one can state that there is a slight performance degradation as secondary base stations increase their transmit power. Furthermore, analogous to the previous scenario, the application of the PL concept generates a significant profit increase for the spectrum while providing appropriate compensation to the primary for the minor effect it experiences due to the increased sharing.

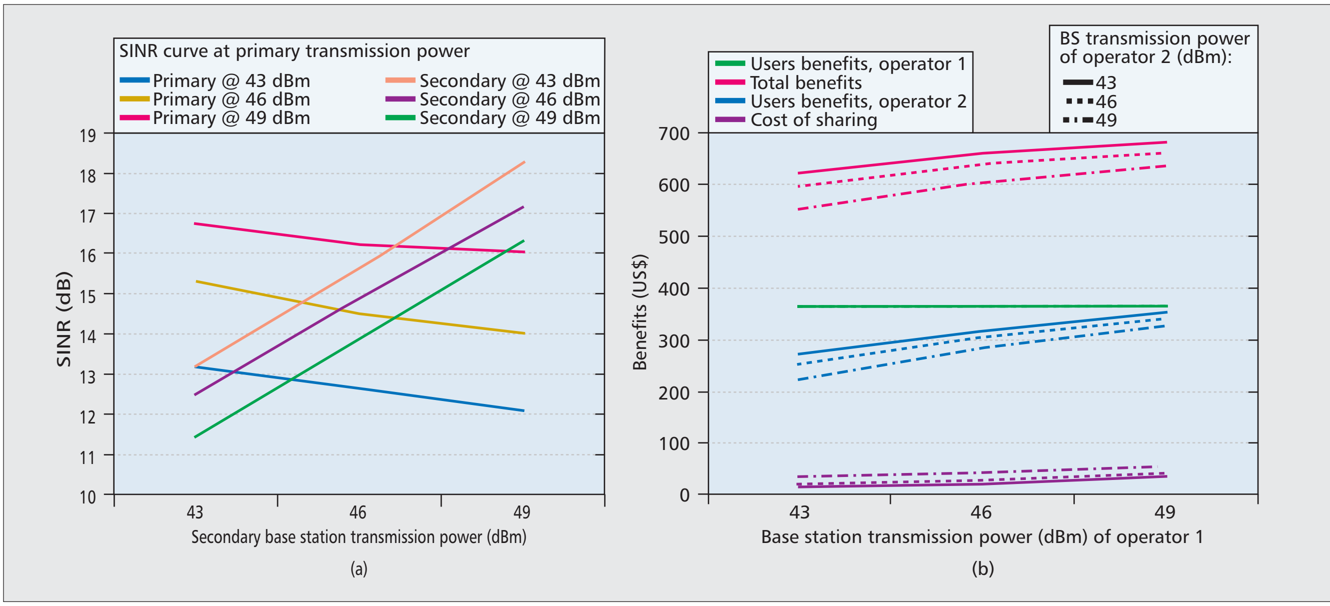


**Figure 4.** Cellular-cellular sharing scenario: a) average SINR of the primary and secondary users as the function of transmit powers of primary and secondary base stations; b) profits of the two sharing operators, individually and combined.

### Scenario 3: Indoor-Indoor Coverage Improvement

In this final scenario, two disjoint sets of users are located inside nearby buildings (Fig. 2), connected to indoor access points (APs) hosted in each of the buildings. They share the same frequency band; hence, they can cause interference to each other. Reflecting a 5G scenario, this frequency band is assumed to be at 60 GHz. These two sets of users might be seen as co-primary users, or implementing a primary-secondary scenario with one set of users in one building being the primary, and the other set in the other building the secondary. Under our results, it is best if the sets of users are seen as co-primary; however, the simulations can also be used to infer what would happen if one set of users were the primary and the other secondary.

The simulation parameters assumed for this case are summarized in the last column in Table 1. The two-strip layered model has been applied to the buildings, and a detailed path loss model has been selected in order to consider wall attenuation [11, Eq. 5]. The goal of the conducted simulations has been to verify the influence of the maximum transmission powers used in each building on the observed averaged SINR values of the sets of users, these maximum transmission powers being variable through the flexibility brought about in a PL scenario. The corresponding results are presented in Fig. 5. It is clear that the average SINR experienced among the sets of users increases significantly if the allowed maximum transmission power is increased for either or both of the sets of users.

### Rational Benefits Achieved by a Spectrum Holder

Finally, we briefly identify the benefits that can be gained by spectrum holders. Practical utilization of the PL concept allows definition of flexible pricing strategies that can be applied. Taking into account various types of traffic, it can be argued that as in one case the interference induced by the other users will potentially lead for high QoS degradation, in another scenario such interference power can easily be tolerated. Such an observation is particularly important in the context of 5G networks, where delivering various services (of different QoS levels and associated guarantees) to the user is envisaged. Thus, the primary user (e.g., network operator) can accept more interference from the other interested player (e.g., another operator, non-first-priority end users) at the price of an increased fee paid by that player. Higher interference means, in fact, a greater leasing region or higher transmit power, thus higher throughput that will be served and managed by the licensee. On the contrary, lower fees can be offered to such players that will not be allowed to transmit with maximum power.

The analysis of the results achieved in the three simulation scenarios has proven that a plethora of interesting variants for flexible spectrum sharing, and in consequence PL, can be applied. This will be attractive for both current spectrum holders and any other player interested in sharing the spectrum. Thus, the LSA approach together with the complementary PL concept can be treated as key regulatory enablers for better utilization of resources in 5G networks and spectrum availability enhancement through sharing.

## Conclusions

It can be foreseen that with the introduction of new, often technically challenging services to the end user, the need for additional spectrum will significantly increase in the very near future. This has led to the conclusion that the current static spectrum management solutions will no longer be applicable, and a new vision for 5G spectrum is required. Realization of the adaptive spectrum sharing concept will definitely pave the way for more efficient utilization of spectrum

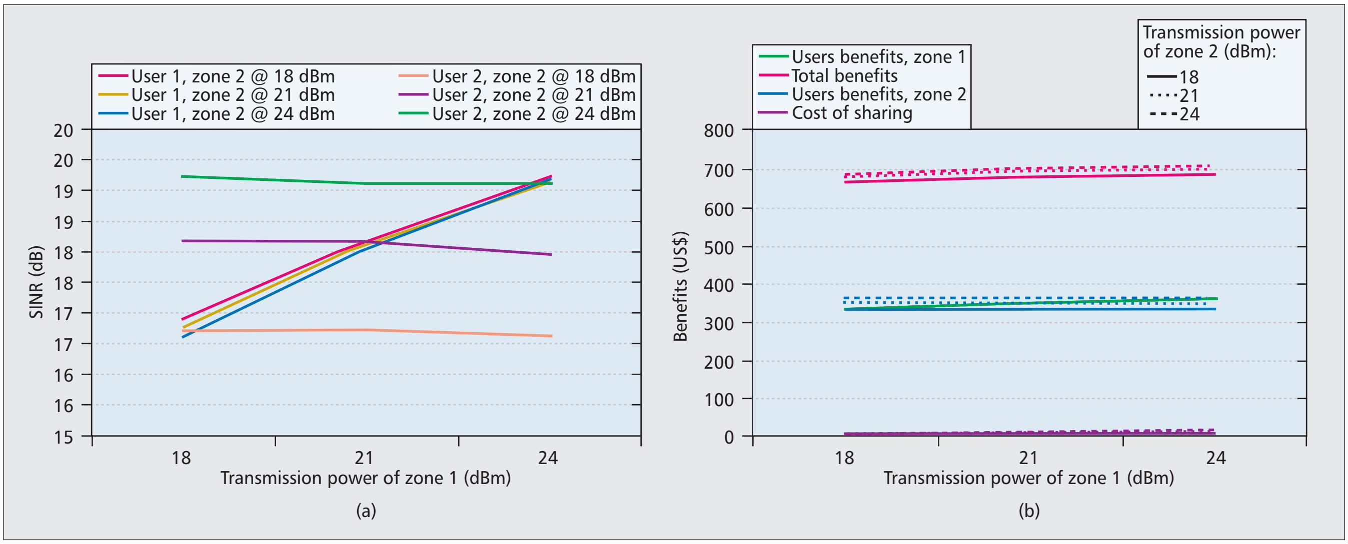


**Figure 5.** a) Achieved average SINRs for the sets of users in Scenario 3, against varied transmission power; and b) profits of the two sharing operators, individually and combined.

resources. Licensed shared access seems to be the first practically available solution, but much more can be beneficial from the application of the flexible pluralistic licensing concept, which at the same time delivers to the spectrum holder a new tool for revenue increase. However, such solutions have to be supported by the appropriate regulatory decisions made at the global level, which will open the doors for new definition of spectrum usage in the context of 5G networks.

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# Publication 4

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# Adoption of dynamic spectrum access technologies: a system dynamics approach

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**Abstract** The introduction of dynamic spectrum access (DSA) technologies in mobile markets faces technical, economic and regulatory challenges. This paper defines industry openness and spectrum centralization as the two key factors that affect the adoption of DSA technologies. The adoption process is analyzed employing a comprehensive System Dynamics model that considers the network and substitution effects. Two possible scenarios, namely operator-centric and user-centric adoption of DSA technologies are explored in the model. The analysis indicates that operator-centric DSA technologies may be adopted in most countries where spectrum is centralized, while end-user centric DSA technologies may be adopted in countries with decentralized spectrum regime and in niche emerging services. The study highlights the role of standards-based design and concludes by citing case studies that show the practicality of this analysis and associated policy prescriptions.

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**Keywords** Dynamic spectrum access · Industry openness · Spectrum centralization · System dynamics · User-centric and operator-centric adoption scenarios

## 1 Introduction

The mobile data traffic is expected to grow nearly ten-fold between 2014 and 2019, while mobile devices were expected to exceed worldwide population by the end of 2014, reaching 1.5 devices per capita by 2019 [1]. Radio spectrum is an essential scarce resource for the provisioning of mobile services. While the demand for wireless services is rapidly growing, the capacity and efficiency of networks has also been increasing, thanks to evolving technologies. Dynamic spectrum access (DSA) technology is one such case that aims to improve capacity of mobile networks by defining a set of protocols and standards allowing end-users, mobile network operators (MNOs) and other types of operators such as local area operators (LAOs)[1] to dynamically access unused or underutilized spectrum bands.

Though coined by Mitola way back in 2000 as *Cognitive Radio* [3] and despite large efforts in R&D, DSA technologies have not been successfully introduced into the mobile market, even though several standards already exist and others are under development. Several technical, economic and regulatory challenges have been identified for this slow deployment.

First, industry structure has a definitive impact on the adoption of new technologies [4–6]. The type and number of MNOs and the existing entry barriers determine the competition level in the industry and consequently the motivation

1 Operator providing wireless internet access in a local basis, such as described in [2].

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of the firms in the industry to adopt new disruptive technologies such as DSA. On the other hand, the adoption of such technologies in turn affects the industry structure, due to possible entry of new firms or incumbent firms exploiting technologies to increase market share.

Second, spectrum management is the core of DSA technologies, since they radically change the method for accessing the radio spectrum. The traditional exclusive licensing provides a MNO access to an entire spectrum band. The usage rights of the spectrum are often stringent, for both allocation and assignment. Under a flexible spectrum regime which allows spectrum sharing, DSA technologies enable end-users and operators to dynamically access different spectrum bands that are not exclusively assigned [7–11]. Realizing the need for efficient use of radio spectrum, National Regulatory Authorities (NRAs) have started to adopt flexible spectrum policies including the creation of a spectrum market and the deployment of associated mechanisms. However, changes require high coordination of all stakeholders; including end-users, mobile device manufacturers, network equipment manufacturers, MNOs, other spectrum holders, standard developing organizations (SDOs) and finally NRAs and policy makers.

Given the extant industry structure and spectrum management regime, this study considers industry openness and spectrum centralization as the two main factors impacting the adoption of DSA technologies. Rogers [12] defines adoption as the process by which an innovation is communicated through certain channels over time among the members of a social system. The author in [13] extends the adoption process to organizations, caused by an innovation which can be internally generated or purchased device, system, policy, program, process, product, or service that is new to the adopting organization. Thus, in the case of DSA technologies, the innovation can be adopted by operators and impact an internal process or can be adopted by the end-users and provide a new service or functionality.

Consequently, DSA technologies allow two possible adoption scenarios: (i) user-centric and (ii) operator-centric. In a user-centric adoption, the device adopted by the end-user decides which spectrum band to access by means of DSA technology. The mechanism for the same and consequent standard decision is made by the mobile handset manufacturer. This form of DSA represents the original concept of *Cognitive Radio* introduced by Mitola [3]. In the alternative approach, operators adopt DSA technologies to make a more efficient use of the spectrum by sharing spectrum. The DSA standard and related technology is incorporated by the network equipment manufacturer in the Radio Access Network (RAN) elements.

As per previous adoption definitions and related work, there are two effects that determine the extent of adoption of technologies. Firstly, the network effect explains the value generated to the user when adopting a new technology, considering the number of users that have already adopted such technology. Secondly, the substitution effect describes the behavior of the adopter of a new technology as a replacement of another, often an older technology.

Along with technology development, new licensing schemes [14–16] have emerged to provide more flexibility, allowing spectrum holders to share a frequency band. From a general perspective, DSA can enable three types of spectrum sharing [17]: (i) dynamic exclusive sharing, in which the incumbent operator employs the exclusively assigned spectrum with certain flexibility, including reselling rights of the whole or part of the assigned band; (ii) hierarchical access sharing, in which one user group has priority access to spectrum while the other group accesses opportunistically with secondary rights as defined by policies and (iii) open sharing, in which all users accessing the shared spectrum enjoy equal priority.[2]

This paper analyzes those DSA technologies which enable any of the three above mentioned types of sharing. Spectrum sharing is defined as two or more parties accessing a spectrum band either at different time or place, executed through an economic transaction or as a free access without monetary value. This paper aims to model the adoption of DSA technologies, addressing all the above factors (industry openness and spectrum centralization), effects (network and substitution effects) and scenarios (operator and user centric adoption scenarios).

The paper is organized as follows: Sect. 2 presents a literature review on DSA standards and the main issues affecting their adoption process; Sect. 3 describes and justify the employed method; Sect. 4 develops the adoption model by means of System Dynamics; Sect. 5 presents the analytical results; Sect. 6 illustrate the applicability of the analysis by different country cases; and finally Sect. 7 concludes.

## 2 Literature review

This study focuses on the adoption of DSA technologies which enable a dynamic access of the spectrum by the end-user device or the operator network. The following section presents an overview on the main issues impacting the adoption process. The adoption of DSA technologies has not been extensively studied in the extant literature. A number of authors have identified DSA adoption as challenging [19]. Others have studied the diffusion of a particular protocol [20], services [21,22] or network technologies [23,24]. However, DSA technologies constitute a group of standards, which may affect the industry differently. In fact, DSA impacts

[2] This framework has been adopted by the US and the EU as a three tiered framework authorization [18].

directly the way spectrum is managed and, at the same time, the market structure. Therefore, this study starts by focusing on the industry openness and spectrum centralization as key factors involved in the DSA adoption. Secondly, this section describes how a DSA standard competes against another when being adopted by the corresponding stakeholder (i.e. it can compete with network or substitution effect). Finally, an overview is given of the existing DSA standards to describe the two possible adoption scenarios: user and operator centric.

### 2.1 Operator-centric versus user-centric DSA

Presently, there are several DSA standards already developed or under development, intended for different use cases, as presented in Table 1.

DSA standards can be classified by several criteria. For this analysis, the most important one is whether the functionality implementing the standard is adopted by the end-user or the operator. If the functionality is developed by the device manufacturer, the end-user will take the decision on whether to adopt such device or not. On the contrary, if it is developed by the network manufacturer, the operator will take the decision on adoption. In any case, some DSA functionalities should be supported by both devices and networks. This table also describes the stakeholder who has driven the standard, which may explain the most important design and architectural decisions. In addition, standards can support either wide area (i.e. cellular) or local area deployments; and can be modular or integral in their design. Standards have modular design if they are replacing and improving an older functionality within an existing system as an evolution of the same; and they have integral design if they are intended to develop a new system. Finally, this table indicates the target frequencies; for instance, some standards were initially developed to transmit in the TV white spaces (TVWS), even though that standards as such do not necessarily imply a certain frequency, while others standards were developed for the mobile licensed or license-exempt frequencies. As follows, this section describes the most important standard developments.

The IEEE standard series (IEEE 802.11af, 802.16h, 802.19) has defined the operation in TVWS, allowing systems to coexist in that band [25]. These standards enable, for instance, the operation of Wi-Fi in TVWS (super Wi-Fi) [26]. An alternative standard developed by the IEEE is the 802.22 which focuses on rural broadband through a wide regional area network (WRAN) and may be also applied to Device-to-Device (D2D) communication [27]. Finally, a more recent effort is IEEE 802.11ah designed to operate in the license-exempt bands below 1GHz to extend the Wi-Fi operation to machine-to-machine (M2M) applications including home networks, industrial process automation, video surveillance, and smart grid communications [28]. After IEEE, the IETF initiated the standardization of a protocol to allow the communication between mobile devices and a white space database referred to as Protocol to Access White Space (PAWS), at the beginning of 2012 [29]. Such database contains the availability information of frequencies and places in which an accessing device can transmit [30,31]. Simultaneously, ETSI Radio Reconfigurable Systems (RRS) has several ongoing standardization efforts [32]. ETSI RRS aims at providing mobile devices (MD) additional radio functionality (e.g. extra coverage at indoor or outdoor locations) through *radioapplications.* In addition, ETSI RRS provides licensed shared access (LSA) functionality [33] by which a MNO may temporally acquire additional spectrum from another spectrum holder. Finally, ETSI is also focusing on database standardization to allow white space devices, such as Programme Making and Special Events (PMSE) and Manually Configurable White Space Devices (MCWSD), to transmit in the TVWS band. On the other hand, 3GPP is aiming to improve spectrum efficiency through LTE Carrier Aggregation (CA) [34] that creates virtual wideband carrier from segments of spectrum across licensed [35] or license-exempt [36] bands. Additionally, 3GPP is including D2D functionality in the license-exempt bands in LTE (3GPP Release 12) [37]. Finally, *Weightless* [38] has been developed by Neul (UK based company) as an open standard and currently it has been applied for some Internet of Things (IoT) applications, such as machine-to-machine (M2M) and smart cities.

In a user-centric adoption scenario, the end-user device accesses the available spectrum space through a DSA functionality on a dynamic basis. The end-user device or an application in the device decides to some extent on the spectrum and the time of access. Most of the logic will be based on the DSA capability of the end-user device. In this case, spectrum sharing is performed between the end-users and the spectrum holder (MNO or other type of operator) or in some cases the end-users can freely access the license-exempt spectrum. For instance, the work in [39] describes how multi-SIM handsets in markets such as India have initiated cognitive-like responses from the end-user, even though cognition relies still on the end-user with low level of automation. Though, in this case spectrum is not shared among different parties, multi-SIM capabilities decrease end-user switching costs and impact competition and industry openness in a similar fashion than a user-centric DSA adoption. On the other hand, in an operator-centric adoption, the DSA functionality and the associated dynamic spectrum management are provided by the MNO to employ spectrum more efficiently. In this case, spectrum sharing is performed between the involved operators.

The user-centric DSA adoption scenario is analogous to unbundled handsets that can be purchased directly from a retailer without the mediation of a MNO. In an operator-centric adoption model, the practice is analogous to bundling

**Table 1** Summary of DSA standards

| 3GPP CA | Driven by | Adopted by | Wide / local area | System design | Target frequencies | Status | Example of application |
|---|---|---|---|---|---|---|---|
| 3GPP CA | Network manufacturers and MNOs | Operator | Local | Modular | Mobile licensed frequencies, license-exempt | Standardized for LTE-A, license-exempt bands. May be extended for inter MNO | Indoor small cells deployment with licensed and license-exempt frequencies |
| 3GPP D2D | Network manufacturers and MNOs | End-user | Local | Modular | License-exempt or mobile licensed frequencies | Included in LTE (3GPP Release 12) for initial development | Communicate with nearby terminals (D2D), public safety (TETRA replacement) |
| ETSI RRS LSA | Network manufacturers and MNOs | Operator | Wide | Modular | 2.3 GHz | Ongoing standardization (ETSI TS 103 154 (10/2014), TS 103 235) | Get additional spectrum for MNOs |
| ETSI RRS Reconfigurable MD | Device manufacturers | End-user | Local | Modular | Mobile licensed frequencies | Ongoing standardization (TR 102 967, TS 103 094) | Through *Radioapps* provide end-users additional radio functionality, extra coverage (indoor, outdoor through ad-hoc) |
| ETSI WSD | TV operators | End-user | Local | Integral | TVWS | Standardized (EN 301 598, TS 103 143) | PMSE (e.g., microphones), MCWSD (manually configurable WSD) |
| IEEE 802.11af/.19/.16h | Wi-Fi manufacturers | End-user | Wide | Modular | TVWS | Standardized | Wi-Fi in TVWS (super WiFi) |
| IEEE 802.11ah | Wi-Fi manufacturers | End-user | Local | Modular | 900 MHz | Ongoing standardization | Wi-Fi extension for M2M applications |
| IEEE 802.22 | Regulator | End-user | Wide | Integral | TVWS | Standardized | Rural broadband (WRAN) |
| IETF PAWS | Application developers | End-user | Wide | Integral | TVWS (initially) | Standardized | Secondary access through geolocation database |
| Weightless (open standard) | Application developers | Both | Wide | Integral | TVWS | Some deployments (Neul and other providers) | IoT (M2M, smart cities) |

**Table 2** User-centric and operator-centric adoption scenarios

| DSA adoption scenarios | User-centric | Operator-centric |
|---|---|---|
| Definition | The end-user adopts a mobile device, capable of accessing dynamically the spectrum. Spectrum sharing happens between end-user devices and spectrum holder | The operator adopts the DSA functionality in their network, to dynamically access the spectrum. Spectrum sharing happens between operators |
| Provider | Device manufacturers provide DSA capabilities to the user device. End-user spectrum access is supported by the operator | Network manufacturer provides DSA capabilities to the network elements |

of handsets with associated contract for services that is being practiced today in many markets, most notably in Japan and USA. In the first case, the end-user device decides on accessing the spectrum, while in the second case, the MNO controls the location and time for accessing the spectrum. However, in both scenarios, the underlying DSA technologies enable to exploit spectrum more efficiently. The adoption scenarios are summarized in Table 2.

While standards on DSA are still evolving, standards such as 3GPP CA and ETSI RRS LSA provide operator-centric solutions, while IEEE and IEFT provide user-centric solutions. Also ETSI WSD and Reconfigurable MD and 3GPP D2D provide user-centric solutions.

### 2.2 Network and substitution effects

Be it an operator or user-centric adoption, the total number of innovation adopters is expected to increase, as a function of time, forming an S-curve. This adoption process has two distinct phases namely the critical mass beyond which innovation exponentially diffuses and the saturation point at which the adoption rate stabilizes and the adoption attains saturation levels. The literature often refer to the pattern of diffusion in mobile telecommunications as being characterized by an S-shaped curve and by positive network effect [40,41], in which the benefits of consumers and producers are positively affected by the number of end-users and operators adopting a certain technology. There are a number of studies analyzing the adoption of products and services in networked environments by means of network effect and diffusion models. For instance, in reference [23], authors explain the dynamic adoption of network technologies by means of Bass diffusion model.[3] Other authors compare the adoption patterns of Internet Protocol (IP)-based services, network-based services and durable goods [22], and finally the work in [43] analyzed the adoption of BITNET in computer networks. There are a number of studies focusing on critical mass[4] requirements in mobile industry [24,45]. Based on the cited literature, this study assumes that network effect is equally applicable to DSA technologies.

The second element is the substitution effect, wherein a newer technology replaces an older one, typically near the end of its life [46]. This happens normally at the saturation level of the S-curve of the incumbent technology. For example, in reference [23], authors describe the substitution effect of two competing mobile generations, validating this model with the historical cellular data of 2G and 3G. In general, there are six types of interaction between an old and a new technology (pure competition, predator-prey, mutualism, commensalism, amensalism and neutralism) [47]. Technology substitution and consequent innovation adoption have been modeled as a predator-prey competition model in various research studies [21,48,49]. Such model describes the competition of two species for a common resource and explains survival, extinction and coexistence of technologies.

In reference [19], authors identify two main steps in the adoption process from research and development to adoption of DSA technologies. The first step is the technology-push, which is related to technology development and evolution of standards. The type and process of standardization defines the potential of this technology to substitute a previous one or to remain as a smaller niche catering to a limited market. The relation between standardization with network and substitution effects have been studied by many authors. For instance, the coordination game on standards and the presence of complementarity and compatibility of products is modeled by [40]. In fact, in the case of GSM, technology harmonization and associated standardization played a very relevant role in its widespread adoption for mobile services [50]. There are several ongoing standardization efforts in DSA technologies as indicated in Table 1, such as those related to Internet Engineering Task Force (IETF), Institute of Electrical and Electronics Engineers (IEEE), Third Generation Partnership Project (3GPP) and European Telecommunications Standards Institute (ETSI). Thus, the final winning standard(s) for DSA may emerge from the cellular (3GPP, ETSI) or Internet (IEFT, IEEE) world. While internet technologies typically coexist with cellular technologies thus providing complementarity and associated network effects, cellular technologies may replace previous ones initiating

[3] For Bass model description and application, see [42].

[4] Critical mass is the “minimum network size that can be sustained in equilibrium” [44].

substitution effects or compete against established networks with high network effects. Thus, the standardization bodies play an important role in the adoption of a new technology, since their decisions impact the type of effect a technology will face.

The second step is the market-pull, which includes the regulatory decisions and the characteristics of the market. The regulatory decisions related to a flexible spectrum regime enable a critical mass of spectrum available for sharing and provides the required impetus for a spectrum market and the corresponding adoption of DSA technologies. For example, the feasibility of business models for service providers participating in the spectrum market, determine whether it is mature enough to adopt DSA technologies.

Depending on the type of technology development, a standard may support modular or integral designs. Integral designs are common in vertically integrated markets, exemplified by the Japanese mobile market. A change in an integral design demands high coordination between the involved actors (i.e. network manufacturers, device manufacturers, and MNOs). In this case, standards offering new holistic solutions (e.g. IEEE 802.22, ETSI WSD, IEFT PAWS or Weightless) present an integral design. Both, the inability to agree on integral standards and the existence of closed systems have a negative impact on reaching a critical mass, as indicated by [51]. On the other side, if the industry is not vertically integrated, much like open systems, modular designs evolve that plugs within an existing integral architecture. These standards take typically the form of an evolution of a previous system (rather than a revolution) by replacing or adding a new functionality without requiring major changes to the existing system. In top of that, new DSA technologies can present high network effect, if they are competing against each other as an integral design, or they can present substitution effect, if a new technology is replacing an older one in a modular way.

Following Table 1, this analysis identifies technologies competing with high network or substitution effects. Technologies with modular design, which can act as an enabler by replacing an older module or process, typically exhibits substitution effect. This is the case of 3GPP CA, ETSI RRS LSA and IEEE 802.11af; since they are substituting an older mechanism by adding a new functionality (the capability of aggregating different frequencies, of communicating with a spectrum database or transmitting in a new frequency band). A substitution may happen as an internal process of the operator, as the case of 3GPP CA, or it may happen as a service offered to the end-user. For instance a M2M or D2D service based on DSA functionality may replace an older similar service based on older technology; or a small cell indoor coverage facilitated by DSA may substitute a macro cellular coverage which does not support DSA. In other words, even though the substitution happens at process level, the end-user may see a concrete offer at service level and thus the adoption in this case still happens at the end-user. In case there are several standards offering a similar functionality, they may compete against each other based on network effect (for instance, IEEE 802.11af with IEEE 802.22; and 3GPP D2D or 3GPP CA with ETSI RRS Reconfigurable MD). Finally, in case of newer technology deployment as an integrated systems (as the case of ETSI WSD with PMSE devices or Weightless with M2M), they may compete with established older technologies based on network effect.

### 2.3 Industry openness

The industry structure can be characterized through several parameters such as size, number of firms, market concentration, and entry and exit barriers. In the case of mobile industry, many authors have focused on the number and types of MNOs. For instance, the work in [4] studied the mobile industry structure from a transaction economic perspective, concluding that competition between vertically integrated MNOs would induce more investment and competition compared to a vertically separated market. Others studied the case of Mobile Virtual Network Operators (MVNOs) [5], and suggested that while they increase competition in the mobile industry, the mandated provision of access lowers the investment intensity of MNOs. In addition, while some authors postulate that a market with horizontal structure facilitates the adoption of MVNOs [52]; others showed that the number of networks and the history of the industry affect the speed of service adoption [6]. Besides vertical integration, the more the number of MNOs, the more intensive is the competition.

To be more specific, and to separate spectrum management issues from others affecting the industry structure, this study focuses on industry openness defined as the level of entry and exit barriers. Thus, the industry is open if entry barriers are low and vice-versa. As per Stigler [53],[5] entry barriers are cost advantages of the incumbent against competition from new entrants. In general, the indicators of entry and exit barriers may include: (i) transaction costs between firms (i.e. operators) in the market and (ii) switching cost of subscribers [56]. As per Coase theorem [57], higher transaction costs lead to vertical integration, and hence increase asset specificity, causing appropriable quasi-rent[6] and giving room

[5] According to [54], spectrum license is an entry barrier according to Bain's definition, but not according to Stigler's definition. Considering that currently spectrum licenses have reselling rights and spectrum regimes are becoming more flexible, this study follows Stigler's definition. Therefore spectrum licenses is not part of industry openness, but it is considered in a separate variable (spectrum centralization). A similar situation happens with taxi licenses, as explained by Demsetz [55].

[6] Quasi rent is a return of a firm, which is temporal in its nature due to e.g. temporal entry barriers. Appropriable quasi rent arise from a vertical integration or a transaction-specific investment.

to individual opportunistic behavior. If transaction costs are low, the industry is more open, with many competing MNOs, and the asset became less specific [58]. Switching costs are those incurred by the end-user when she/he changes from one service provider to another and they are often related to the degree of competition [59]. Higher switching costs constitute an entry barrier, since they give incumbent firms significant market power over their existing customers. Under high switching costs, firms compete under a multi-period problem, in which a provider decreases prices to attract the customer in a first period to build the required critical mass and then increase prices in a second period after locking-in the customer.

As depicted in Appendix 3, switching and transaction costs change from one market to another. For instance, subscriber switching costs are relatively high in Japan and USA (in terms of churn rate, mobile ARPU, etc.), while they are considerably lower in India and in Finland. In addition, Japan and USA shows a highly integrated industry with high transaction costs while in India and Finland these costs are lower (as they exhibit higher cooperation between MNOs in infrastructure sharing, national roaming, etc.).

### 2.4 Spectrum centralization

Spectrum management has a significant impact on the mobile industry, as spectrum assignment has implicitly affected the number of MNOs. The academic literature often assumes a tight link between spectrum and market concentration [60–62], and thus spectrum management affects market competition. However, the introduction of new DSA technologies and the new related spectrum regimes enable more flexible business models, and considerably decrease the importance of holding spectrum as a condition for market entrance. Therefore, this study considers spectrum centralization as a separate factor.

In this work, spectrum centralization refers to the mode of allocation and assignment of spectrum, associated usage rights, and consequent spectrum concentration. On one hand, NRAs can allocate and assign spectrum in a centralized way, with the objective of harmonizing spectrum usage, thereby defining the service and the technology to be deployed. In this regime, the industry structure depends on the decision of the NRA on the number of MNOs and the amount of spectrum to be assigned to each MNO. On the other hand, the usage rights specified in the license can be flexible with respect to its access, allowing spectrum trading and sharing [63], and thus creating a decentralized spectrum market. A flexible spectrum regime allows spectrum sharing by enabling two or more parties to coexist in same frequency band at different time or place. Spectrum sharing can happen between operators in a coordinated manner, or it may happen between the access provider and the end-users in an ad-hoc mode. The initial concentration of spectrum of each market has a significant impact in facilitating centralized or decentralized spectrum sharing.

Countries have taken varied positions with respect to spectrum centralization. For example, most European countries have assigned larger blocks of spectrum amongst a selected set of three or four MNOs to favor industry coordination and harmonization [64]. On the other hand, countries such as India have favored competition in the market place, by assigning the available spectrum amongst many MNOs (as high as ten or more per service area), leading to a very high spectrum fragmentation. There is a trade-off between competition and economies of scale effect of spectrum holding; a high spectrum concentration or a very high spectrum fragmentation beyond a threshold limit induces industry inefficiencies [65].

Several markets are gradually moving towards flexible spectrum regimes. In USA, MNOs are able to trade spectrum from each other as well as from broadcasters and other niche spectrum holders. Some authors affirm that such spectrum market is already positively impacting the mobile industry [66]. In Europe, though spectrum trading studies were initiated around the turn of the millennium, it is only recently that country regulators have allowed MNOs to trade spectrum. OfCom, the national regulatory authority in the UK, allowed spectrum trading in 900 MHz, 1800 MHz and 2100 MHz in 2011 followed by a more recent announcement in 2013 for including the 800 MHz and 2600 MHz bands. Many other European markets are introducing similar policies; however, not much action has taken place as yet. In India, spectrum trading is being discussed since 2012, and recently the Indian regulator, announced guidelines on spectrum trading [67] and sharing [68]. Some authors suggest that spectrum trading is beneficial especially in a market with high spectrum fragmentation, such as India [69]. Table 3 illustrates the differences between the traditional approach and a flexible regime of spectrum management. This Table indicates that DSA requires a flexible spectrum regime to allow spectrum sharing.

## 3 Note on research methods

The ICT ecosystem has become a complex dynamic system, consisting of several interacting agents [70], which evolves through incremental and radical innovations achieving periodically revolutionary changes or *redomainings* [71]. The above sections illustrate these complex relationships between technology, market structure, and regulatory decisions on the success of adoption of DSA standards, technologies and associated services. System Dynamics is intended for analyzing the dynamic behavior of complex systems, such as the mobile

**Table 3** Difference between traditional approach and a flexible regime

| Aspect | Traditional approach (exclusive and license-exempt regimes) | Flexible spectrum regime |
|---|---|---|
| Assignment of spectrum | Administratively controlled; limited based on availability of licensed bands for mobile services and license-exempt bands for Wi-Fi and other services. Latest tendency to incorporate reselling rights in licenses | Initially based on assignment mechanism, such as auction. Later, the spectrum is made available through spectrum market and usage rights enabling sharing (dynamic exclusive, hierarchical access and open sharing) |
| Allocation of spectrum (Technology and service deployed) | Mandated by the NRA, can be rigid at times. Latest tendency towards technology and service neutrality | Determined by the market by means of DSA technologies. NRA makes available other frequency bands for mobile services |
| Usage rights of spectrum | Often exclusive use for mobile services. If spectrum license is reassigned, the new spectrum holder obtain the former obligations and conditions | Regime allows spectrum sharing, permitting to coexist the same spectrum band between two or more parties |
| Spectrum concentration | Guided by rules defined by the NRA | Evolves based on successful adoption of technologies |

market, by modeling the relations between different interacting factors.

System Dynamics is a simulation technique developed by Jay Forrester in the 1950s [72]. Even though early applications focused on modeling corporate systems and control engineering, it is being widely applied in various areas including techno-economic, socio-economic and public policy studies. The feedback loop is the most significant modeling element in System Dynamics, which exists whenever decision made by agents in a system affects the overall state of the system.

System Dynamics has been proven to be a valid method for understanding the behavior of complex telecommunication markets and associated policies. For instance, some authors studied the adoption of broadband in remote and rural Scotland using this method [73]. Others described the cause-effect relationships relating to spectrum management and associated market developments and policy decisions [39], while the study in [74] performs a similar analysis for describing the competition in the mobile industry. Finally, other authors analyzed the adoption of mobile voice [50]. In all these cases, a System Dynamics approach successfully identified the most relevant relations of a system consisting on multiple interacting factors.

On the other side, other authors studied technology adoption by analyzing historical data. For example, the reference in [75] identifies the determinant for broadband adoption in the OECD countries by employing regression analysis. Other author employed a regression model to study the adoption of mobile telephony [76]. In these cases, authors employed rich panel data sets for their analysis. The work in [77] studies mobile subscriber churn by means of regression and Bayes analysis with smaller samples. Data analysis is usually a much more precise method when the required data is available, which this is not the case of future technological deployments. In System Dynamics, the causality is understood through feedback loops and thus the whole system structure causes the analyzed behavior. In a regression analysis, and more generally in the traditional view, the causality is explained through independent and dependent variables. Thus, while in the traditional view causality is exogenous, in System Dynamics causality is endogenous.

Finally, other authors studied the spectrum market by means of Agent-based modeling, by simulating spectrum holders as interacting agents [9, 11]. Even though this method also captures the dynamic behavior of a complex system, it does not address well enough the characteristics of adoption, such as critical mass and network effect. From this perspective, the top-down modeling approach of System Dynamics aggregates better the overall behavior of a system rather than analyzing the behavior of particular agents.

Both Agent-based and System Dynamics modeling aim at analyzing the dynamics of complexity [78] in a wide range of fields; however, through opposite approaches. While Agent-based modeling focuses on agent rules and their resulting emerging dynamic behaviors, System Dynamics focuses on the system structure consisting on feedback loops at an aggregate level. Thus, while Agent-based modeling is unable to study the overall structure without knowing the agent rules, System Dynamics cannot reach credible results if the notion of circular causality and its underlying feedback structure is subject of controversy. The extensive study of prior literature

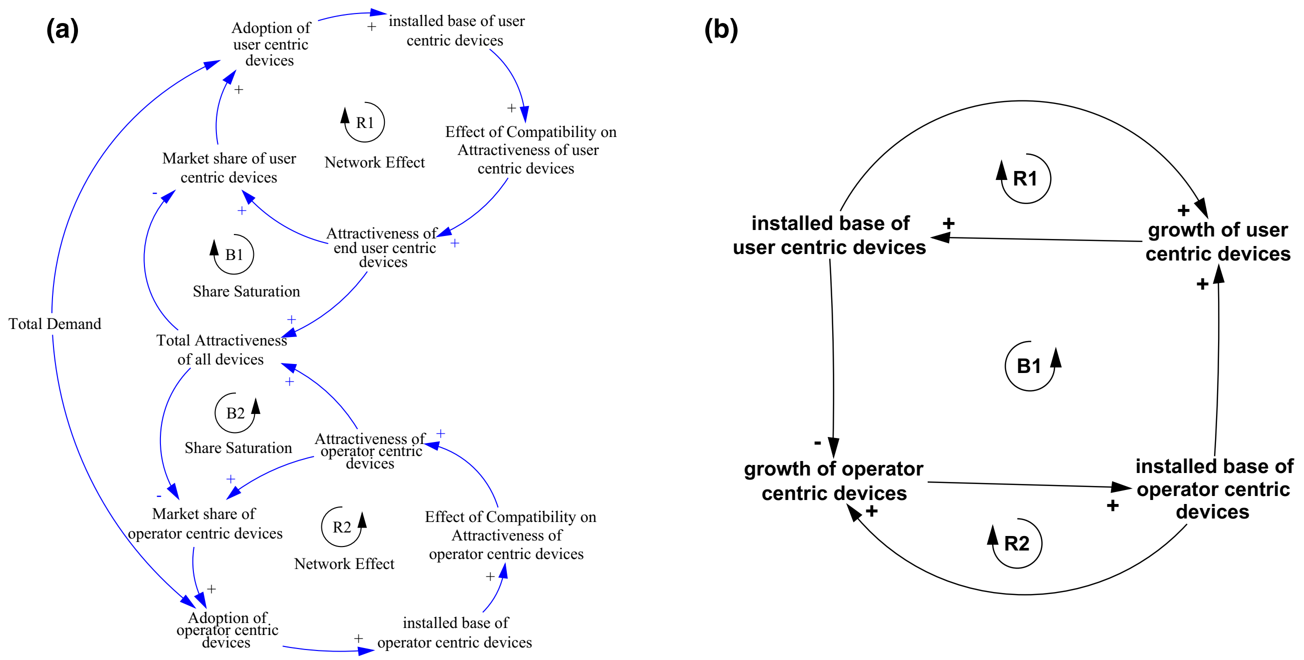


**Fig. 1** System dynamic diagram describing competition between two technologies with **a** network and **b** substitution effects, based on previous works [79] and [48]

combined with the expertise of the authors on mobile markets of various geographies provide the basis for reaching credible results in the System Dynamics models developed herein.

## 4 Adoption model

The adoption model of this section includes all the variables of interest, described by the previous sections, to analyze the dynamics of DSA adoption. The main contribution of this model is to bring together as a synthesis the previous work of other authors, regarding spectrum centralization [39], industry openness [74], network [79] and substitution [48] effects, with the understanding on DSA technologies and standards previously presented in this paper.

System Dynamics employs causal loop diagrams, as shown in the following Figs. 1, 2, 3, and 4, to visualize how different variables are interrelated in a system. The diagram consists of a set of nodes and edges. Nodes represent the variables and edges describe the relation between two variables. An edge with positive sign ("+") indicates a positive causal link, i.e. the two nodes change in the same direction. An edge with negative sign ("−") indicates a negative causal link, i.e. the two nodes change in opposite directions. The closed cycles or loops in the diagram are very important in System Dynamics. A loop is reinforcing ("R") if the effect of a variation in any variable propagates through the loop and returns to the initial variable with the same direction, further stimulating the initial variation. A loop is balancing ("B") if the effect of a variation in any variable propagates through the loop and returns to the initial variable with the opposite direction, and thus causing the contrary effect of the initial variation.

### 4.1 Modeling network and substitution effects

This section describes the modeling of network and substitution effects, based on previous work by [79] and [48]. Fig. 1 depicts the System Dynamics models of these effects.

Figure 1a depicts a causal loop diagram of the path dependence of two competing technologies [79] which generates the network effect. In this figure, the variables adoption of user-centric devices and adoption of operator-centric devices describe the performance (i.e. sales) of each type of devices. The accumulation of the adopted devices constitutes the installed base of such devices; the higher the installed base, the higher the level of compatibility for new adopters,[7] which attracts more adoption from stakeholders (end-users or operators); and this in turn increases the market share of the adopted devices. This closed loop creates a spiraling network effect (depicted by reinforcing loops R1 and R2).

In addition, the increase in adoption and attractiveness of user-centric devices (or operator-centric devices) decreases the market share of the other type of devices. This slows down the rate of adoption of the last type of devices, since they

[7] Under network effect, the number of adopters increases the value of a new adopter, since there are more connected devices to interact. In DSA, compatibility issues are relevant at both device and network sides.

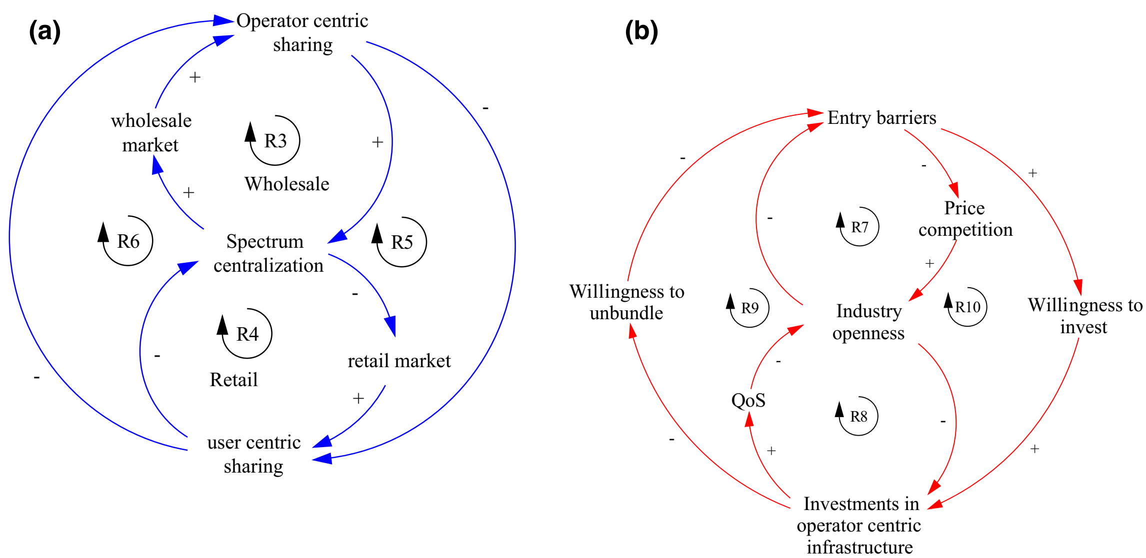


**Fig. 2** System Dynamics modeling for **a** spectrum centralization; **b** industry openness; based on previous works [39] and [74]

become comparably less attractive, which finally affects the chain of causal links leading to another closed loop depicted as *share saturation* (balancing loops B2 and B1). The system of equations that describe the mathematical formulation of the network effect and saturations as postulated in this model is presented in Appendix 1.

Figure 1b illustrates a causal loop diagram of the substitution effect employing a predator-prey competition model, which is described by the so-called Lotka-Volterra equations [48] and represents a technological substitution. These equations can be represented in a causal loop diagram, as exemplified by [80]. This model presents a logic similar to the competition model with network effect, except that the growth of user-centric devices, also referred to as predators, leads to the substitution of operator-centric devices, also referred to as prey. Hence the reinforcing loops R1 and R2 are offset by the balancing effect (B1) of substitution. See in Appendix 1 a mathematical formulation of the substitution effect.

### 4.2 Modeling industry openness and spectrum centralization

Figure 2a depicts an adaptation of the model of [39]. This model explains that a centralized spectrum management incentivizes a wholesale spectrum market, this leading to the adoption of operator-centric DSA by MNOs.[8] However, it does not encourage user-centric adoption in the retail market. On the other hand, a market driven and decentralized spectrum assignment incentivizes user-centric adoption of DSA technologies by end-users. These are captured through two reinforcing loops starting from spectrum centralization, R3 (wholesale) and R4 (retail). In the wholesale loop, an initial efficient harmonization of the spectrum allocation induces high spectrum concentration and stimulates operator-centric sharing that subsequently stimulates high spectrum concentration, without requiring major changes to the spectrum regime. In loop R4, lower spectrum concentration induces end-users to access the available spectrum, which in turn promotes user-centric devices to be deployed thus promoting spectrum de-centralization further together with a flexible spectrum regime. The reinforcing loops R5 and R6 indicates how the growth in one type of spectrum sharing reduces the demand for the other type of spectrum sharing. Figure 2b depicts an adaptation of the model of [74] that explains the dynamics of market behavior. This model describes how low entry barriers (i.e. open industry) favored by regulators to incentivize competition can have a negative impact on investments due to a decrease in MNO profits.[9] In a similar manner, increasing entry barriers makes the industry closer and incentivizes operator-centric investments. In Fig. 2b, decreasing entry barriers leads to price competition that decreases the level of prices and opens the industry further; depicted in the

[8] Low market concentration increases the probability of having spectrum transactions at retail level, since it provides the end-user buying power and increased service offer. If market concentration (and spectrum concentration) is higher, there will be less transactions at retail level (less switching possibilities for end-users), but operators instead may develop a wholesale market, through cooperative or market based mechanisms, if they see it beneficial. Note that under dominant position

Footnote 8 Continued
(i.e. monopoly), the probability of having transactions decreases at both levels.

[9] The literature has identified an inverted U-relationship between competition and investment [81,82], in which investment is low with too high and too little competition. This relation has been widely acknowledged by more recent authors, such as [83,84].

Fig. as reinforcing loop R7. In the other reinforcing loop (R8), an increase in barriers to entry, caused by a regulatory effort to improve Quality of Service (QoS), provides market participants incentives to invest in operator-centric infrastructure. This leads to improvements in QoS, which decreases industry openness and hence acts as disincentive for providing user-centric technologies. The reinforcing loops R9 and R10 illustrate how lowering entry barriers (and opening the industry) decreases the willingness of MNOs to invest in operator-centric infrastructure and makes the user-centric proposition attractive, for both incumbent and new entrants.

### 4.3 Integration of industry openness and spectrum centralization into the adoption models

This section integrates the previous diagrams depicted in Figs. 1 and 2 into the adoption models, by including the industry openness and spectrum centralization as main factors affecting the competition based on network or substitution effects.

The integrated diagrams are presented in Figs. 3 and 4. These models assume a flexible spectrum regime allowing spectrum sharing, which can be centralized or decentralized, as referred by the variable spectrum centralization. If the spectrum regime is centralized, spectrum sharing is performed in an operator-centric fashion, for instance by allowing the participating MNOs to share or trade their spectrum. If the spectrum regime is decentralized, spectrum sharing is performed in a user-centric fashion, by allowing the DSA capable user devices to access the available spectrum. Thus, the variable *amount of spectrum available for user access* describes the amount of available spectrum for end-user access. If spectrum is decentralized, end-users have more choices of access networks, and thus the operators have more incentives to provide end-user centric access through DSA. This in turn stimulates the adoption of user-centric devices while correspondingly decreasing operator-centric devices.

Figure 3 depicts the integrated diagram that describes the DSA adoption based on competition with network effect. This model merges Figs. 1a, 2a, b. The additional reinforcing

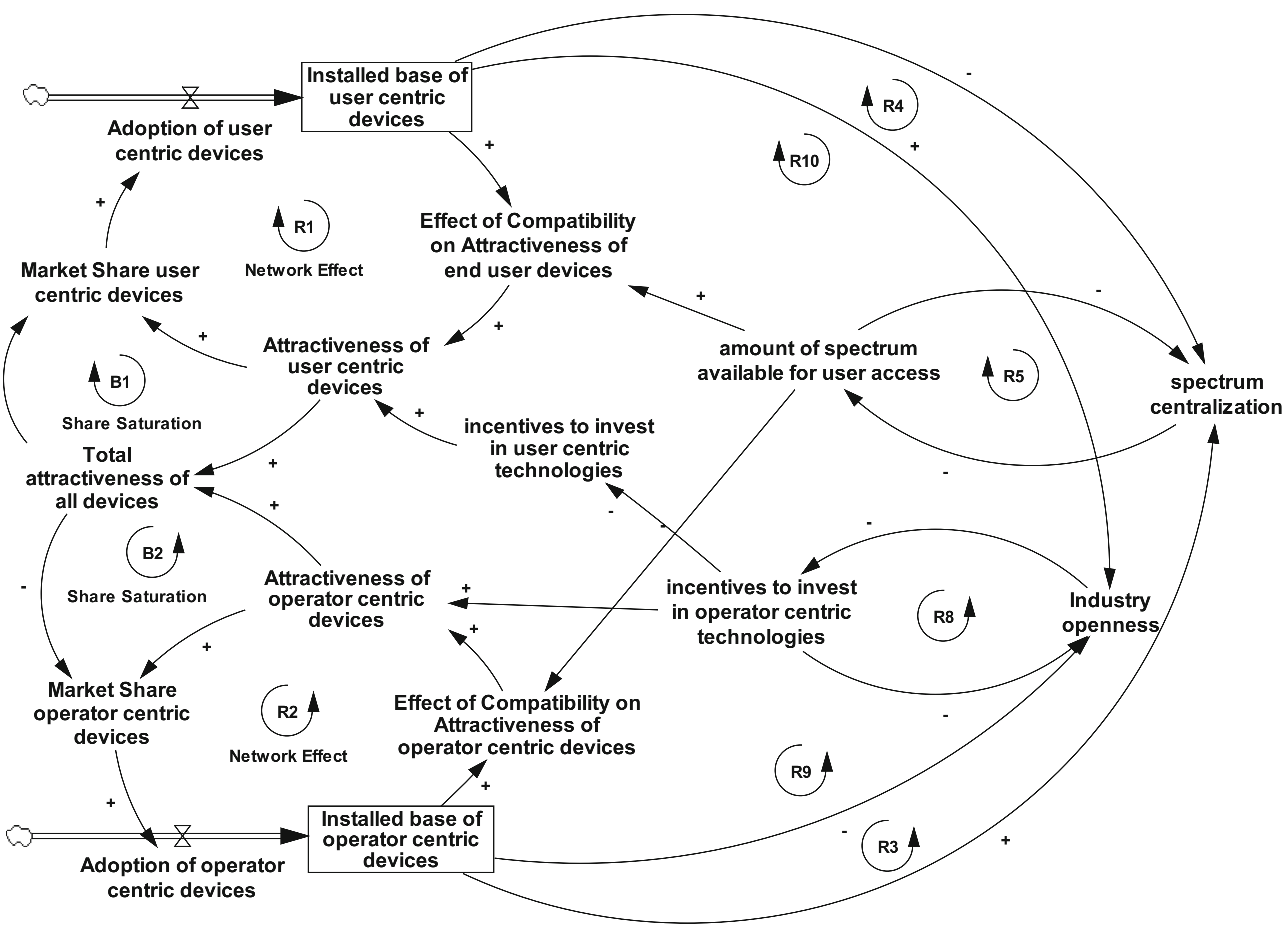


**Fig. 3** System approach to describe the DSA technologies adoption based on network effect

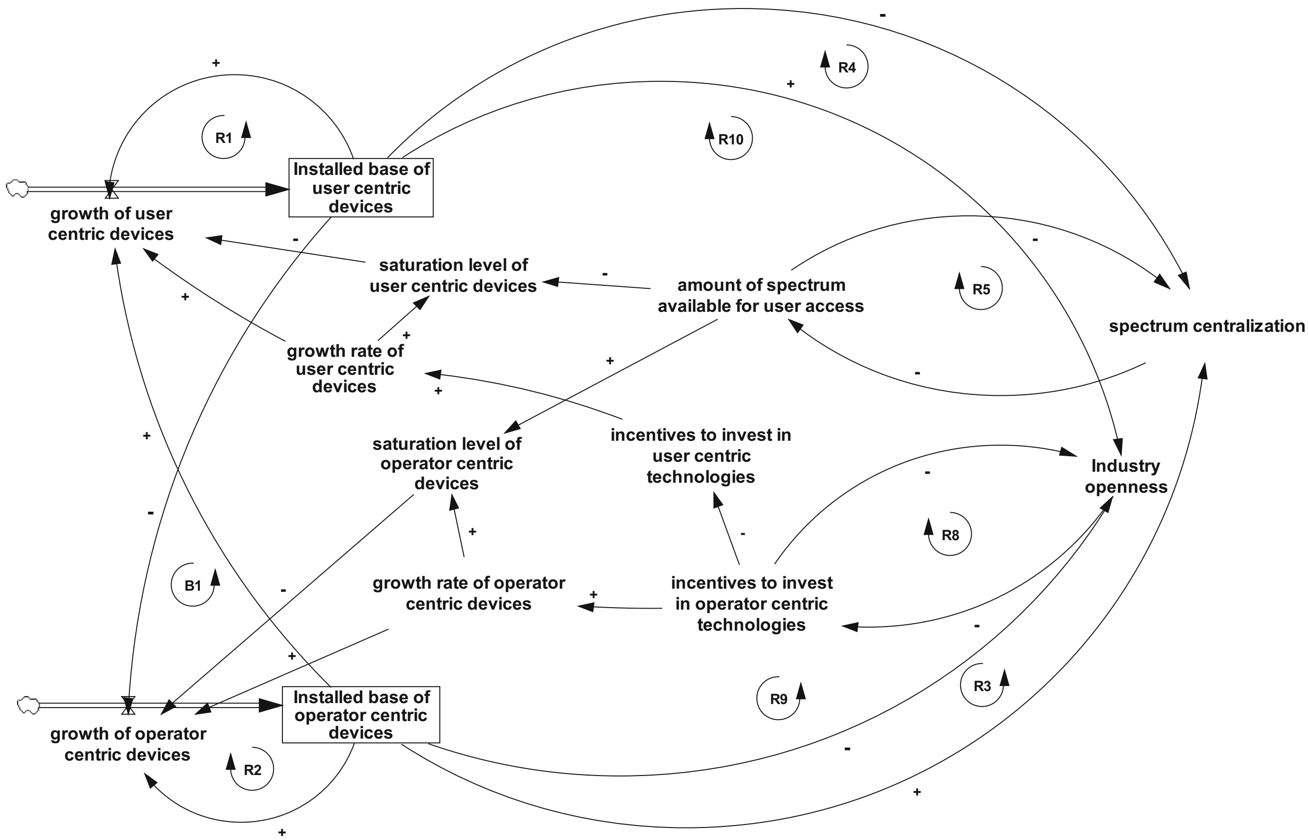


**Fig. 4** System approach to describe DSA technologies adoption based on substitution effect

loops are discussed below. The numbers of the loops maintain the numeration of the previous figures.

- R3 and R4 (Reinforcing loops): An increase in the adoption of user-centric devices increases the level of spectrum sharing at retail level and thus it further incentivizes a lower spectrum concentration, which in turn fuels the adoption of user-centric devices. Following the same logic, an adoption of operator-centric devices maintains high spectrum concentration and stimulates a wholesale spectrum market between MNOs. These loops corresponds to R3 and R4 of Fig. 2a and are based on [39].
- R5 (Reinforcing loop): A lower spectrum centralization, indicative of high spectrum fragmentation, increases the available spectrum for end-user access, which in turn stimulates retail spectrum sharing and lowers the centralization further. Thus, a decentralized spectrum will get more decentralized under the adoption of user-centric DSA. On the contrary, operator-centric spectrum sharing is more probable under a centralized spectrum market. This loop includes R5 and R6 of Fig. 2a and is supported by [39].
- R8 (Reinforcing loop): An open industry, with low entry barriers, results in lower revenues for the MNO and less incentives to invest in operator-centric DSA technologies [81–84]. At the same time, the incentives for investing in user-centric DSA technologies are increased along with a decrease in the incentives for investing in operator-centric DSA technologies. This loop includes R7 and R8 of Fig. 2b and is supported by [74].
- R9 and R10 (Reinforcing loops): the adoption of user-centric devices has a positive impact on industry openness, because these devices offer low switching costs, by allowing end-users to change easily from one network to another. This has a spiraling effect on investment in user-centric devices, which further propagates to an increased market share of such devices. Consequently, an adoption of operator-centric devices has a negative impact on industry openness, since such devices have higher switching costs, and it incentivizes MNOs to invest further in operator-centric infrastructure. These loops corresponds to R9 and R10 of Fig. 2b and are based on [74].

The other loops are those related to network and saturation effects (reinforcing loop R1 and balance loop B1 respectively), as explained in Sect. 4.1. The variable *amount of spectrum available for user access* affects the level of compatibility, since devices become more compatible with the available network access if the amount of spectrum increases. Similarly, the incentives for investing in one type of technology positively affect the attractiveness of adopting such technology, as depicted in the diagram.

Figure 4 presents the integrated diagram that describes the DSA adoption based on predator-prey competition, which embeds the substitution effect (Fig. 1b) with the dynamic of industry openness and spectrum centralization (Figs. 2a, b). This model considers the user-centric devices as predator and operator-centric devices as prey (this relation is defined in the competition effect variable, see Appendix 1 for further details). Due to the modular design, diverse functionality, and its attractiveness to end-users, it is more likely that a user-centric device can potentially substitute an operator-centric device.[10] The growth rate of these technologies is determined by the variables related to industry openness and spectrum centralization. For instance, the author in [85] suggests that the rate of technology adoption is directly proportional to the expected profitability and it is a decreasing function of the investment size. Based on this, the model indicates that the level of saturation of a type of device is inversely proportional to the amount of spectrum available for that type of device, since the availability of spectrum increases the potential for that technology. On the other hand, the incentives for investing in one type of technology positively affect the growth rate of that technology, and at the same time, they positively affect the saturation of that technology, since its growth potential is reduced.

Note that the adoption model with substitution effect follows a similar logic than the one with network effect. Therefore, the reinforce loops of Fig. 4 (R3, R4, R5, R8, R9 and R10) behave in a similar way than those of Fig. 3. As in the previous model, industry openness forms the reinforcing loop R8, while the spectrum centralization forms the reinforcing loop R5. Finally, the adoption of devices originate the reinforcing loops R3, R4, R9 and R10.

The main difference between these two models is the interaction between the competing technologies. Figure 4 represent a situation wherein the two technologies compete with each other, and thus the growth of each technology disincentivize the growth of the other technology. Figure 5 represent a situation wherein one technology substitutes the other; and thus the installed base of one technology stimulates the adoption of the other technology.

## 5 Results

The System Dynamics models described by Figs. 3 and 4 were simulated using Vensim PLE ®. The parameters of the model are summarized in Appendix 2. Spectrum centralization, industry openness and investment incentives are parameterized in a scale from 0 to 1, where 0 is the minimum and 1 is the maximum. In *spectrum centralization*, the value 0.33 represents the average value of market concentration in the mobile industry (equivalent to an HHI index of 0.33), under which spectrum is decentralized. For *industry openness* (and consequently for investment incentives) the average value is 0.5. Over this value, the industry is open, and bellow this value it is closed. The *amount of spectrum available for user access* is initially set to 5 % of the total spectrum. This does not consider the whole license-exempt spectrum, but only the portion of the licensed and license-exempt spectrum which has been gradually dedicated for user-centric DSA access. When this amount has achieved a threshold of 25 %, the economies of scales pushes towards a positive feedback loop which stimulates user-centric devices. On the contrary, bellow this threshold, the feedback loop stimulates operator-centric devices. For the model with network effect, the initial amount of user-centric devices is the same than operator-centric ones. If one technology has considerable higher amount of initial installed base, it will dominate. For the model with substitution effect, the simulation assumes that operator-centric devices start with 90 % of the installed base, while user-centric devices start with 10 %. This is to illustrate a case, in which user-centric devices are initially substituting operator-centric ones, since they offer a new or improved functionality. Finally, the competition effect coefficient is -0.02 for user-centric devices and 0.02 for operator-centric devices, meaning that user-centric devices substitute operator-centric ones.[11] Table 4 shows the four simulated scenarios with different initial values for spectrum centralization and industry openness, which represent four different markets. Scenario A refers to a country such as India or until certain extent UK, where spectrum is highly fragmented and the industry is highly open; scenario B is indicative of the situation in Nordic countries such as Finland or Sweden, where the number of MNOs are few, partly due to limited number of subscribers with an open industry presenting low switching costs for end-users; scenario C represents to some extent the situation in USA, which has decentralized spectrum and a bundled service offer (and hence closed industry); and finally scenario D refers to Japan or China, in which there are few MNOs and the entry of firms is very difficult or even strictly controlled by the government (as in China).

[10] This exercise models user-centric devices substituting operator-centric devices. However, it may be easily extrapolated to include other scenarios, such as an operator-centric DSA process substituting an older process without DSA.

[11] This competition coefficient affects the speed of convergence in the simulation results. This coefficient is in line with the one utilized in similar simulation exercises for telecom service substitution [86,87] and was adjusted to converge for all the simulated scenarios.

**Table 4** The simulation scenarios and the model parameters

| Simulation Scenarios | A | B | C | D |
|---|---|---|---|---|
| Spectrum centralization | 0.2 (low) | 0.5 (high) | 0.2 (low) | 0.5 (high) |
| Industry openness | 0.6 (open) | 0.6 (open) | 0.3 (closed) | 0.3 (closed) |

Figure 5 illustrates the simulation results for the competition model with network effect described in Fig. 3. Note that the adoption of user-centric devices is successful only under open industry and decentralized spectrum (i.e. scenario A). In all the other conditions, operator-centric scenario dominates. Industry openness which reduces entry barriers together with low spectrum concentration and a flexible spectrum regime allowing spectrum sharing, lead new entrants to invest, along with the incumbents, in user-centric DSA technologies. Thus, under high network effect, both spectrum decentralization and industry openness enable user-centric DSA to reach economies of scale and critical mass required for its successful adoption. However, not many countries possess these characteristics. One peculiar case is that of India, with highly fragmented spectrum assignment and very low price and investment indexes (indicative of an open industry). In most of the cases, for instance most European countries, US, Latin America and Asia (such as Japan, China and Korea), spectrum evidences high concentration and industry openness varies from country to country.

Figure 6 depicts the simulation results for the competition model with substitution effect described in Fig. 4. They indicate that a successful adoption of user-centric devices requires only a decentralized spectrum and therefore it can happen more often; however, the adoption process is slower as compared with the one with network effect. In fact, in a centralized spectrum regime (scenarios B and D), both operator- and user-centric devices coexist, with operator-centric devices dominating. However the substituting technology or predator (i.e. user-centric devices) dominates when the spectrum is decentralized (scenarios A and C). The adoption of user-centric devices over time substitutes the operator-centric devices. In most of the cases, the competition model with substitution effect allows a certain level of coexistence for both technologies during several

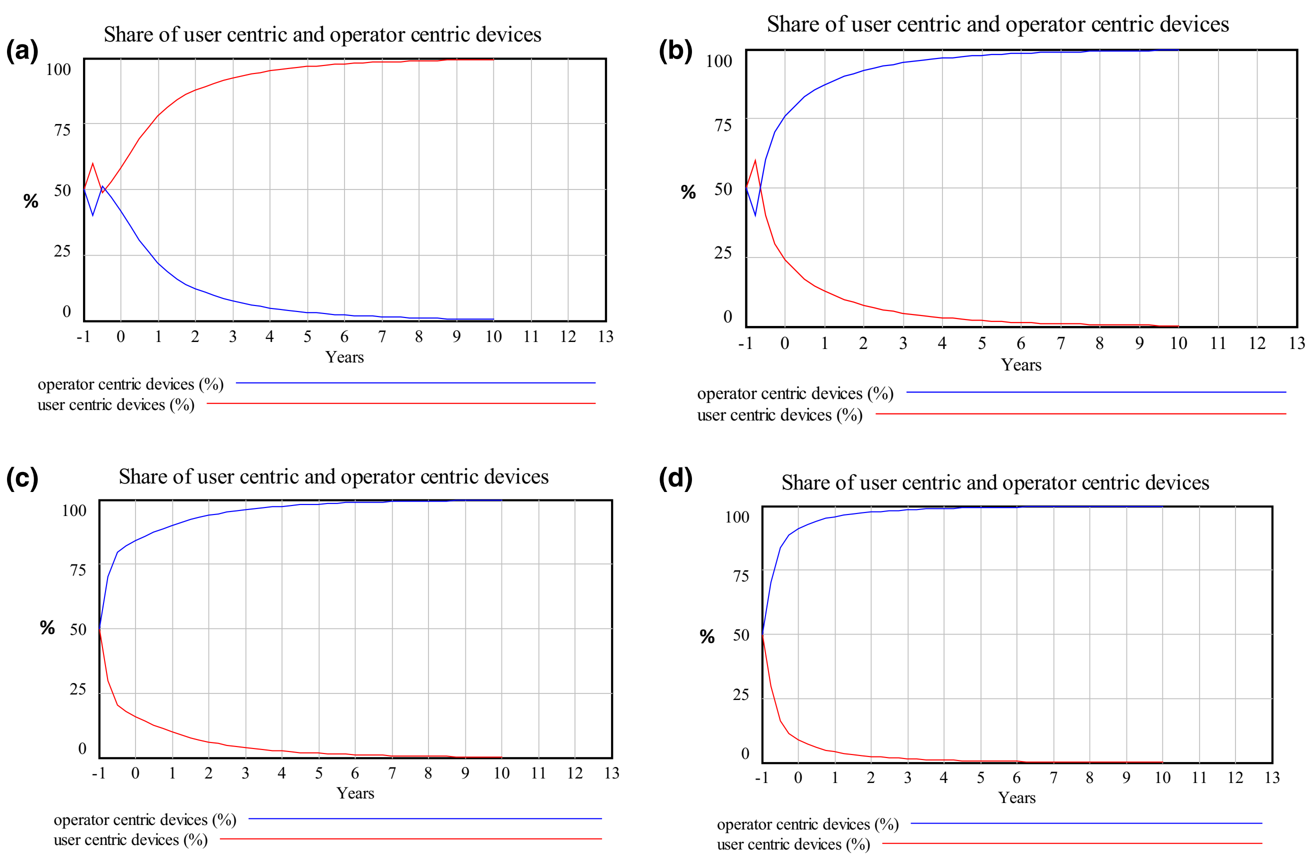


**Fig. 5** Results for system simulation of a market with strong network effect

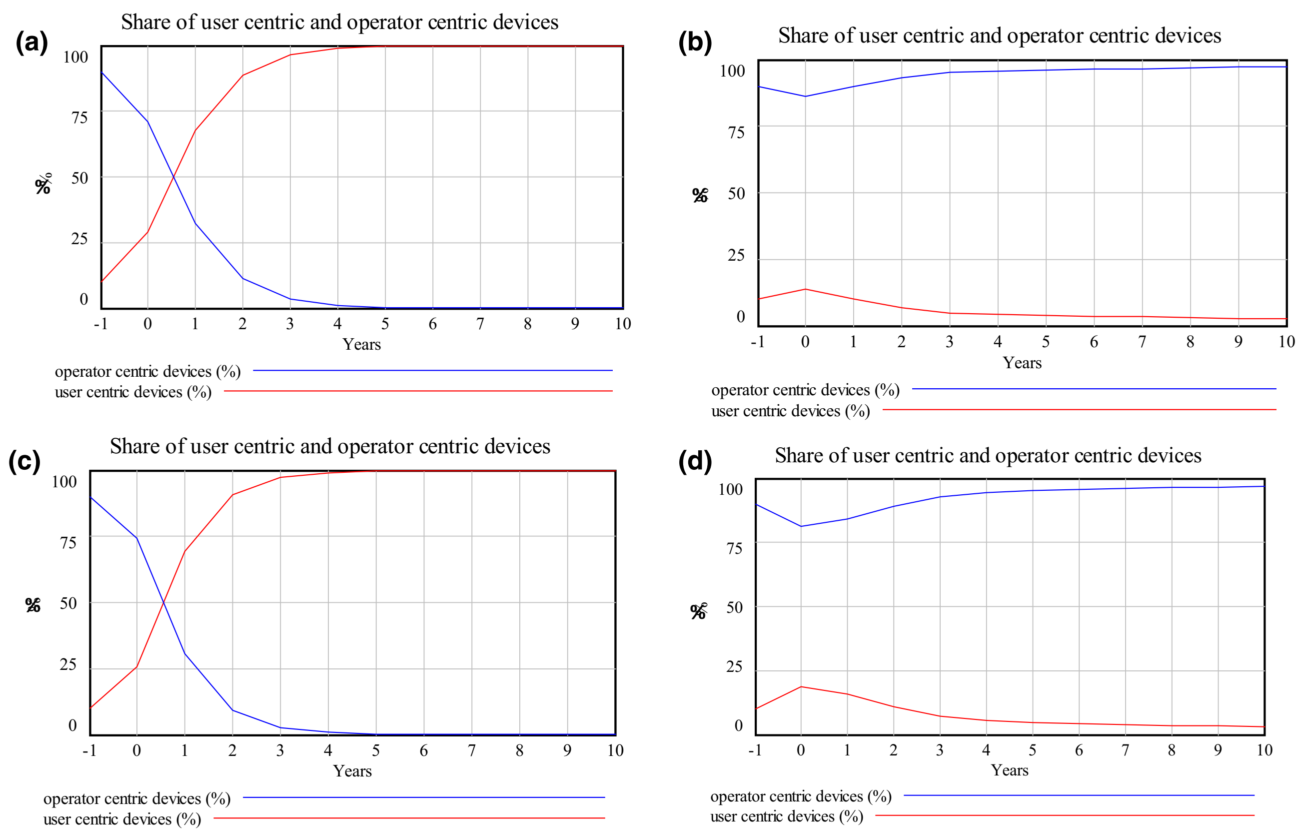


**Fig. 6** Results for the system simulation of a market with a predator-prey type of competition

**Table 5** Summary of the results on DSA technology adoption. Ticket indicates the dominating scenario for each case

| | Spectrum | Industry | Operator-Centric | User-centric |
|---|---|---|---|---|
| Network effect | Centralized | Open | √ | |
| | | Closed | √ | |
| | Decentralized | Open | | √ |
| | | Closed | √ | |
| Substitution effect | Centralized | Open | √ | |
| | | Closed | √ | |
| | Decentralized | Open | | √ |
| | | Closed | | √ |

**Table 6** Example of dominant standards based on results

| Spectrum | Industry | Network effect | Substitution effect |
|---|---|---|---|
| Centralized | Open<br>Closed | Weightless | ETSI RRS LSA, 3GPP CA |
| Decentralized | Open | ETSi WSD, Weightless, IEEE 802.22, IEFT PAWS | 3GPP D2D, ETSI RRS reconfigurable MD, IEEE 802.11af, IEEE 802.11ah |
| | Closed | – | |

years, until one dominates over the other. The time period of replacement depends on the competition effect between the technologies. Tables 5 summarizes the simulation results for both models and Table 6 provides examples of associated dominant standards, which illustrate possible adoption patterns.

## 6 Discussion

The models and results presented in this paper provide useful references and guidance to policy makers while introducing DSA technologies in different markets. The developed models focus on market dynamics. They do not consider issues such as technical feasibility of the frequencies to be employed or demand for new services, which also determine the success of adoption.

Table 6 provides examples of dominant standards based on the obtained results and thus it illustrates that different markets may adopt different standards. In fact, given that most countries have a centralized spectrum, in which few operators hold most of the available spectrum, an operator–centric adoption of standards such as ETSI RRS LSA, 3GPP CA and open standards like Weightless offering specific IoT integral solutions may dominate. For those markets with decentralized spectrum, both user-centric and operator-centric standards may be adopted. If the industry is open, standards having modular design may be adopted, such as 3GPP D2D, ETSI Reconfigurable MD, IEEE 802.11af and 802.11ah. If the industry is closed, standards with integral design (operator centric adoption) may dominate together with a user-centric adoption based on standards with modular design.

This work is the first in studying the adoption of DSA technologies in concrete, bringing together previous work on spectrum management [39], industry dynamics [74], and adoption modeling [48,79] with an analysis of the state-of-the-art of DSA standardization. The results are relevant especially for policy makers and they urge them to analyze the spectrum concentration and industry openness of their markets.

As follows, this section briefly discusses some selected market cases, to illustrate the possible applicability of the results as presented in the previous section. Statistical information on the analyzed markets is gathered in Appendix 3.

### 6.1 Case of operator centricity and industry openness in Finland and other EU markets

Finland, much like most of the Nordic countries was an early adopter of mobile technologies. It was the first country to operate a GSM network in 1991, and had continued to play an early adopter role in the deployment of latest cellular generations. In spectrum policy, the Finnish authorities have aimed at stimulating the deployment of latest technologies rather than collecting revenues from auctions [88]. In fact, MNOs had typically paid only nominal administrative charges for spectrum [89]. Over a period of time, most the European countries including Finland have adopted technology and service neutral spectrum policies and started allowing flexible use of spectrum [64]. MVNOs were allowed in Finland as early as 2003, this affecting on industry openness and competition. In addition, Finland has a long tradition of handset unbundling indicative of industry openness and bundling was only allowed for the 3G services in 2006 [90]. However, due to its limited subscriber base, the government has consciously allowed a limited number of MNOs (currently three). Hence Finland represents a case where the spectrum is concentrated in the hands of three MNOs and it is likely that MNOs may adopt operator-centric DSA technologies. Recent efforts for infrastructure and spectrum sharing are indicative of this trend [91], which evidence the willingness of MNOs to cooperate and develop operator-centric mechanisms. In addition, Finland has being testing LSA which is an operator-centric DSA solution [33]. Thus, end-user centric DSA adoption may remain in niche and emerging services, without playing a major role in the mobile market, if spectrum centralization policy remains unchanged by the authorities.

### 6.2 Case of multi-SIMs in India and other emerging markets

India has a mobile a market with high levels of spectrum decentralization and a very open industry. In fact, there are about 10 to 12 MNOs in each service area. With a spectrum HHI of 0.13, India enjoys one of the lowest spectrum concentration in the world [92]. In addition, not all the MNOs hold countrywide spectrum and are able to provide coverage in all locations, especially in remote and rural areas. Moreover, MNOs often have congested network conditions, especially in dense urban areas and they face capacity and coverage limitations. Handsets are unbundled though not dictated by regulation, but due to industry structure. The prepaid subscriber base constitute about 80 percent of the total subscriber base. With Mobile Number Portability in place, the switching cost to subscribers is very minimal indicative of the industry openness.

Due to intense competition, MNOs in India release many tariff plans for subscribers. Subscribers and local mobile handset manufacturers found a way to tackle the problems described above through multi-SIM handsets [92]. It is reported that the share of multi-SIM phones is increasing, especially within the young population [93]. The subscribers manually optimize their usage taking into account price, coverage and capacity of networks by activating corresponding SIMs in the phone. More interesting is the latest development towards an automated multi-SIM functionality, the so-called embedded SIM (eSIM) [94]. This is akin to user-centric spectrum access, where the eSIM enabled device executes a policy defined beforehand to access different networks. Moreover, penetration of wired broadband is very low (about 5 percent of households), which also stimulates the growth of mobile broadband subscriptions. Thus, terminals with user-centric capabilities such as eSIM or DSA are likely to be adopted better in markets such as India. As per this analysis, countries with these characteristics are suitable candidates for the adoption of user-centric DSA technologies, as well as alternative user-centric solutions such as eSIM. As indicated in Table 6, most DSA standards seems to suit especially well to such markets, except ETSI RRS LSA and 3GPP CA. This Table further suggests that standards from the cellular world (ETSI, 3GPP) may coexists with those from the internet world (IEEE, IEFT).

### 6.3 Case of operator centricity and closed industry in the US and Japan

In the USA, handset bundling is the norm and it enables vertical integration of MNOs and application content providers, which causes high switching cost for the end-user [95]. Similarly in Japan, the MNOs closely work with selected handset vendors and provide bundled service offerings. The price and investment indices in these countries are high; which indicates a closed industry structure. While spectrum is fragmented amongst several MNOs in USA (spectrum concentration of 0.287), Japan is a highly concentrated market and spectrum is in the hands of mainly three MNOs (spectrum concentration of 0.347). These countries are evident of closed markets with decentralized or centralized spectrum regime.

According to our analysis summarized in Tables 5 and 6, the most probable scenarios for USA, Japan and other countries with similar industry structure, is that the strong role of MNOs continues with an operator-centric development of DSA. The alliances and partnerships occurring in USA amongst MNOs for spectrum sharing and trading are indicative of this possibility [92]. In addition, countries such as USA, which evidence decentralized spectrum, can also adopt modular user-centric DSA solutions, both in emerging service areas (M2M) and as an extended functionality of the mobile services (D2D). For example, Google has started a MVNO in some regions of USA in cooperation with MNOs to provide seamless access to Wi-Fi networks. The fact that spectrum is decentralized provides incentives for both MNOs and new entrants such as Google to cooperatively deploy DSA technologies, for example in the license-exempt band. These trends are supported by this model and analysis.

### 6.4 Case of Wi-Fi adoption and the license-exempt band

Wi-Fi is an excellent case where under the conditions of industry being open and spectrum decentralized (i.e. license-exempt), technology adoption by user-centric devices became dominant. Modular design and standardization efforts through IEEE enabled Wi-Fi capabilities to be included in almost all wireless and mobile end-user devices. Therefore, under a decentralized spectrum regime, standards such as IEEE 802.11af, IEEE 802.11ah and IEFT PAWS are a good candidate for end-user adoption. On the other hand, operator-centric standards may be expanded to the license-exempt band, by considering this possibility already in the standardization stage, as it happens with 3GPP CA. The fact that license-exempt frequency bands provide free access, make that operator-centric standards may also include user-centric functionality.

## 7 Conclusions

As policy makers and NRAs move towards a flexible spectrum regime, the DSA technologies that allow spectrum sharing are moving from test labs to commercial deployment. In this scenario, this paper aims to understand how DSA technologies and standards diffuse through the mobile ecosystem for a successful adoption. In general, DSA is either adopted by operators or by end-users. This paper analyzes such adoption under varied conditions of industry openness and spectrum centralization, by employing System Dynamics models grounded on network and substitution effects.

The main contribution of this paper is to make a synthesis of the previous literature by modeling and analyzing the adoption of DSA. This work gathers together stakeholders and factors impacting DSA adoption to illustrate the challenges of such a process. Moreover, this study provides a deeper understanding on the relationship between mobile market and the adoption of DSA in different types of markets.

As a result of this modeling exercise, this paper has identified four types of standardization efforts in the DSA area: (i) user-centric with modular design; (ii) user-centric with integral design; (iii) operator-centric with modular design; and (iv) operator-centric with integral design. For each case, this paper describes the conditions for a successful adoption in Tables 4 and 5. The above mentioned standards interact between them. In a case of substitution, a new modular technology replaces an older one. In a case with network effect, two integral systems or modular designs compete against each other. In each case, the characteristics of a particular market (industry openness and spectrum centralization) affect the standard suitability and the adopted standard in its turn affects the industry structure.

As illustrated, under the presence of high network effect, user-centric devices are expected to dominate only under an open industry and a decentralized spectrum regime. Under substitution effect, a decentralized spectrum is enough to promote the adoption of user-centric devices. Operator-centric DSA is therefore expected to dominate in countries with centralized spectrum, which in practice is the case for most markets. On the contrary, user-centric DSA may be adopted in countries with decentralized spectrum regime and in niche emerging services (e.g. IoT). In general, a successful adoption of user-centric devices requires modularization, standardization, backward compatibility and horizontalization of the ecosystem. This is a relevant observation, since most of the standard efforts are user-centric. With current market conditions (centralized spectrum), standards such as 3GPP CA and ETSI RRS LSA possess higher probability of adoption and user-centric standards may remain in niche areas.

By analyzing the current status of their markets, NRAs and interested stakeholders can study the adoption behaviors of different technology standards. The NRAs can also simulate the adoption profiles for various standards based on the existing market and spectrum conditions and can make policy decisions accordingly. An operator-centric adoption may provide MNOs a means to increase their network efficiency; but may not necessarily increase the level of competition. On the other hand, a user-centric adoption may stimulate further competition; however, the incumbent incentives for investing in such technologies remain uncertain and the role of new entrants becomes more important. This model provide NRAs understanding on how their policy decisions affect the adoption of standards which consequently impact the level of competition and investments in the market. Moreover, the model developed herein might help all stakeholders (i.e. NRA, MNOs, spectrum holders, device and network manufacturers) to better understand the implications of introducing DSA technologies and services.

Future research for this area may include a more detailed analysis on particular sharing models, such as licensed shared access (LSA) in Europe and spectrum access system (SAS) in the USA. In addition, it may be useful to compare DSA technologies against other competing technologies which are not related to spectrum access, but are pushing mobile markets towards an operator-centric or user-centric evolution, such as national roaming or end-user multihoming.

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## Appendices

### Appendix 1: Formulation of network and substitution effects

Under high network effect, path dependence implies that technologies rapidly lock-in to a stable equilibrium after reaching a critical mass. The attractiveness of each product is determined by several elements, one being the effect of compatibility on attractiveness of the technology due to the network effect [79], which can be described by an exponential function[12]:

$$\mathrm{Eca}\,(\mathrm{t}) = e^{\mathrm{se}*\mathrm{b}\,(\mathrm{t}-1)/\mathrm{th}},$$

where Eca(t)= effect of compatibility on attractiveness at $t$, se = sensitivity of attractiveness; b(t-1) = installed base of devices at $t-1$, and th = threshold for compatibility effect.

Then, the technology attractiveness is also affected by the investment incentives which are determined by the market structure:

$$\mathrm{Aud}\ (\mathrm{t}) = \mathrm{Eca}\ \ (\mathrm{t}-1)\ *\ \mathrm{Ii}\,(\mathrm{t}-1)\,,$$

where Aud(t) = Attractiveness of devices at $t$, Eca(t-1) = Effect of compatibility on attractiveness of devices at $t-1$, and Ii(t-1) = incentives to invest at $t-1$.

During the simulation time, the model accumulates the number of adopted devices, which is calculated by the following integral:

$$\mathrm{Ib}\,(\mathrm{t}) = Ibo + \int sa\,(t)\,dt,$$

where Ib(t) = Installed base of devices at $t$, sa(t) = sales of devices at t; Ibo: initial installed base of devices.

The first formula indicates that the number of devices should reach a threshold value to positively impact the attractiveness of the technology. In addition to this, other compatibility elements may also impact attractiveness. Market share is determined by the attractiveness of the technology divided by the total attractiveness of all competing technologies. This relies on the assumption that these two competing technologies are not complement.

Under substitution effect, a new technology substitutes an older one. The substitution effect can be described through a predator-prey competition model by means of the Lotka-Volterra equations which are shown as follows [48]:

$$\begin{aligned}\frac{dM}{dt} &= a_M M - b_M M^2 \pm c_{ME} EM,\\ &\quad a_M > 0, b_M > 0, c_{ME} > 0\\ \frac{dE}{dt} &= a_E E - b_E E^2 \pm c_{EM} ME,\\ &\quad a_E > 0, b_E > 0, c_{EM} > 0,\end{aligned}$$

12 The value of a network can be described as $N^2$ by Metcalfe's law or as $e^N$ by Reed's law.

where $a$ is the growth or positive feedback from the adoption, $b$ is the *inhibition* or *saturation coefficient,* which describes the loss of potential market due to the growth of a technology, and therefore can be expressed as *growth rate/capacity*. Finally $c$ is the competition coefficient between two technologies (E and M in this case). If $c_{EM}$ is positive, the technology $E$ influences positively the technology $M$. If $c_{EM}$ is negative, the technology $E$ influences negatively the technology $M$. If $c_{EM}$ is zero, the influence is neutral. In a predator-prey scenario, the $c$ coefficient of the prey is positive, while the $c$ coefficient of the predator is negative.

These models are adopted in Figs. 3 and 4 by utilizing causal loop diagrams.

## Appendix 2: Parameter description of system dynamics models

Network effect model

| Variable | Value |
|---|---|
| Spectrum centralization | from 0 to 1 |
| Industry openness | from 0 to 1 |
| Incentives to invest | from 0 to 1 |
| Threshold for spectrum sharing | 25 %[a] |
| Initial amount of spectrum available for user access | 5 % |
| Initial base of user-centric devices | 100 |
| Initial base of operator-centric devices | 100 |

Substitution model

| Variable | Value |
|---|---|
| Spectrum centralization | from 0 to 1 |
| Industry openness | from 0 to 1 |
| Incentives to invest | from 0 to 1 |
| Threshold for user-centric spectrum access | 25 % |
| Initial amount of spectrum available for user access | 5 % |
| Initial base of operator-centric devices | 90 % |
| Initial base of user-centric devices | 10 % |
| Competition effect user-centric devices | −0.02 |
| Competition effect operator-centric devices | 0.02 |

[a] Amongst the OECD countries [96], the average market share of the top four MNOs is 43, 31, 19 and 6 % respectively, yielding an average market share of about 25 %. Using this data, we have considered the minimum threshold for entry of an MNO to be approximately 5 % (the fourth market share). The average of the top four MNOs (25 %) is considered as indicative of the average critical size for sustainable equilibrium, utilized as a threshold value of available spectrum for user-centric adoption

## Appendix 3: Country data

List of selected countries with variables describing spectrum centralization and industry openness[13]:

| Countries | Finland | India | Japan | United States |
|---|---|---|---|---|
| Market concentration (HHI) | 0.332 | 0.186 | 0.348 | 0.247 |
| Spectrum concentration (HHI) | 0.327 | 0.131 | 0.347 | 0.287 |
| Reselling rights | Yes | No | No | Yes |
| Mobile monthly ARPU | 32 | 3 | 84 | 47 |
| Churn rate (% monthly) | 1,60 | 5,80 | 0,60 | 1,80 |
| Cellular investment per capita per year (USD) | 34,33 | 6,05 | 134,49 | 77,91 |
| Price (USD per minute) | 0,14 | 0,04 | 0,63 | 0,39 |
| Fraction of prepaid subscriptions (%) | 10 | 95 | 1 | 22 |
| Separation of network and service operators | Yes | No | No | No |
| Number of MNOs (per service area or nationwide) | 3 | 10 | 3 | 6 |

[13] Sources: [96,97] and [98].

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# Publication 5

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# Effects of capacity sharing on mobile access competition

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***Abstract*—The growth of mobile Internet usage is raising concerns about the sufficiency of capacity in networks. Therefore, several technical solutions are currently being developed and standardized to increase the efficiency in the radio access and on the entire end-to-end Internet path. If successfully deployed, these technologies will have a significant impact on the Internet connectivity market, especially the mobile access competition. The objective of this paper is to shed light on the different evolution paths of the mobile access market which developments in technical, economic and regulatory domains could induce in the future. This paper envisions operator and end-user centric competition scenarios and compares them against the current vertical competition between mobile network operators (MNOs). The analysis shows that the degree of competition in the mobile access in the future is highly dependent on the level of transaction and switching costs. The end user scenario with related multipath protocol deployments intensifies the competition more than the operator scenario enabled by software-based dynamic spectrum management.**

***Keywords—competition; dynamic spectrum management; multipath protocols; transaction costs; switching costs***

## I. Introduction

The volume of mobile data traffic carried over the Internet is growing all the time rapidly, and the growth rate is increasing [1]. The data growth has even been predicted to be faster than the growth of the network capacity. Therefore, research communities have started developing new technologies that would utilize the network resources more efficiently and provide a wireless Internet connectivity of decent quality for end users. The developments are taking place on different layers of the Internet protocol suite. ETSI and IEEE are focusing on dynamic spectrum management (DSM)

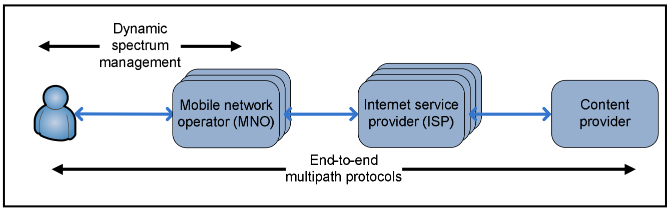


Fig. 1. Scale of the benefits of dynamic spectrum management and end-to-end multipath protocols

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in the link layer whereas IETF has proposed several multipath and mobility protocols in the network, transport and application layers. Some of the solutions are fully distributed and intended to be implemented in end devices and others require centralized coordination from the network side. The scale of the benefits of capacity sharing also varies from one technology to another (see Fig. 1).

Technological developments can alter market dynamics very rapidly. Therefore, the understanding of the ongoing technological developments and their fundamental effects on the market is important. The capacity sharing and load balancing are not mere technical issues, but they affect value networks of the Internet and the structure of the telecom industry. If successfully deployed, these technologies will have a major impact on the mobile access market. Even end-to-end protocols will mostly affect the stakeholders in the radio access, especially mobile network operators (MNO).

A traditional and pragmatic method for studying the competitiveness of the mobile access market is elaborating the market shares and concentration by collecting and analyzing market data, e.g. [2]. These studies are especially useful for regulators to analyze *ex-post* whether enough competition exists in the market. Another major but more theoretical research direction is the analysis of different pricing schemes and optimal resource allocations of competing operators with different kinds of demand or utility models. For example, the study conducted in [3] seeks the market equilibrium when end users send traffic from multihomed devices. Competitive market mechanisms in dynamic spectrum based cellular networks were studied, for example in [4]. These studies are important in guiding the market players to envision *ex-ante* novel pricing and resource allocation mechanisms but they may prove to be impossible to implement in practice.

To the authors' best knowledge, the effects of emerging communication technologies on the level of mobile access competition have not been studied earlier. This study envisions and compares two scenarios for the future of the mobile data access market: operator and end-user centric competition. Although these technologies enable capacity sharing between the wide and local area access, this study focuses on the sharing between the wide area access (cellular) operators. The theories of transaction and switching costs are used as theoretical frameworks for the competition analysis. This study should be interesting to the engineers developing new capacity sharing technologies, practitioners in MNO business and regulators.

## II. THEORY AND METHODOLOGY

The evolution of operator centric scenario is driven by the reduction of transaction costs whereas the end-user centric scenario is based on the decrease of switching costs. This section introduces these cost theories.

### *A. Transaction costs*

First introduced by Coase [5], transaction costs refer to the costs of using the price mechanism offered by the market for performing a transaction. We utilize a framework developed by Alston and Gillespie [6] to analyze transaction costs involved in a spectrum transaction. This framework divides the production process of the transaction into three periods: *pre-production*, *production* and *post-production*. It also considers three factors of productions. *Physical and financial capital* consists of machines and tools of the production process plus all liquid capital. *Human capital* consists of knowledge, skills and labor used in the production whereas *work intensity* refers to the application of work effort.

Table 1 classifies transaction costs from a production process perspective. In the pre-production process, asset specificity refers to the extent to which the investment performed for a transaction is re-deployable. This refers to the costs stemming from using the same infrastructure for a new good or service. Information costs are low when the transfer of information creates a potential for appropriation of rents; allowing a transaction that is mutually beneficial. In the production process, agency costs arise when the manager and the owner of a transacted good or service have different interests. According to Coase [5], coordination costs are high when firms get large. In addition, the market needs coordination of parties to avoid high coordination costs. Finally, the ability of contract enforcement reduces shirking costs. In the post-production, costs are mostly associated with the measuring of the output. All these elements are relevant to our analysis.

### *B. Switching costs*

Switching costs are generally seen as a barrier to enter a market and defined as one-time costs that a buyer faces when switching from one provider's product to another's. If the switching costs are high, the customer is said to be *locked-in* to the incumbent provider. The customer will switch only if the longer term benefits of the new provider exceed the switching costs. Providers tend to intentionally increase the switching costs since they are straight proportional to the profit of the incumbent provider, and setting up new customer contracts is costly. The most seminal work on consumer switching costs was made by Klemperer [7] who concluded that in most cases switching costs make the markets less competitive. However, some exceptions exist when competition is seen as a multi-period problem. Providers, who desire to charge higher prices from their locked-in customers in the future, may end up charging too low prices when trying to attract customers in the first place. This may highly intensify the competition in the first phase and decrease the total profit of providers.

TABLE I. A STRUCTURE OF TRANSACTION COSTS

| **Factors of production** | **Production process** | | |
|---|---|---|---|
| | **Pre-production** | **Production** | **Post-production** |
| **Physical and financial capital** | Asset specificity | Agency costs | |
| **Human capital** | Information costs | Coordination costs | Measurement of the output |
| **Work intensity** | | Shirking costs | |

Klemperer first categorized switching costs as transaction, contractual and learning costs but later complemented the list with psychological and emotional costs [7]. A highly cited study conducted by Burnham et al. [8] categorized switching costs based on the type of cost they incur: *financial*, *procedural* and *relational*. Financial costs consist of monetary expenses. Procedural costs require time and effort of the customer whereas relational costs involve psychological or emotional discomfort due to the lost relationship. Since this categorization is a clear and orthogonal categorization of switching costs, we use this approach for analyzing the end-user centric competition scenario. Since the relational costs are highly subjective and close to impossible to measure, they are excluded from the analysis.

The switching and transaction costs overlap in many cases. For this analysis, the main difference is that transaction costs apply when an economic exchange of a new product or service is considered. Switching costs, on the other hand, incur when the customer switches the provider in the desire of increasing his overall utility.

## III. CURRENT MARKET OVERVIEW

In order to understand the origins of transaction and switching costs in each scenario, this section provides an overview of the current market environment.

### *A. Technical domain*

Currently, the connectivity in the mobile data access is being established by using spectrum statically. This means that the spectrum band, which has been assigned for a certain MNO, cannot be used by any other party, although it would remain unused by the primary owner. Nowadays, MNOs are sharing parts of the radio access network by sharing their towers, sites, radio equipment and, in some cases, core network elements [9]. Operators can also establish roaming agreements with mobile virtual network operators (MVNO) or with other MNOs for improving service coverage and quality. This cooperation in infrastructure can appear voluntarily or be pushed by regulation. Nowadays, operators practice bandwidth rather than spectrum sharing. Spectrum sharing technologies can add new dimensions to the infrastructure sharing.

DSM technologies, such as cognitive radio systems (CRS) [10], may allow accessing the spectrum dynamically in different time and space scenarios to take advantages of the "spectrum holes", increasing the spectrum efficiency. Several standards for DSM are currently under development in ETSI and IEEE standard organizations. For example, ETSI is focusing on the development of a cognitive pilot channel and a functional architecture for a dynamic spectrum access based on software defined radio (SDR) [11]. On the other hand, IEEE has several efforts for DSM standardization. IEEE 802.19 develops coexistence methods for enabling IEEE 802 wireless standards to use white spaces. IEEE SCC41 develops standards for improving spectrum usage in dynamic spectrum access networks. Additionally, IETF PAWS (protocol for accessing white spaces) standardizes the usage of spectrum database for accessing white spaces [12]. 3GPP is making effort to improve the spectrum usage within one operator network (LTE carrier aggregation [13]).

When it comes to the entire Internet path, mobile devices are using single-path communication. This means that TCP/IP packets of a certain piece of content are being transferred through the same path. Small variations may exist inside an ISP due to the internal traffic routing but the inter-ISP route is roughly the same. IETF is proposing mobility and multipath protocols which would change this paradigm. For example, multipath TCP (MPTCP) would allow a seamless transition and a simultaneous usage of cellular interfaces [14]. In practice, these protocols would let end devices automatically switch the MNO based on different parameters and pre-coded algorithms.

### B. Economic domain

A representative structure of a western mobile market is an oligopoly with few mobile operators (typically 3-4), which are nationally or internationally active. These operators have sufficient market power to collaborate with device vendors. The contracts made with the customers typically bundle a device and a post-payment subscription. The subscription has flat or tiered data plan, and it is valid for a certain fixed time period (e.g., two years). Since the users contract with a single MNO at a time, the MNO has a monopoly over the customer over the contracted period of time. In prepaid contracts, the end user is charged per usage without longer commitments with a specific MNO. In Europe, for example, the market share of prepaid subscriptions is 52% although local variations are huge (Finland 9%, Italy 82%) [15].

Some emerging markets are more competitive. For example, the mobile access market in India is fragmented where up to seven MNOs can be active in a certain local area. This is mostly because of market-driven spectrum allocations [16]. In addition, due to the price sensitivity of the people, multi-SIM phones have been introduced in India to allow multihoming. Multi-SIM phones are also increasing popularity e.g., in China where people tend to buy separate voice and data plans from different MNOs in lieu of more expensive, bundled subscriptions. Typically, the multi-SIM devices are embedded with a 2G and a 3G interface but a tablet, supporting two 3G subscriptions, has been launched [17]. The most common pricing scheme in emerging markets is usage based [16].

### C. Regulatory domain

Since the emergence of the Internet protocol (IP) technology and services, the regulation of the Internet has been low. Many studies conclude that competition has been high enough, and both the fixed Internet access and interconnections between ISPs have remained unregulated [18]. IP has kept the entry barriers low for new content providers and maintained the competition. In addition, multihoming of content providers has become a common practice. Technology has enabled network-level multihoming from the early days of the commercial Internet, and it has increased its popularity ever since. Multihoming is practiced to increase the resiliency of the content services but also to acquire provider independence.

Regulation of MNOs and their interconnections has been more frequent. The high investment costs of the mobile access technology (leading to higher entry barriers), and the contractual control of the end-to-end path in voice services have kept the MNOs under constant regulatory scrutiny. National regulatory authorities (NRA) have used different means to affect the competition. For example, setting price caps and forcing number portability have been common practices. Another direction of regulation has been the spectrum policy. In the western markets, the spectrum has been allocated for several years (10 to 15) by using valuation mechanisms such as auctions or “beauty contests”, in which the spectrum is allocated to providers that best meet predefined criteria. The latest development of DSM technologies has raised the question for new spectrum regimes.

Current spectrum regimes are two: exclusive licensing, which allocates spectrum to MNOs for deploying mobile networks and commons regime for allowing free access without any license. Recently, several new regime proposals are emerging. Authorized Shared Access (ASA) [19] is a mechanism that allows a MNO to lease additional spectrum from another spectrum owners. Light licensing [20] provides a common usage of a frequency band, limiting the number of users or the type of usage by technical requirements. While ASA has come from the industry, light licensing has been proposed by the European Commission. Finally, pluralistic licensing [21] introduces flexible concept for applying a trade-off between interference tolerance and spectrum fee. Pluralistic licensing still remains as an academic contribution.

## IV. Scenarios For Mobile Access Competition

This section discusses two alternative scenarios for mobile access competition enabled by the deployment of the emerging capacity sharing technologies.

### A. Operator centric competition

This section introduces the transaction costs based on the scenario where devices have a single contract with one MNO, but the MNOs use dynamic spectrum allocation to maximize the usage of spectrum resources. Four evolution phases are seen in the operator centric competition. The first phase is *bandwidth leasing* which currently exists as roaming agreements between MNOs and MVNOs. *An inter-operator spectrum sharing* is an LTE-based solution for sharing spectrum between MNOs [22]. *A database spectrum sharing* represents a phase, in which a spectrum database manager facilitates the information for accessing the unused spectrum (so called “whitespaces”) from other users. Finally, *dynamic spectrum sharing* enables the most agile sharing, in which end devices can detect the local availability of spectrum, based on sensing technologies, such as SDR. We assume that these phases are driven by the operator, thus load balancing decisions are made by the network rather than the end device. Fig. 2 describes the evolution of transaction costs in the operator centric scenario. Transaction costs of transferring the spectrum diminishes along with DSM technology development. Lower transaction costs allow shorter spectrum leasing time, thus improving the spectrum utilization and increasing competition.

Costs related to asset specificity depend on the spectrum availability and fungibility. This should not be high for MNOs, when radio technologies enable spectrum access dynamically (e.g., by means of carrier aggregation and other sharing technologies). Current technologies still generate costs when adapting to other frequency bands. However, they are clearly reducing these costs through DSM technologies [23], e.g., TDD/FDD convergence, smaller cell size, achieving higher frequency adaptability, etc. Information costs of knowing the network performance are currently high. For instance, a MVNO has less information on the state of the spectrum than a MNO. In general, information costs are higher for smaller players which have less radio infrastructure than larger MNOs. DSM technologies enable low information costs for all operators, since the information is shared equally. Agency costs are also relevant, because operators usually outsource the management of their networks to focus in the service offer. Coordination costs can be related to internal coordination (high for large firms) or to external coordination with other firms (high for markets with many players). Standardization reduces costs of external coordination, and technological development reduces costs of internal coordination. Finally, the costs of measuring the output relates to gathering and updating the characteristics of the spectrum offered in a transaction. These costs remain high if measuring activities require human effort. Shirking costs arise when a party involved in a transaction unfulfils its duties because of the impossibility of being controlled by the counterpart.

Bandwidth leasing phase involves all the costs elements explained above, being the asset specificity and agency costs less critical than the others. Inter-operator spectrum sharing phase decreases the costs of asset specificity, since it allows spectrum sharing from different bands between mobile operators. In addition, this phase decreases agency costs, because operators perform a joint management of their spectrum resources, connecting the spectrum management to the business side. Database spectrum sharing phase pushes transaction costs drastically down. The information costs are significantly decreased, because a spectrum database publishes information equally to all interested parties. Additionally, a database, gathering information from spectrum measurements, decreases the costs related to this activity. Finally, the availability of information reduces costs related to shirking and coordination between parties. The requirements of a spectrum database are described in [24]. The last phase, dynamic spectrum sharing, pushes coordination, shirking and measurement costs to its minimum because the development

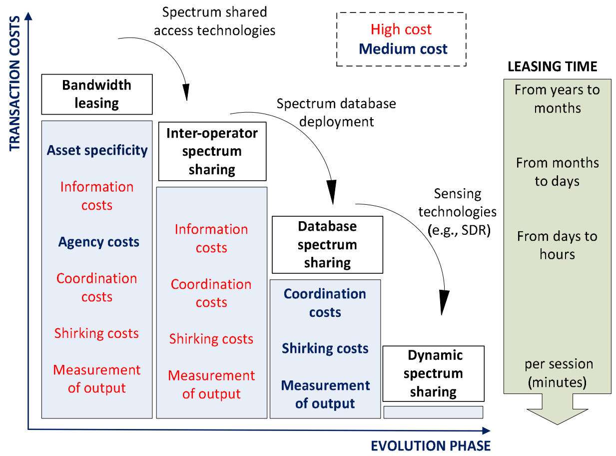


Fig. 2. The evolution of transaction costs in the operator centric scenario

of sensing technologies allow higher automation through the continuous monitoring and learning of the radio environment. Currently, sensing technologies present several challenges, such as the sensing time and delay, cooperation and energy efficiency, tracking mobile users and channel impairment [25]. The last two phases require changes in spectrum regulation.

### B. End-user centric competition

This section focuses on the evolution of end-user centric competition. The realization of this scenario requires developments of the capabilities of end devices available in the market but the allocated spectrum bands remain in the full control of the MNOs, and no secondary usage is being practiced. Three evolution phases are identified in the end-user centric competition: switching *through subscription*, *through multi-SIM device* and *through multipath protocols.* Fig. 3 shows a graphical illustration of the evolution of switching costs in the end-user centric scenario.

Switching through subscription represents the current flat competition which is based on relatively high switching costs for the end users, and the switching frequency varies from several years to months. Inter-operator load balancing occurs when a user decides to switch the MNO. The biggest share of the financial switching costs consists of contract penalties if the end user desires to switch the operator during the contract period. In prepaid contracts, the exit fee may occur in the form of unused balance but this cost can be minimized easily. MNOs may also charge a subscription setup fee but they also often provide discounts on the setup and monthly fees of the subscription. On circuit switched side, MNOs are seen to provide low-priced or even free on-net calls, which increases the switching costs of end users having a major portion of their connections within the same MNO. With mobile data services, these network-effect based discounts are more difficult to implement but any type of loyalty discount would have an increasing effect on the switching costs. The procedural costs consist of the time consumed for the search, the settlement of the new subscription and change of the SIM card. This is made easy for the end user since the new provider often takes care of the switching process. If the end user is quality sensitive, he needs to accept the effort of bearing the uncertainty about the

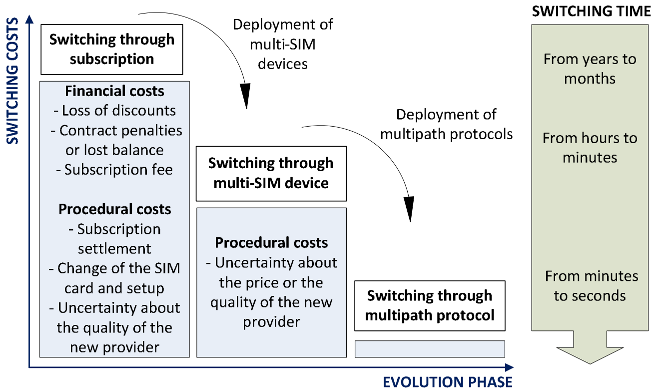


Fig. 3. The evolution of switching costs in the end-user centric scenario

overall quality of the new provider. For a price sensitive customer, the uncertainty is much lower since the prices of the new provider are easier to track.

The second evolution phase will emerge if equipment vendors will start providing multi-SIM devices on a larger scale. In some emerging markets, this is already happening to some extent, mostly for circuit-switched services since the access to mobile broadband is still limited. In the western markets the MNOs have strong bonds with the device vendors and can partly affect the features which are embedded in the devices. With a multi-SIM device, the end user would have the capability to manually select which MNO to use in each specific location and session. This would increase the switching frequency to hours and even up to minutes. The acquisition of a multi-SIM device and several MNO subscriptions embodies all the financial switching costs, and only procedural switching costs remain. The procedural switching costs culminate into the uncertainty about the quality or the price of the operator in a certain location and time depending on whether the end user is price or quality sensitive. For example, some operators use time dependent pricing to shift the demand outside peak hours. The end user may not be able to remember the prices in different locations and points of time. When it comes to the quality optimization, the uncertainty is much higher since few capabilities exist for the end user to estimate the performance of each MNO in a certain point of time and location.

The third and the highest level of competition will emerge by switching through a multipath protocol. The realization of this scenario phase requires the deployment of multipath capability in the end devices (mobile devices and content servers). The majority of the proposed IETF standards are supposed to be implemented in the operating system (OS) kernel, which requires the involvement of OS vendors. However, the multipath capability could also be implemented as a functionality of a specific application. The deployment of multipath protocols would increase the intensity of the switching from minutes up to seconds. The multipath protocol algorithms are designed to improve the end-to-end performance for the end users. For example, MPTCP algorithm monitors the quality of each path by detecting dropped packets. Based on the monitored information, the protocol automatically switches the traffic (even per packet basis) to the path of better quality, i.e., the protocol will automatically optimize the end-to-end performance without a human intervention. In the most optimal case, the protocol would choose the best quality network(s) in each location. If the end user had the real-time price information available from the operator, a multipath protocol could, in theory, minimize the cost of a price sensitive customer. Assuming that a multipath protocol optimizes the right parameters for a price and quality sensitive customer, the switching costs will decrease to zero, i.e., no financial or procedural switching costs exist.

### C. *Scenario comparison*

The two scenarios presented in the previous sections illustrate the evolution of competition in mobile data access enabled by new capacity sharing technologies. The probability of each scenario depends on standardization efforts, market developments and legislative actions. The standardization of spectrum sharing for mobile operators is the first step towards DSM, but solutions based on sensing technologies require further regulatory and development work. For instance, the secondary usage of the spectrum requires a new regulatory regime, which is still under discussion. On the other hand, the first standards of multipath communication have already been finalized in the IETF but the deployment has so far been low. Newer proposals that bypass deficiencies of older specifications are being standardized. As multipath protocols are part of the Internet architecture, no further regulatory interventions are expected to enable their usage between licensed spectrum bands. Only in case of traffic blocking regulators would intervene. Table 2 summarizes the comparison of the final phases of each scenario in order to evaluate their potential and effect on the market dynamics.

## V. Discussion And Conclusions

Both scenarios presented in this study map into earlier efforts made in scenario building of mobile ecosystems. Smura and Sorri [26] constructed their scenarios in terms of access technology fragmentation and the level of vertical integration in content provisioning. Although the scope of this analysis restricts to wide area access provisioning, the end-user centric competition can be mapped into the decentralized and horizontal ends of the scenario axes. Operator centric scenario proposes more centralized view but the mapping in the vertical axis depends on the type of services provided with DSM. However, in general terms, DSM makes the industry more horizontal, because it allows more interaction between mobile operators. In addition, DSM technologies may still push the market towards the end-user centric scenario if the spectrum selection remains with the end device.

TABLE II. Scenario Comparison

| | **Scenario** | |
|---|---|---|
| | ***Operator centric*** | ***End-user centric*** |
| Intensity of competition | Medium | High |
| Required standardization effort | High | Medium |
| Amount of regulation required for deployment | High | Low |

DSM technologies and multipath protocols can be seen as competing solutions since they both aim at increasing the efficiency of the existing network resources. They both propose a potential evolution path towards higher competition but also other scenarios exist. The current vertical competition and market structure may continue if the regulator sees that the value for the end users remain sufficient. Besides capacity sharing, other technological developments may change the market dynamics in the mobile access. For example, the deployment of software SIMs would also remove the burden of changing the physical SIM card and decrease the switching costs. In addition, the deployment of DSM and multipath protocols might happen simultaneously, which raises a question: should the access network be selected based on measurements in the radio interface or on the entire end-to-end path? DSM and end-to-end multipath protocols are implemented in different network layers, and the effects of their simultaneous usage are unknown. The optimization based on information on both layers would require cross-layer design, which would break the fundamental layer-based construction of the Internet. The key issue is to recognize where the bottleneck exists and adapt technologies accordingly.

This study presents the first effort to elaborate the impact of different capacity sharing technologies on mobile access competition. The scope of the paper has been holistic on purpose in order to increase understanding of the different trends pressuring the operators. However, this study should be followed by numerical modeling of each scenario, which could more explicitly reveal the causalities between different factors affecting the degree of their impact on competition. As the DSM requires the involvement of the operators when creating new spectrum allocation regimes, multipath protocols can emerge independently from the operators. In any case, MNOs will be most affected by the developments of capacity sharing, and they may need to reconsider their pricing schemes to affect the risks entailed by capacity sharing technologies. Smaller time scales of capacity sharing likely mean higher competition since the traffic of a single end user can more dynamically shift from one MNO to another. Based on these assumptions, the end-user centric scenario results in more intense competition in the mobile access than the operator centric scenario.

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# Publication 6

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# Transaction vs. switching costs—Comparison of three core mechanisms for mobile markets

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ABSTRACT

The fast growth in demand of mobile Internet urges mobile network operators (MNOs) to rapidly increase the wireless network capacity. For this purpose, governments are allocating large parts of the valuable low frequency spectrum to MNOs. This expansion also adds pressure to better optimize the intra-MNO and inter-MNO spectrum usage. Regulators are concerned about problems such as network blackouts, coverage disparities and congestion. Latest technology developments provide new mechanisms to address these problems through two alternative evolution paths, operator-driven and user-driven. The operator-driven path permits operators to trade network capacity and spectrum through, for instance, *national roaming* and *dynamic spectrum access* mechanisms, respectively. On the other hand, the user-driven path enables users (and traffic) to rapidly switch between networks through an *end-user multihoming* mechanism which intensifies retail competition. MNOs are reluctant to adopt these mechanisms if they involve risks. However, regulators can facilitate the deployment of these mechanisms by guiding the level of inter-MNO transaction costs and end-user switching costs. This paper analyzes the market dynamics of these three core mechanisms by employing agent-based modeling. Initial results indicate that each mechanism improves allocative efficiency on a dynamic basis and that such mechanisms become necessary if the current static market model based on vertically integrated MNOs is not able to meet the requirements of service quality, capacity and coverage. One promising use case of the proposed mechanisms is the indoor femto-cellular deployment which suffers from coverage disparity due to static single-MNO base stations. Moreover, either end-user multihoming or national roaming may provide MNOs a feasible business case for building indoor infrastructure by solving coverage disparity problems, by means of competition or cooperation, respectively. Dynamic spectrum access may work as an extension of the previous mechanisms for solving congestion; however, it requires higher technical and business coordination.



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## 1. Introduction

The mobile Internet market is presently characterized by a rapid traffic growth due to an increase in demand for new services and higher quality. Mobile network operators (MNOs) respond not only by building new infrastructure but also by exploring new mechanisms which improve network and spectrum utilization by matching network supply with user demand. MNOs on the same domestic market could increase their joint utilization level through *national roaming,*[1] *dynamic spectrum access* (DSA),[2] or *end-user multihoming.*[3] The motivation of industry actors, including device vendors, MNOs, and end-users, to choose a certain mechanism depends on the structure of the mobile market and on the level of inter-MNO transaction costs and end-user switching costs. Regulators have an interest and power to guide the evolution of market mechanisms and the related transaction and switching costs.[4]

So far, MNOs have not been active in deploying these new mechanisms because of the risks each one involves. On the other hand, even though the mobile market in many countries is considered competitive, the allocative efficiency may not be optimal yet. Regulators are concerned about problems such as network blackouts, coverage disparities and congestion, which frequently occur in every market. These problems can be understood as market failures, since they prevent assigning network resources to users who value them most. This paper investigates emerging mechanisms having the potential to decrease such market failures.

The economic theory suggests that a scarce resource, such as spectrum or network capacity, achieves its maximum allocative efficiency when the price of the last sold unit equals its marginal costs (Markovits, 1979), and therefore the production represents end-user preferences. To achieve this optimum and respond to the above failures, regulators can stimulate retail competition[5] by decreasing end-user switching costs through e.g., mobile number portability (MNP) or handset unbundling. On the other hand, regulators may favor cooperation[6] between MNOs to improve network coverage and quality through wholesale trading mechanisms, which decrease inter-MNO transaction costs, such as national roaming, infrastructure sharing and mobile virtual network operators (MVNO). Latest standard and technology development include end-user multihoming and dynamic spectrum access as possible future mechanisms of interest.

In the telecommunications field, a number of authors have investigated the relation between competition and cooperation. Markendahl (2011, Chap. 3) analyzes the competition and cooperation mechanisms between MNOs, while Hazlett (2006) studies the dynamics of competing networks with compulsory infrastructure sharing. In general terms, the studies indicate that even though competition is usually favorable, an excessive competition may lower the level of investments, because it lowers retail prices and reduce MNO profits.[7] In practice, a regulator can mandate incumbent MNOs to provide competitors with access to their facilities or encourage facilities-based competition. In any case, legislators regulate the wholesale trading between MNOs to avoid the risk of anti-competitive behavior (i.e. collusion).

The role of wholesale trading and its connection with retail trading is still poorly studied in the mobile market literature. One exception is Cricelli, Grimaldi, and Ghiron (2011), who claim that symmetric reduction of mobile termination rates at wholesale level force MNOs to reduce retail prices. Other interesting analysis was performed by Poyhonen et al. (2007), which compares terminal centric versus network centric strategies for handovers in heterogeneous mobile network deployments. However, this work investigates the technical rather than the market perspective. In other markets, this issue has been more widely addressed, in particular in the electricity and energy markets. A number of authors emphasize the importance of competition at retail level and the role of wholesale trading in the market performance. For instance, Bohi and Palmer (1996) report that while retail competition brings lower electricity prices, wholesale trading may encourage higher investments. Mirza and Bergland (2012) emphasize the role of user prices as a signal for attaining efficiency in energy allocation, while Goulding, Rufin, and Swinand (1999) claim in this same line that a lack of true retail competition results in wholesale prices providing wrong signals. Finally, Polo and Scarpa (2013) suggest that an introduction of a compulsory wholesale market generates retail competition. Even though mobile telecommunications and energy markets are very different, the previous references suggest that further study of mobile market dynamics at wholesale and retail levels, may be especially beneficial for regulators and policymakers.

[1] National Roaming is a service whereby an user equipment (UE) of a given public land mobile network (PLMN) is able to obtain service from another PLMN of the same country, anywhere, or on a regional basis. The availability of National Roaming depends on the home PLMN of the requesting UE and the visited PLMN; it does not depend on subscription arrangements (3GPP TS 22.011 V13.1.0, 2014-09).

[2] Dynamic spectrum access is a general term, which refers to a set of technologies enabling two or more parties to coexist in the same frequency band, either at different time or location. The original concept was introduced by Mitola (2000) with the name of Cognitive Radio (CR), in which users are able to access dynamically the spectrum. Cognitive Radio Systems (CRS) refers to a general framework defined by ITU.

[3] End-user multihoming refers in this context to any mechanism, solution or protocol enabling the user to maintain several concurrent and active subscriptions to different MNOs. For a detailed explanation on multihoming mechanisms, see Suomi (2014).

[4] For the purpose of this study, transaction costs refer to inter-MNO and switching costs refer to end-user.

[5] Competition is herein understood as the effort of two or more parties acting independently to secure the business of a third party by offering the most favorable terms (Merriam-Webster Online dictionary).

[6] Cooperation is understood as similar or complementary coordinated actions taken by firms in interdependent relationships to achieve mutual outcomes or singular outcomes with expected reciprocation over time (Anderson & Narus, 1990).

[7] According to Schumpeter, there is a positive relationship between monopoly power and technological innovation. This conjecture was criticized by Scherer (1967), who introduced the idea of an inverted U-shape relation between competition and innovation. Aghion, Bloom, Blundell, Griffith, and Howitt (2002) formalized this relation.

This paper studies the benefits and risks of a regulator introducing operator-driven (national roaming and dynamic spectrum access) or user-driven (end-user multihoming) mechanisms, as a means to increase economic efficiency. In particular, this work responds to the following question: Under which conditions should a regulator deploy any of these mechanisms? To answer this question, this study analyzes how each of these three mechanisms impact transaction and switching costs and the overall dynamic of the market.

This analysis builds on the work started by Suomi, Basaure, and Hämmäinen (2013), which identifies the future phases for mobile access competition and the technologies lowering the transaction and switching costs. As to the method, this study employs agent-based simulation to analyze the overall effect of many interacting agents with changing cost conditions.

The paper is structured as follows. Section 2 introduces the evolution of transaction and switching costs in the mobile market and Section 3 describes the chosen method for this analysis. Section 4 elaborates the simulation scenarios and presents the results whereas Section 5 discusses the implications of the findings and Section 6 concludes the study.

## 2. Background

Transaction and switching costs are the two key cost elements which affect the dynamics and structure of a market. Transaction costs are induced when employing the price mechanism offered by the market when performing an economic exchange. The importance of these costs was firstly introduced by Coase (1937). The level of transaction costs may explain, for instance, the level of vertical integration of an industry. Changes in transaction conditions achieve a restructuring of the industry due to increased efficiency (Ulset, 2007). Low transaction costs increase efficiency by diminishing opportunistic behaviors of agents[8] (Hill, 1990). On the contrary, an increase in transaction costs results in governance deficiency explained by agency costs and a market restructuring characterized by expansion to non-related activities (e.g. vertical integration). In general, transaction costs can be classified into search and information costs, bargaining costs and policy end enforcement costs (Dahlman, 1979). For the purpose of this study, inter-MNO transaction costs are related to the level of technical and business coordination between MNOs in a wholesale market. If the coordination is high, MNOs have the required information on the possible trading (searching and information costs), they can agree on contracts (bargaining costs) and they can make sure the contract is being fulfilled by the involved parties (policy and enforcement costs).

Switching costs, on the other hand, are seen as barriers to new products or service providers to enter a specific market, and are defined as one-time costs that a buyer faces when switching from one provider to another (Porter, 1980). Burnham, Frels, and Mahajan (2003) characterized switching costs by classifying the types of resulting costs into financial, procedural and relational. Relational costs are highly subjective, since they involve psychological or emotional discomfort due to the lost relationship; therefore, this study focuses on financial and procedural costs. Financial costs consist of monetary expenses, while procedural costs consist on the require time and effort of the customer. For example, if an end-user considers switching to another MNO, financial costs refer to the expenses caused by annulling the present and setting up a new contract (SIM). Procedural costs are often measured in time and effort required to acquire this new SIM.

While inter-MNO transaction costs affect the market structure by determining the level of vertical integration, end-user switching costs determine the market concentration and the monopoly power of incumbent firms. Both costs affect barriers to entry and other relevant capital and operational expenditures, such as infrastructure investments, subscriber acquisition costs, etc.[9] The emergence of new technologies and regulations affect the level of inter-MNO transaction and end-user switching costs in telecommunications markets. This section describes such evolution in the mobile telecommunications market. In addition, it introduces the three market mechanisms and their relationship to transaction and switching costs.

### *2.1. Evolution of transaction costs in the mobile market*

From the liberalization of mobile telecommunication markets at the beginning of 1990s, many countries have harmonized their mobile network standards to achieve interoperability and scale benefits. This compatibility also enables resource trading between MNOs with lower transaction costs. This trading induces efficiency through reallocation of network resources at different levels. Regulators can reduce transaction costs by mandating fair access to essential facilities, for example, by demanding network operators to allow access to multiple service operators at non-discriminatory prices.[10] Furthermore, the regulator has enforced national roaming and infrastructure sharing[11] in some cases to facilitate market entry or better network coverage. Nonetheless, it has been historically difficult for regulators to maintain equilibrium

[8] This refers to the economic meaning of opportunism, which means a self-interest seeking with guile and not to an engineering perspective, which may imply an increase in efficiency.

[9] Note that transaction and switching costs are not typically analyzed together, since they belong to different areas of economic analysis. While transaction costs belong to Transaction Cost Economics (TCE) and impact business-to-business relationship; switching costs is related to Porter´s forces of competition and impacts customer-to-business relationship.

[10] This also facilitated the entrance of MVNOs.

[11] Infrastructure sharing is performed at two levels: passive elements (e.g., antenna locations) or at active elements (network elements such as base stations).

between permitting and forcing wholesale trading. For instance, Hazlett (2006) claims that compulsory trading raises the costs of infrastructure if the conditions are favorable for new entrants, or it can stimulate too little entry, if conditions are favorable for the incumbent. To illustrate the challenges of this balance, Cave (2006) suggests that regulators set an access charge which increases over time, and thus encourages new entrants to climb the *ladder of investment,* providing them with time for investing in assets which are difficult to acquire. Even though this approach has been well received by some regulators, it has also earned criticism (Bourreau, Doğan, & Manant, 2010).

The mechanisms mentioned above have been favored by MNOs, resulting in cooperative strategies. Such cooperation includes roaming agreements with entrant MNO, agreements with MVNOs, and infrastructure sharing at certain agreed locations to make the service offer more cost efficient.[12] These mechanisms have been studied for example by Markendahl (2011), who concludes that cooperation between MNOs will continue to be relevant in the future, since it usually implies higher revenues and no negative impact on MNOs.

Infrastructure sharing is currently better conceived as a cooperative process rather than one imposed by the law. For instance, Hazlett (2006) finds that mandatory network sharing regimes may effectively increase competition on a retail level, but at the expense of diminishing investment of infrastructure. In this same line, Kim et al. (2011) show that the mandated provision of mobile access to MVNOs results in less infrastructure investment, while voluntary access provisioning has no negative effect on investments. From this perspective, this study focuses on mechanisms, such as national roaming and dynamic spectrum access, which allow MNOs to develop cooperative strategies. The regulator can facilitate these mechanisms by diminishing transaction costs by means of fixing prices, defining trading mechanisms, and allowing capacity or spectrum transactions.

National roaming is employed in large countries, such as USA and India, to improve national coverage. In such cases, MNOs cooperate with each other to become more competitive. In other countries, such as the UK, national roaming agreements have enabled new entrant MNOs to deploy new infrastructure (e.g., 3G network) with less investment requirements (Sutherland, 2011). National roaming lowers entry barriers facilitating MNOs to deploy networks without the necessity of national coverage. Nevertheless, the experience shows that national roaming requires a careful regulation. For instance, Fabrizi and Wertlen (2008) argue that without regulatory intervention, MNOs can agree high national roaming fees to charge the final user high retail prices. To avoid such situation, the regulator can demand MNOs a minimum network coverage or cap the roaming fees. In this line, Stühmeier (2012) identifies a trade-off for pricing regulation in national roaming for new network deployment; below cost charge stimulates MNOs to increase investments but to decrease roaming quality, while above cost charges decrease investments but increase roaming quality.

In this same context, dynamic spectrum access technologies decrease costs associated with spectrum transactions, allowing MNOs to trade their spectrum, and thus increase network efficiency by employing the *spectrum holes.* Dynamic spectrum access can be classified according to spectrum transaction rights; mode (use or ownership), extent (complete transfer or shared spectrum) and duration (short/long lease versus short/permanent sale) (Caicedo & Weiss, 2007). It also can be classified according to the user access rights; dynamic exclusive sharing (incumbent spectrum holder utilizes the spectrum with flexibility), hierarchical access sharing (incumbent permit the access of secondary users ensuring a priority access for own users) and open sharing (all users from different parties enjoy equal priority) (Zhao & Sadler, 2007). This paper deals with those cases which enable spectrum sharing or transactions between MNOs, being shared or leased, without changing the ownership of the spectrum or the access priority of the users (dynamic exclusive regime or open sharing). From this perspective, dynamic spectrum access offers new means for cooperation between MNOs. If the dynamic spectrum market is properly regulated, transaction costs become lower, the number of mutually beneficial transactions increases, and consequently the spectrum market becomes more dynamic (Basaure, Marianov, & Paredes, 2015). Thus, an efficient wholesale market may also favor competition by decreasing entry barriers and allowing new entrants. The resulting levels of cooperation and competition depend on the deployed trading mechanism and related regulation.

This paper focuses on dynamic spectrum access that enables spectrum transactions between MNOs (such as those described by Yoon, Hwang, & Weiss, 2012). These transactions could be performed through some predefined rules bilaterally, mediated by a broker, or through automated on-line auctions. In any case, dynamic spectrum access aims to stimulate wholesale trading. However, Shapiro (2001) argues that in cooperative settings, such as cooperative patent pools, welfare is increased when traded resources are perfect complements and decreased when they are perfect substitutes, because of anti-competitive behaviors. Lerner and Tirole (2002) expand these observations to other cooperative situations, such as airlines. This observation may be relevant for a spectrum market, since dynamic spectrum access turns spectrum into a substitute for MNOs.

Dynamic Spectrum Access technologies involve a set of protocols and standards, most of them still under development, such as those related to the IETF, IEEE, 3GPP and ETSI organizations. For example, IEEE standard series (IEEE 802.11af, 802.16h, 802.19, 802.11ah) has defined several end-user driven mechanisms, for instance, the operation of Wi-Fi in such band or a Wi-Fi extension for machine-to-machine (M2M) applications (Xiao, Hu, Qian, Gong, & Wang, 2013). In addition, IETF has put effort in standardizing the communication between mobile devices and spectrum database, also referred to as Protocol to Access White Space (PAWS) (Mancuso, Probasco, & Patil, 2013). ETSI Radio Reconfigurable Systems (RRS) has also

[12] As an example of cooperative infrastructure sharing, see the case of Elisa and DNA joint agreement to build network coverage in the east and north of Finland, an area with low population density (Liikenne- ja viestintäministeriö, 2014).

several ongoing standardization efforts, both for end-users and operators (Mueck, 2014). ETSI RRS provides mobile devices (MD) with extra coverage functionality through *radioapplications*. Also, ETSI RRS has standardized a licensed shared access (LSA) functionality (Palola et al., 2014), by which a MNO may temporally acquire additional spectrum from another spectrum holder. Finally, 3GPP is improving the spectrum usage within one or several networks through LTE carrier aggregation (CA) (Yuan, Zhang, Wang, & Yang, 2010), or even between LTE and Wi-Fi networks (Alkhansa, Artail, & Gutierrez-Estevez, 2014), which allow to transmit the traffic coming from one source through different frequency bands and thus improving the spectrum utilization. CA deployment between MNOs may be implemented through dual connectivity functionality, while CA between LTE and the unlicensed Wi-Fi spectrum may be implemented through Licensed Assisted Access (LAA) (4G Americas, 2014). Given the existence of several standardization efforts, this study focuses on those standards enabling spectrum transaction between MNOs, such as 3GPP CA or ETSI RRS LSA.

### *2.2. Evolution of switching costs in the mobile market*

There is a common view that a decrease in switching costs intensifies competition, causing prices to drop at retail level. Thus, the lower the switching costs, the fiercer the price competition, which consequently reduces MNO profits (Farrell & Klemperer, 2007). In many occasions, a decrease in switching costs can achieve an increase in social welfare. However, this may not be always the case. A number of authors (Aghion et al., 2002; Hazlett, 2006; Markendahl, 2011) have suggested that excessive competition has a negative impact on investments and therefore may reduce the social welfare in the longer term. In addition, Bouckaert, Degryse, and Provoost (2012) claim that even though a *proportional*[13] decrease in switching costs increases competition and social welfare, a *lump-sum*[14] decrease in switching costs may soften competition and reduce the social welfare. Finally, Chen (2011) affirms that the role of switching costs critically depends on the strength of the network effect and on the quality of the alternative option.

In practice, regulators have historically reduced user switching costs to drive market competition. Examples of such reductions are the limitations in bundling of a device and a connectivity service as well as the implementation of mobile number portability (MNP). For instance, Tallberg, Hammainen, Töyli, Kamppari, and Kivi (2007) describe the effect of handset bundling (and thus increasing the user switching costs) on the Finnish market. The introduction of MNP by regulators has stimulated the entrance of new MNOs, such as MVNOs. However, the impact of MNP on competition highly depends on the type of implementation. While Sanchez and Asimakopoulos (2012) claim that the results of MNP have been diverse across Europe, Shin (2007) affirms that US MNOs have maintained high switching costs despite the MNP implementation. For instance, Grzybowski (2008) estimates the switching costs for the UK mobile market by means of a regression analysis, arguing that these costs are already low due to an early MNP implementation. In the case of Japan, MNOs are vertically integrated and therefore a MNP implementation may have limited impact on switching costs (Nakamura, 2010).

In most western countries (including Europe and USA), the dominant model for providing mobile services is *single-homed*. This means that the user has only one single contract with an MNO attached to a specific device. To switch to another MNO, a mobile user needs to cease the contract with the current MNO and set up a new one by acquiring a new subscriber identity module (SIM).[15] In some emerging markets, however, users are adopting *multihoming* devices which support several subscriptions with different MNOs. For example, in India and China users actively use multi-SIM mobile phones and tablets (Sridhar, Casey, & Hämmäinen, 2012; Tech2, 2013). The multihoming functionality decreases switching costs because the user can instantly switch to a desired MNO when the required contracts are set-up.

Embedded SIM (eSIM) (GSM Association, 2014) is another interesting direction of development, which reduces switching costs. The primary purpose of eSIM is to foster the development of machine-to-machine (M2M) communications since the MNO subscription can be updated remotely without changing the physical SIM card. eSIM may also allow two active profiles of different MNOs (i.e. *multihoming*) which could be used interchangeably between user sessions. eSIM would further decrease the switching costs, consequently intensifying the retail competition.

Furthermore, mobility and multipath protocols make user switching between MNOs even more dynamic. These protocols are being developed in the IETF at different Internet layers, but they are not yet widely deployed (Suomi, 2014). They aim for better utilizing the network resources and thus improving the quality of service and experience (QoS/QoE). One such example is the Multipath Transmission Control Protocol (MPTCP), which is already implemented by Apple in its operating system (iOS7) (Bonaventure, 2013). MPTCP is capable of switching the user connection automatically from one MNO to another (even in the middle of an online session) or, alternatively, using simultaneously two paths (passing through different access networks). The protocol makes the switching decisions according to a pre-coded algorithm in terms of, for example, performance on each path. This means that any MPTCP-like protocol would reduce switching costs practically to zero.

[13] A proportional decrease arises when consumers with high switching costs experience a higher absolute decrease than other consumers.

[14] A lump-sum (fixed amount) decrease arises, for example, when enhanced compatibility cuts the adaptation cost by a certain fixed amount, irrespective of the initial level of switching costs.

[15] Note that users having a device with Wi-Fi and cellular interfaces are already capable of multihoming if the cellular and Wi-Fi networks are overlapping each other.

**Table 1**
Comparison of the target mechanisms.

| Mechanism | Dynamic spectrum access | National roaming | End-user multihoming |
|---|---|---|---|
| **Market mode** | Operator-driven | Operator-driven | User-driven |
| **Cost impact** | Inter-MNO transaction costs (search and information costs) | Inter-MNO transaction costs (search and information costs) | End-user switching costs (financial and procedural costs) |
| **MNO–subscriber relationship** | Static subscription | Static subscription | Fast switching between subscriptions |
| **MNO–MNO relationship** | Spectrum trading through brokerage system | Roaming contracts (home MNO controls) | Competition for user choice |
| **Trading type** | Wholesale | Wholesale | Retail |
| **Trading event** | Access to spectrum band, (e.g., minutes, hours, days) | User session | User session |
| **Spectrum management** | Dynamic | Static | Static |
| **Required CAPEX (MNO)** | High | Low | Low |
| **Required OPEX (MNO)** | Medium | Medium | Low |
| **New spectrum regulation needed** | Yes | No | No |
| **Standards development needed** | Yes | No | No |
| **Other requirements** | Spectrum trading mechanism | Access price regulation | Metered pricing |

### *2.3. Comparison of the target mechanisms*

Table 1 compares dynamic spectrum access, national roaming and end-user multihoming. The main difference between the analyzed mechanisms is the impact they have on transaction and switching costs. Regarding the investment perspective, while multihoming and national roaming are not capital intensive mechanisms, dynamic spectrum access requires major investments. In the case of dynamic spectrum access, the costs depend on the detailed implementation. This study considers a brokerage trading system, such as the one presented by Yoon et al. (2012), in which each MNO lease the free spectrum to other market participants. For this purpose, each MNO should deploy base stations capable of accessing spectrum dynamically (such as those referred by Anchora, Mezzavilla, Badia, & Zorzi, 2012). In addition, a brokerage system requires operational and capital costs of running a server, a database, and maintaining real-time information on spectrum trading.[16] This brokerage system matches demand and supply to maximize social welfare, and thus it could be run by the regulator or a third party. Notice that for the purpose of this analysis, the broker does not own the spectrum, but it only facilitates the spectrum information for making trading possible. Finally, MNOs face the costs of communicating with the broker and keeping updated spectrum information. Dynamic spectrum access technology decreases inter-MNO transaction costs related to searching and information. The deployed trading system, such as brokerage, decreases both bargaining, and policing and enforcement costs. In the case of national roaming, there are additional costs due to home network routing and the related double book keeping. In this case, the national roaming mechanism decreases searching and information costs, while the related trading arrangement (how MNOs make the bookkeeping and charge to each other) decreases the bargaining and policing and enforcement costs. Finally, in the case of end-user multihoming, the number of subscriptions is increased, causing additional costs to maintain up-to-date SIM and location information. In addition, end-users may not be willing to maintain several flat-rate subscriptions, so most probably MNOs need to deploy e.g. metered pricing in an end-user multihoming scenario, or at least a hybrid combination between metered and flat rate pricing, which also adds complexity to the charging and billing process. End-user multihoming decreases both financial and procedural costs of switching.

The regulatory requirements and the willingness of incumbent MNOs affect the adoption of these mechanisms, and may significantly vary from one market to another. While MNOs are typically reluctant to adopt end-user multihoming; national roaming and dynamic spectrum access require major changes in regulation. National roaming requires access price regulation to balance the incentives of incumbent and new entrant MNOs. Dynamic spectrum access requires a new spectrum regime allowing transactions; and, on top of that, the regulator should design a trading mechanism which improves the service supply and avoids high market concentration. For instance, Yoon et al. (2012) compare different approaches for spectrum trading, and conclude that while auctions favor the seller, direct trading or a brokerage system may optimize social welfare. This study assumes a spectrum market based on a broker.

## 3. Method

Behind the research question of this paper resides the relation between competition and cooperation; retail and wholesale trading. This paper compares transaction and switching costs between the three target mechanisms. Due to

[16] See Weiss and Altamimi (2011) for a description of costs elements for several dynamic spectrum access scenarios.

technology innovation, the mobile market is dynamic, i.e. complex and evolving (Tesfatsion & Judd, 2006), rather than static. While classical economics studies the equilibrium, recent methods emphasize the evolving dynamic nature of the system. Agent-based modeling (ABM) considers the dynamic behavior of an economic system consisting of interacting agents (bottom-up approach). In such economic systems, agents react to micro-level environmental conditions thus producing the macro-level system behavior. Other methods, such as system dynamics, study the dynamics of the system in a top-down manner.

This study employs ABM to analyze an evolving mobile market, affected by a gradual decrease of transaction and switching costs. ABM is a suitable method when the natural representation of a problem consists of interacting agents. In this case, end-users interact with MNOs to obtain network access while MNOs interact between each other to better serve their end-user customers. Moreover, since the future evolution is always uncertain, ABM simulations provide a feasible means to analyze several possible scenarios.

There are a number of studies analyzing transaction costs through ABM. Klos and Nooteboom (2001) study the trading between firms by incorporating trust into a transaction cost analysis and thus evaluating the role of trust behavior under different market conditions. Tonmukayakul and Weiss (2008) model a secondary spectrum market consisting of agents with bounded rationality (i.e. implementing a learning algorithm). In such a case, transaction costs are defined endogenously through the bounded rationality and the type of spectrum trading. Yoon et al. (2012) compare mechanisms of secondary spectrum trading by estimating the economic value of spectrum transactions. In other fields, Nguyen, Shortle, Reed, and Nguyen (2013) simulates water quality trading considering asymmetry of information and transaction costs, concluding that both bilateral and clearinghouse mechanisms result in cost saving. Finally, Zhang, Zhang, and Bi (2011) study the effect of transaction costs on emission trading markets based on real data, concluding that transaction costs are still high and can block emission trading and decrease market efficiency.

There are very few studies employing an agent-based approach to analyze switching costs. One such example is performed by Liu, Zhang, Xu, Andersen, and Xu (2014).

This study performs a bottom-up analysis of the behavior of end-users and MNOs. The model developed herein can be characterized as being representative of an environment with Euclidean space (2D), with agents having bounded rationality, meaning that their knowledge is limited given certain technology and environmental circumstances. With the deployment of a new technology (and the consequent decrease in cost conditions), the agents are able to learn more from their environment. Method wise, this study presents a novel approach by modeling an evolving market which includes both transaction and switching costs.

According to Macal and North (2010), ABM involves (i) a set of agents, which in this case are end-users and MNOs; (ii) agent relationships, meaning that agents are connected through a network; in our case, end-users belong to one MNO and, given cost conditions, end-users switch from one MNO to another while MNOs trade spectrum or capacity between each other; and (iii) agent environment which is the spatial location related to other agents and characteristics, that constrain agent actions. In this case, besides location, agent environment is determined by transaction and switching costs which in turn are determined by the deployed technology per mechanism. Thus, in our model, transaction and switching costs are given by the agent environment and they are exogenous.

## 4. Analysis of MNO and user interaction to match demand with supply

This section describes the model, assumptions, and obtained results for scenarios consisting of MNOs and end-users that interact to match the mobile demand with the network supply.

### *4.1. Analysis of different mobile markets*

This model describes a mobile market with several competing MNOs. Appendix II depicts general characteristics of 20 selected mobile markets. This sample shows an average number of MNOs of 4 and an average market concentration index (HHI) of 0.334. Other variables related to switching or transaction costs such as termination rate, number of MVNOs, mobile ARPU, and churn rate, highly vary from one country to another. Given this, the following model describes a market consisting of three MNOs with similar initial market shares; or in other words, an initial market concentration of 0.333, in line with an average mobile market as per described in Appendix II. A sensitivity analysis of switching and transaction costs is performed based on this model. Note that this model does not include market entrance.

### *4.2. Simulation model and setup*

The simulation considers three MNOs and 72[17] end-users with different traffic characteristics, each user being subscribed to one of the three existing MNOs. In the simulated area defined as 2 km × 2 km (4 $km^2$), each MNO has four base stations,

[17] The total number of 72 end-users assumes a density of 18 active end-users per $km^2$, such as suggested for urban areas for the 790–862 MHz band by ITU-R 5-6/180-E, Annex II (ITU-R, 2010).

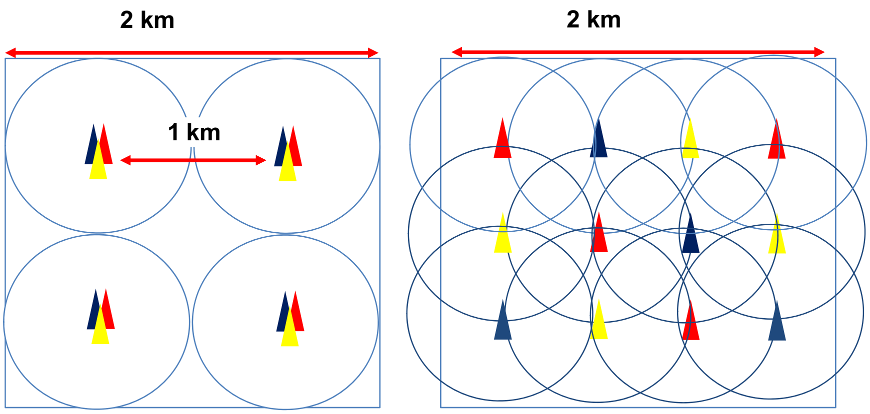


**Fig. 1.** Simulation setup for the MNO scenarios. Each triangle represents a base station; each color indicates one of the three MNOs. Circles illustrate the coverage area of base stations.

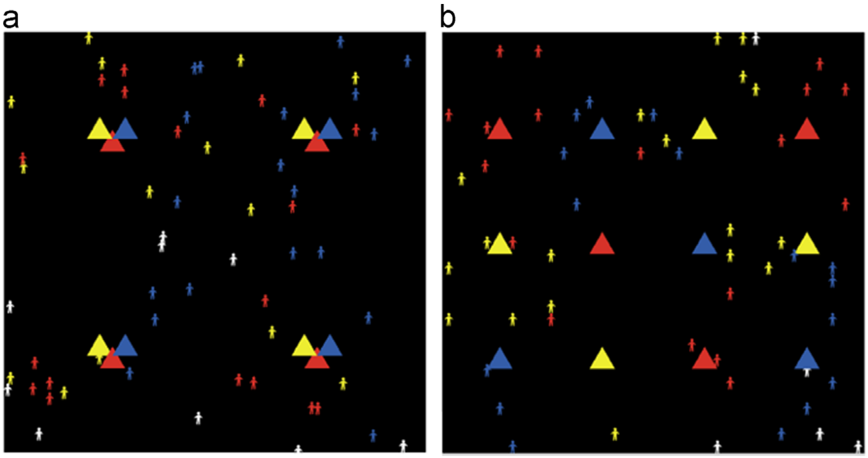


**Fig. 2.** Model implementation by means of the ABM simulation tool, Repast Symphony 2.2. Each color indicates a particular MNO. When a user is served, he/she gets the color of the serving MNO: (a) colocated topology and (b) non-colocated topology.

each base station having a radius of 0.5 km of coverage and a capacity of 100 Mbps.[18] Base stations and their coverage areas are located to describe two different scenarios: colocated and non-colocated topology. Mobile users move at a constant speed of 2.5 km/h (by means of a random walk algorithm[19]) and their average traffic requirements change from 10 to 30 Mbps, depending on the utilized service. Users move throughout the simulation area without any predefined pattern, unless otherwise stated. In all simulated scenarios, the total amount of available spectrum and network capacity, as well as the average service demand are constant. The simulation does not consider the interaction with other networks, such as Wi-Fi, or the possibility of getting additional spectrum outside the already allocated to MNOs. The assumptions of the simulation are intended to enable scenarios that describes at best the dynamic of MNOs rather than realistic, and also are computationally possible for the ABM processing. See Appendix I for a list consisting of the simulation parameters.

The simulation scenarios are depicted in Figs. 1 and 2. Fig. 1 illustrates the simulation setup for the base station locations of the three MNOs, the left side for a colocated topology and the right side for a non-colocated topology. The scenario with colocated topology describes a situation in which MNOs have similar network coverages and thus they cooperate in passive elements (location of antennas). The scenario with non-colocated topology describes a situation in which MNOs exhibit higher network coverage disparities. The colocated scenario may be understood as describing an outdoor deployment based on macro- and micro-cellular networks, while the non-colocated scenario describing an indoor deployment based on small cellular networks. Both outdoor and indoor cases are equally represented by the same simulation scheme; in the indoor case each base station depicts a local network deployed through several small cells. Fig. 2 shows a visualization of the model implemented by means of an ABM simulation tool.

[18] A throughput of 100 Mbps assumes a $2 \times 2$ MIMO configuration, 64QAM modulation and a QRM-MLD receiver in a frequency band of 20 MHz (3GPP TR 25.814 V7.1.0, 2006, Fig. 8.1.2.2.1-1).

[19] Random walk algorithm is typically employed for analyzing the performance of a system (Camp, Boleng, & Davies, 2002), which is the purpose of this study.

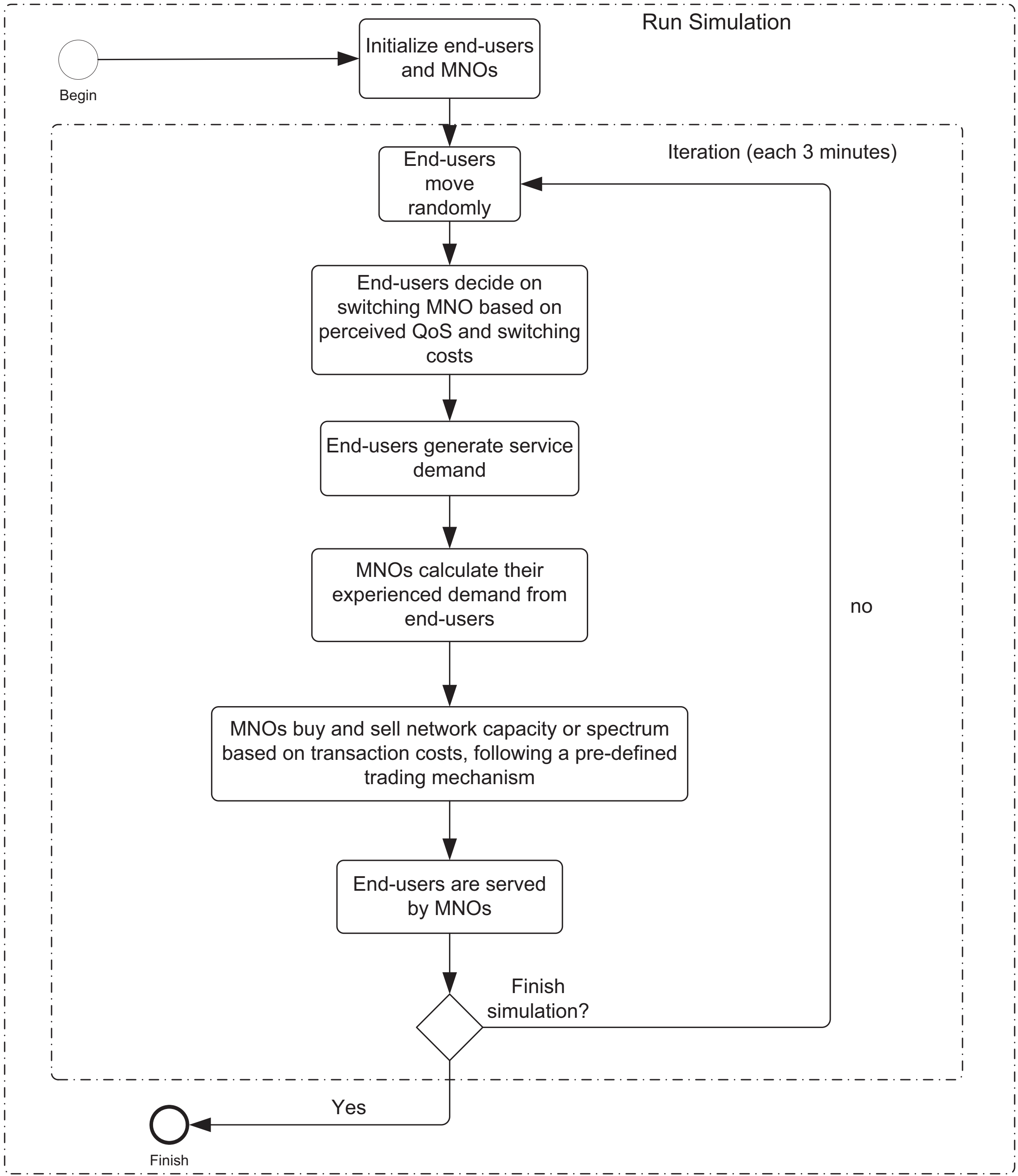


**Fig. 3.** The ABM logic diagram for one simulation iteration of the developed model.

### *4.3. Modeling transaction and switching costs*

In each simulation iteration, end-users can change their MNO depending on the experienced quality of service (QoS) and switching costs. In addition, MNOs can buy and sell network capacity or spectrum, depending on their transaction costs, which in turn depend on the deployed technology. Fig. 3 depicts a logic diagram of one simulation iteration for the ABM model. The duration of such iteration equals one average mobile user session (3 min). Note that end-user multihoming with multi-access radio technology could allow network choice even on per IP packet basis within user sessions but that extremely fast trading is not included in the model.

**Table 2**
Definition of switching and transaction costs for the simulations.

| | **Switching costs** | **Transaction costs** | |
|---|---|---|---|
| | **End-user multihoming** Number of experienced failures, after which the user switches MNO | **National roaming** Number of roaming agreements available for a user | **Dynamic spectrum access** Frequency of spectrum trading transactions |
| **Low** | 0 (automated eSIM) | 2 (wholesale, optimal routing) | 3 min (femtos, automated inter-MNO CA) |
| **Medium** | 1 (manual multiSIM) | 1 (wholesale, home routing) | 3 h (femtos, manual inter-MNO CA) |
| **High** | 10 (SIM replacement) | 0 (retail, home routing) | Never (no femtos) |

Table 2 describes how transaction and switching costs are modeled in the simulation. Switching costs consist of the easiness of the user to switch from one MNO to another. A user switches MNO, if the perceived benefits of switching to another MNO (in present value) exceed his/her switching costs.[20] The user estimates switching costs based on own experience on QoS failures and on the availability of real-time information.[21] A failure is defined in terms of signal strength (the user is out of the area of coverage) and congestion (not enough capacity to serve that user). Switching costs are considered high when the user tolerates many QoS failures before switching MNO. This is the situation of many Western mobile markets in which users change to another MNO after experiencing several failures during a longer period of time. In the simulation, end-users with high switching cost are set to switch MNO after 10 failures, which reflects an average end-user QoS tolerance, and represents the switching cost of a manual SIM card replacement. At this level, the model assumes that the end-user changes from one MNO to another randomly, that is, without knowledge of the quality of other MNO's service. When switching costs decrease to a medium level, users switch MNO after a smaller number of perceived failures. In our simulation, users adopt multi-SIM devices and switch after one failure. This represents a market situation such as that of India where the market share of multi-SIM devices is relatively high, in which financial costs are low and procedural costs still remain due to the uncertainty on the new MNO quality and coverage conditions. At this level, the model assumes that the end-user chooses the nearest base station based on previous knowledge or available information on location of base stations. Finally, switching costs are low, when users are able to proactively choose the base station with the best QoS offer each time they access the service. This phase assumes the deployment of automated eSIM or similar functionality where the real-time QoS comparison is based for instance on MPTCP. Such a set-up enables users to switch MNO for each session through an automated switching decision based on user-configured settings for network quality and (metered) price. In this situation, all cost items are very low. At this level, the model assumes that the end-user chooses the base station with least congestion.

Transaction costs are quantified here indirectly via the break-even point between scale benefits and transaction costs, as described in Table 2. This means that the maturity of the technology enables higher level of coordination between MNOs, which in turn allows capacity or spectrum transactions with certain restrictions. Lower the costs, lower the restrictions of such transactions. In national roaming this point is shown by the number of roaming agreements available for end-users. If the roaming related inter-MNO book-keeping is performed on a retail level by both MNOs and the routing is non-optimal (i.e. it is performed through the home network), roaming agreements most probably will not be available for users. Thus, this high level of transaction costs is modeled as zero roaming agreements. Transaction costs are decreased until medium level if the inter-MNO book-keeping is performed at wholesale level. This situation is modeled as one roaming agreement available to end-users. Transaction costs are assumed low if inter-MNO book-keeping is performed at wholesale level and routing is optimized through the visited network. This requires a higher level of trust between MNOs and a well-defined trading mechanism, to really decrease both bargaining and policing and enforcement costs. In the simulation this situation includes two roaming agreements available to end-users or, in other words, a full national roaming.

For dynamic spectrum access, the assumptions on transaction costs specifically describe a deployment of femto-cellular networks, however the same mechanism may be in theory applied to spectrum transactions between LTE sites (e.g., by means of LSA). Currently, end-users are served by macro and micro-cellular infrastructure and transaction costs related to spectrum trading are high, in practice spectrum trading is non-existent. With the deployment of femto-cellular networks indoors, the femto-cellular base station customer (e.g. home owner) wants to provide access for an identified group of end-users (e.g. home guests). In this situation, spectrum trading is enabled through inter-MNO carrier CA and can be requested manually by femto-cellular customers. In the simulation, the transaction costs of manual inter-MNO CA are modeled as medium level with spectrum trading happening in time-slots of 3 h. Transaction costs are considered low, when inter-MNO CA spectrum transactions are automated and performed in time-slots of 3 min (i.e. base iteration of simulation) without

[20] See Courcoubetis and Weber (2003) for a mathematical formulation.

[21] Note that the decision on switching involve other factors, such as price, additional services, marketing, etc. This study only considers the technical component, assuming that all other factors are equal for all users, because it compares different technologies.

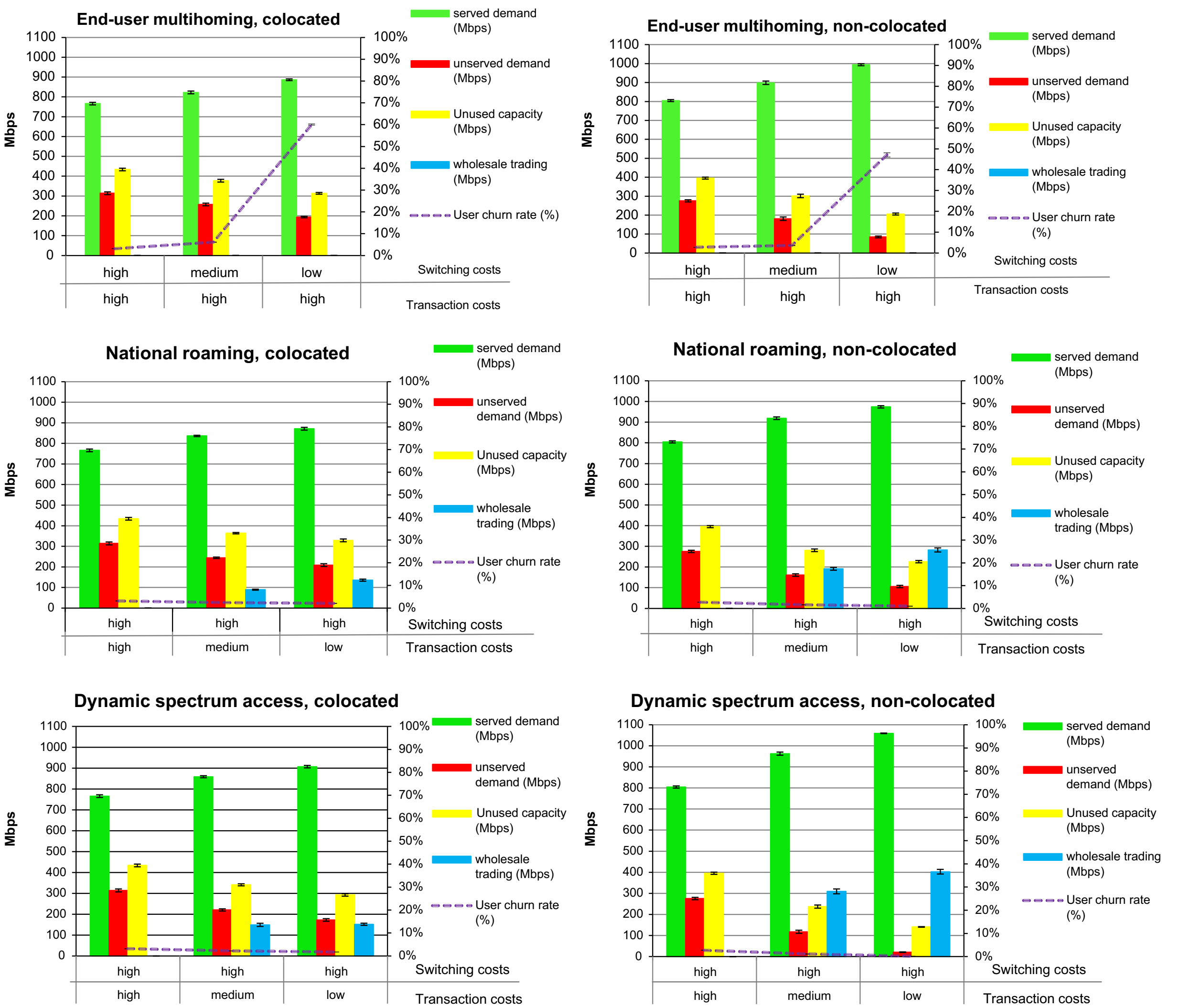


**Fig. 4.** Separate effect of decreasing transaction costs (national roaming, dynamic spectrum access) against switching costs (end-user multihoming) for colocated and non-colocated topologies.

direct interaction of end-users. In this scenario, each base station represent a local network deployed by femto-cells. Spectrum transactions are performed upon request, mediated by a broker. The broker considerably decreases bargaining and policing and procedural costs, even though it requires operational expenses from all participants. CA permits to aggregate bandwidth of different sizes, from 1.4 to 20 MHz, thus providing high flexibility in the amount of traded spectrum. The broker does not own spectrum, but only provides permission to a femto-cell network to transmit in such frequencies that are not utilized by adjacent networks. In a spectrum transaction, the involved base stations vary their throughput (in Mbps) proportionally to the amount of utilized spectrum. The simulation assumes that end-users are always identified by the home owner, who requests additional spectrum if needed.

See in Table 2 a summary of the definition of transaction and switching costs for the simulation. Note that the level of costs (high, medium, low) are not directly comparable between different mechanisms. However, the cost levels aim to match with the major cost reduction steps of each mechanism as enabled by technology.

In each simulation run, a cost and technology stage is tested by letting MNOs and end-users interact and learn from their environment. Different cost parameters are run separately to describe a market, which is evolving in time due to technology development. Thus, each evolution scenario representing the deployment of one mechanism consists of a set of runs, to describe an evolving market and agents interacting between them based on changing market conditions. Note that the transaction-based mechanisms (national roaming and dynamic spectrum access) are assumed voluntary and cooperative between MNOs. Alternatively, the regulator could drive end-user choice in national roaming or inter-MNO competition in dynamic spectrum access but these scenarios are not considered in the simulation.

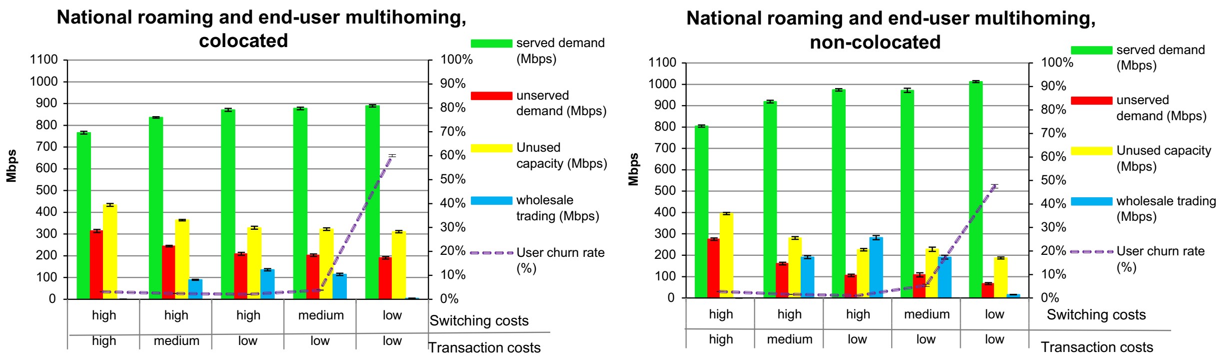


**Fig. 5.** Effect of decreasing both costs, first through national roaming and then though end-user multihoming, for colocated and non-colocated network topologies.

### 4.4. Simulation results

This section presents the simulation results based on the three mechanisms, that is, the effect of decreasing switching and transaction costs. The model and the obtained results are dynamic in two ways. Firstly, at each combination of parameters, end-users and MNOs are dynamically interacting between each other throughout the simulation, even though only the average values are being reported. Secondly, the results describe an evolution path by showing how the simulated market changes as a function of cost level.

Figs. 4 and 5 illustrate the achieved allocative efficiency (i.e. network capacity and spectrum utilization) when transaction and switching costs decrease.[22] The base stations can be colocated or non-colocated, as described in Fig. 1. The figures show the average amount of demand (in Mbps) which is being served and unserved; as well as the unused network capacity at each simulation iteration. In addition, wholesale trading refers to the amount of network capacity or spectrum traded (in Mbps) between MNOs, and user churn rate describes the average amount of users, in percentage (%), which switched from one MNO to another, at each simulation iteration. Note that the unit of the left y axis is Mbps (for the first four variables), while the unit of the right *y*-axis is % (for user churn rate). In addition, error bars are depicted for each average value and correspond to one standard deviation for each direction ($\pm$ standard deviation).[23] The total network capacity and the amount of assigned spectrum remain constant in time (the unlicensed spectrum is not considered). Each MNO has initially assigned 20 MHz and each base station has a capacity rate of 100 Mbps. Both spectrum and network capacity are traded, when transaction costs allow such trading.

Fig. 4 shows that all three mechanisms improve allocative efficiency, by increasing the served demand and decreasing the unused capacity, when the corresponding cost decreases, but the non-colocated topology is more efficient than the colocated for all mechanisms. This indicates that cooperative strategies between MNOs may have a positive impact on the allocative efficiency if the impact of possibly reduced competition is ignored. Fig. 4 also indicates that both end-user multihoming and national roaming reach a similar level of efficiency, although end-user multihoming is slightly more efficient. This is due to the ability of end-users to choose each time the best network, against a centralized mechanism to provide national roaming. Dynamic spectrum access is especially efficient for the non-colocated topology; however, this mechanism is not directly comparable with the other two, since the simulated femto-cellular deployment describes only indoor efficiency, while other mechanisms describe both indoor and outdoor. In any case, spectrum trading by means of LSA or similar mechanism may bring additional benefits in outdoor deployment as well, since it further increases the level of wholesale trading. Dynamic spectrum access requires that indoor base stations are open for all users; otherwise, base stations serving users belonging to one MNO lack the demand required for a spectrum transaction. Thus, the benefits of dynamic spectrum access are cumulative when combined with other mechanisms such as national roaming or end/user multihoming (see additionally Fig. 11 from Appendix III).

Appendix III shows a sensitivity analysis on the cost parameters for the analyzed mechanisms. Such analysis illustrates the criticality of each cost element for achieving higher efficiency. In fact, for end-user multihoming, the efficiency is obtained from the level of knowledge (i.e. automation) of the end-user device rather than from the speed of change. National roaming generates larger benefits in fragmented markets, however in such case it also demands more coordination

[22] At maximum allocative efficiency, the price of the last sold unit equals its marginal costs. We assume this condition holds under competitive market conditions, such as the one simulated. At this point, the production (i.e. network access) represent end-user preferences which varies in time and place. Additionally, allocative efficiency is increased on a dynamic basis (over time), therefore dynamic efficiency is also increased.

[23] Each simulation (combination of parameters) consists of 10 runs of thousand iterations each. For each run, average values were calculated. For each parameter combination, the final average values and their corresponding standard deviations were obtained from these 10 runs. As shown, the number of iterations is high enough to achieve small error margins, since the employed random walk algorithm does not describe end-user mobility patterns and thus it is not sensitive to the time of the day, but it is typically utilized for analyzing the performance of a system.

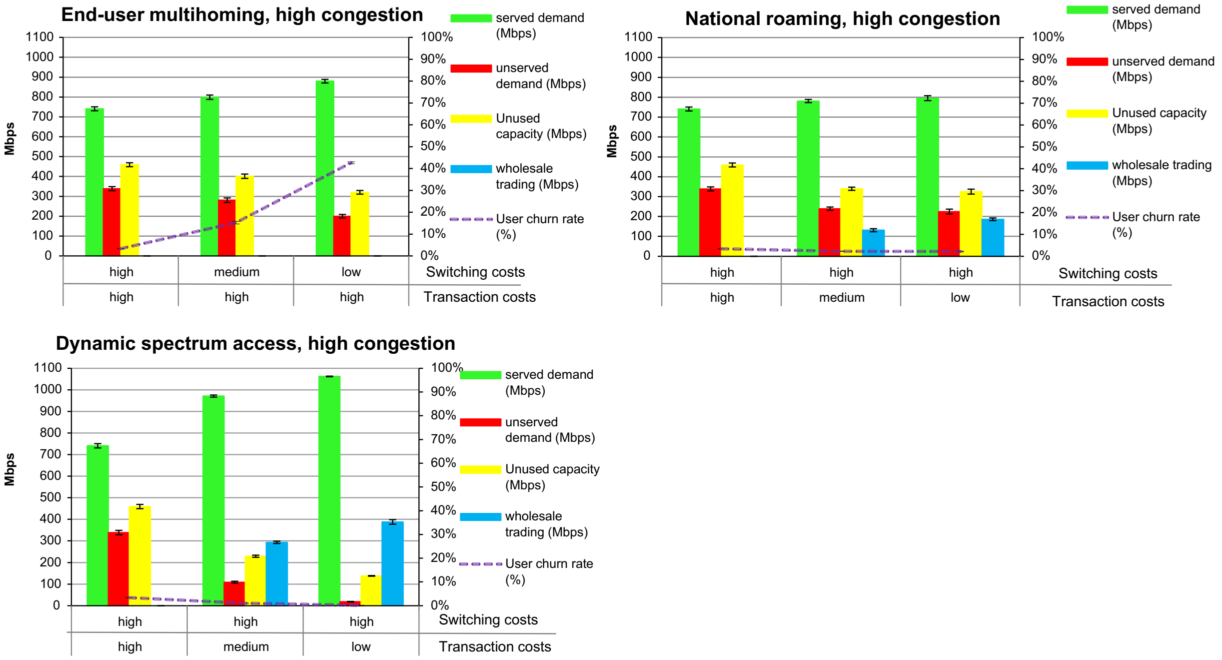


**Fig. 6.** Performance of the mechanisms for a high congestion case with non-colocated topology.

efforts. Finally, dynamic spectrum access requires short transaction times to increase efficiency, except in a high congestion case.

Fig. 5 depicts the impact of decreasing costs for both national roaming and end-user multihoming. This hypothetical case of combined mechanisms shows that the level of served demand is driven by the more efficient technology (the amount of served demand behaves as in the case of end-user multihoming in Fig. 4). This observation tells that the impact of these two mechanisms is not cumulative and that these mechanisms interact on the market. The figures demonstrate that the non-colocated topology reaches higher efficiency than the colocated one in the case of combined mechanisms. The behavior of wholesale trading and user churn rate curves is especially interesting. While wholesale trading achieves a high volume in the case of medium switching and low transaction costs, the user churn rate radically increases and wholesale trading decreases in the case of low switching costs. This is an indication of the high impact that a technology step, and its resulting cost reduction, may have on the market performance.

Finally, Fig. 6 shows the results for the non-colocated topology for a high congestion case. In this case the end-user mobility pattern is biased to the right (biased random walk[24]), so that end-users move randomly with a slight tendency toward the right side of the simulation area. This causes an area of high congestion on the right and an area of low congestion on the left. This set-up simulates a deviation in the end-user mobility pattern, such as an event, accident, etc. The results show that dynamic spectrum access reaches considerably higher efficiency when the end-user mobility pattern creates additional congestion, since spectrum is employed in those base stations which experience higher demand. Moreover, Appendix III (Fig. 11) indicates that dynamic spectrum access already generates efficiency with long transaction times, which further supports the suitability of this mechanism for high congestion scenarios. Additionally, end-user multihoming slightly outperforms national roaming in this case, in line with the previous results of Fig. 4.

The novelty of this simulation does not rely on the mere fact that resource allocation is improved by decreasing transaction or switching costs, but rather on the comparison of three real mechanisms, that are available in the market and are rarely compared. Thus, the novelty of the performed simulations relies on the elements utilized in the comparison: colocated versus non-colocated topology, competition versus cooperation, transaction versus switching costs. The simulation results provide a deeper understanding of their dynamics and address their strengths and weaknesses. Based on the simulation results, the following section provides further qualitative analysis on the overall benefits and challenges of each mechanisms. Appendix III performs a sensitivity analysis of other selected parameters; such as number of end-users, number of MNOs and location of base station. The purpose of this Appendix III is to validate the obtained results by showing how they vary with other parameters.

[24] See in Hughes (1996) a detailed explanation of biased random walk algorithm.

## 5. Discussion

The simulation results show that the allocative efficiency of a mobile market can be improved dynamically by adopting any of the three analyzed mechanisms. In other words, higher efficiency can be achieved by either decreasing switching or transaction costs, that is, by competition or cooperation. In general, under similar benefits, a regulator should favor end-user multihoming, since it is the easiest and cheapest mechanism. However, MNOs may prefer to cooperate, even though cooperative mechanisms demand coordination. Each mechanism may have finally different applications, for instance, dynamic spectrum access has the potential to solve congestion, while national roaming and end-user multihoming address especially coverage problems. Note that national roaming and end-user multihoming also alleviate congestion until certain extent, since end-user traffic is served by different networks at the same location; however, dynamic spectrum access performs better in a high congestion scenario. If end-user multihoming includes solutions based on MPTCP protocol, end-users may offload their traffic simultaneously into several networks, including Wi-Fi. In this case, end-user multihoming may be also an efficient congestion relief mechanism.

Even though this simulation model is relatively simple, and qualitative rather than quantitative, the results describe the general impact of the analyzed mechanisms on the dynamics of the mobile market. The relevance depends on the size of the improvement opportunity, that is, on the size of the quality difference between real MNOs. As a reference, empirical service quality measurements in Finland show that congestion and coverage disparity create significant momentary quality difference between MNOs (Sonntag, 2016). However, the main purpose of these simulations is to describe the dynamic behavior of the analyzed mechanisms and not to quantify the net benefits for concrete market cases. Therefore, the significance of the results relies on understanding the factors impacting the dynamic of each mechanism.

In general, regulators may be reluctant to introduce the proposed mechanisms because of their possible impact on industry dynamics. If MNOs achieve a high performance in terms of coverage, congestion and blackouts, the regulator has less incentives to introduce these mechanisms. Correspondingly, the regulator may consider new mechanisms if the market suffers from coverage disparities, high congestion and blackout problems.

These results further indicate that the level of colocation of base stations highly affects the efficiency attained by the analyzed mechanisms. Thus, colocation decreases the need for these mechanisms, while coverage disparities due to non-colocation increase the need. However, the overall impact of network topology depends also on other factors, since MNOs can colocate part of their base stations to reduce costs and to be able to increase coverage in other areas with higher demand in a non-colocated fashion. Typically, base stations can be non-colocated in urban areas, since base stations may be located at rooftops, while colocation is especially suitable for rural areas which have lower traffic demand. In any case, the clearest scenario for non-colocation is at indoor deployments, which highly differs from outdoor deployment; while outdoor networks are already deployed, indoor networks have not been yet deployed. From this perspective, new network deployment is typically driven through competition, while existing networks may increase their efficiency through cooperation. However, there are examples of the opposite case, such as rural deployment through infrastructure sharing. In general, a balanced combination of cooperation and competition is needed for indoor and outdoor deployments to achieve higher efficiency. These findings are in line with literature suggesting that if some cooperation enhances social welfare, the maximum degree of competition may not be efficient (e.g., Canegallo, Ortona, Ottone, Ponzano, & Scacciati, 2008). For indoor deployment, these mechanisms may be a suitable solution for addressing coverage and capacity disparities of small cells together with the challenges for developing a good business case; thus MNOs may have high incentives for the analyzed mechanisms in the indoor case.

These simulations analyze the mechanisms through concrete technical examples. In this way, it studies the linkage between the core dimensional aspects of mobile communications, namely user traffic, network capacity and spectrum. In the simulation, MNOs trade by leasing their own network capacity and own spectrum in a cooperative way. Consequently, their traffic market shares remain spectrum ownership limited and relatively stable as in the current MNO oligopoly markets. This situation would change if the spectrum ownership is relaxed, for instance through a 3rd party spectrum ownership or dynamic spectrum ownership. Table 3 summarizes the specific observations for each mechanism.

According to simulation results dynamic spectrum access attains the highest efficiency when network topology is non-colocated and congestion is high. However, in practice dynamic spectrum trading still faces significant technical challenges and may therefore take a longer time to enter the market. All three mechanisms behave similarly when network topology is colocated and congestion is lower, while end-user multihoming outperforms national roaming when topology is non-colocated. Additionally, when end-user multihoming and national roaming are simulated together, and both transaction and switching costs decreased at the same time, the efficiency is driven by the technology with higher performance and, in general, their effect is not cumulative. On the other hand, when dynamic spectrum access is combined with national roaming or end-user multihoming, the effect is cumulative, if it addresses a different problem (i.e. congestion). However, end-user multihoming may also address congestion if it is deployed through MPTCP. Note that these simulations are structural rather than quantitative and therefore cannot be used to find the optimal balance between cooperation and competition, or between the analyzed mechanisms. Although theoretically desirable, such an optimum point is dynamic and context-dependent. Thus, this study assumes that understanding the related dynamics maybe more important than searching for the optimum.

Each mechanism faces different strategic challenges. End-user multihoming is confronted with the reluctance of MNOs, since it stimulates retail competition. In addition, MNOs lose visibility to the whole user behavior and are forced to deploy new business models based on intense competition and metered pricing. However, MNOs are gradually losing the control of

**Table 3**
Summary of the simulation-based observations.

| Observations | Dynamic spectrum access | National roaming | End-user multihoming |
|---|---|---|---|
| **Simulation performance** | Most efficient in non-colocated topology and high congestion | In par with other mechanisms in colocated topology | Slightly more efficient than national roaming |
| **Main strategic challenge** | Business and technical coordination between MNOs | Trust between MNOs | Reluctance of MNOs |
| **Initial use case – indoors** | Extension to femto-cellular national roaming or end-user multihoming via inter-MNO CA | Cooperative femto-cellular deployment | Competitive femto-cellular deployment |
| **Initial use case – outdoors** | – | Coverage support for entrant MNOs. Security network with foreign SIM. | High-availability MVNOs, e.g. authorities, IoT applications |
| **Regulator's means to push mechanisms** | Set quality targets. Include trading in new spectrum licenses. Establish or act as a broker. | Set coverage targets. Include national roaming requirement in new spectrum licenses and regulate roaming prices. | Set coverage (and quality) targets. Push retail competition through unbundling of subscription and device. |

their customers through new smartphone applications based on data services; thus end-user multihoming may be seen as a continuation of the current evolution. For national roaming the main challenge is the trust required to deploy optimal routing and wholesale trading of capacity. This would turn MNO pricing more toward internet like pricing. In the case of dynamic spectrum access, fast trading requires high business and technical coordination compared to the current static spectrum usage. In general, spectrum trading seems more feasible for higher frequencies that require less coordination due to shorter propagation range and indoor use cases. Note that dynamic spectrum access presents a trade-off between coordination and quality of spectrum; coordination requirements are reduced in higher frequencies; however, lower frequencies possess better propagation characteristics.

As to the possible use cases, the analyzed mechanisms are especially promising for indoor deployments due to non-colocation and coverage disparity. Femto-cellular networks are typically deployed by a single MNO per indoor space. Indoors, national roaming may provide a cooperative mechanism for femto-cellular deployment, while end-user multihoming a competitive one. Dynamic spectrum access may serve as an extension of the cooperative national roaming deployment, providing additional network efficiency. In theory, it may also serve as an extension for end-user multihoming, but this may be challenging for MNOs since this scenario requires that MNOs compete at the same time for end-user traffic and cooperate for spectrum trading. However, as discussed, while national roaming and end-user multihoming especially solve coverage problems, dynamic spectrum access addresses better congestion.

In outdoor networks, national roaming may facilitate new MNO entrants by decreasing entry barriers related to infrastructure investment and nationwide coverage, but it may also serve to improve coverage for new applications demanding high availability, such as public safety and security. End-user multihoming may also be deployed for introducing high-availability services such as the mentioned public safety and security, for example, by means of a high availability MVNO service, or for supporting new IoT applications, for example, by facilitating a high quality connection in car applications.

## 6. Conclusions

The societal importance of mobile Internet is increasing. Although the current static market model based on vertically integrated MNOs is considered competitive, regulators are concerned about the market failures and inefficiencies related to blackouts, coverage disparities and congestion. This study indicates that the allocative efficiency can be improved dynamically by reducing the inter-MNO transaction and end-user switching costs as demonstrated. However, any of the three compared core mechanisms would cause a major change to the current market dynamics. Therefore, such improvements become necessary only if the current static market model cannot meet the increasing service quality requirements of regulators and end-users.

These simulations show that all three mechanisms can attain a significant increase in efficiency, especially in a scenario of non-colocated topology. This observation is particularly relevant for small cellular networks which may be the main use case for non-colocated deployment. From this perspective, the proposed mechanisms provide MNOs a feasible means for deploying such networks in indoor environment. This observation is important, considering the trend towards mobile offloading into Wi-Fi networks (as high as 46% of mobile traffic in 2014, according to Cisco (Cisco, 2015)). Thus these mechanisms may provide MNOs a feasible means to retain the end-user on their networks.

Even though all analyzed mechanisms increase allocative efficiency similarly and they are especially suitable for indoor deployment, each one may have different use cases. Dynamic spectrum access is especially suitable for a case with high congestion. In addition, a regulator should favor end-user multihoming to increase market competition, or national roaming in a case of a new entrant or otherwise if competition is high enough but the market suffers from coverage problems. In terms of deployment requirement, end-user multihoming is the least demanding, which make it the most attractive alternative for regulators. However, MNOs may still favor cooperation based on national roaming and dynamic spectrum access mechanisms.

From a regulatory perspective, congestion and blackouts can be reduced with sanctions which would improve MNO service quality (and increase prices) without affecting the current vertical market dynamics. Regulators could also seek quality improvements by promoting the cooperative inter-MNO trading mechanisms or the competitive end-user multi-homing, as demonstrated. A risk-averse regulator prefers traditional sanctions while a risk seeking one experiments with new mechanisms. The possibility for efficiency improvements fundamentally depends on the similarity of MNO network topologies. By encouraging base station colocation, a regulator can reduce the need for using the analyzed mechanisms. On the other hand, inter-MNO cooperation such as colocation tends to reduce competition, which again calls for competition enhancing instruments such as end-user multihoming. Because of complexity and context sensitivity the proposed mechanisms can be seen as tools for the regulator's toolbox rather than standard solutions.

This research analyzes three mechanisms in the context of two scenarios, colocated and non-colocated. Future research may for instance include a more detailed quantitative analysis of the improvement potential on real markets and of the cooperative mechanisms for small cell deployment.

## Acknowledgment

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## Appendices

### *Appendix I*

| Simulation parameters | |
|---|---|
| Number of MNOs | 3 |
| Number of base stations per MNO | 4 |
| Number of users | 72 (ITU-R document 5-6/180-E, Annex 2) |
| User traffic | Poisson distributed ~ Poisson (15) Mbps |
| Capacity of each base station | 100 Mbps (3GPP TR 25.814 V77.1.0) |
| Assigned spectrum for each MNO | 20 MHz |
| Simulation area | 2 km × 2 km |
| Coverage radius of each base station | 0.5 km |
| User randomly moves at speed | 2.5 km/h |
| Each iteration represents (1 tick equals to) | 3 min |
| Number of iterations per simulation run | 1000 (3000 min or approx. 2.1 days each run) |
| Number of runs per combination of parameters | 10 (30 000 min or approx. 21 days in total) |

### *Appendix II*

This appendix summarizes the data describing the level of transaction and switching costs for selected mobile markets. These tables have not been directly applied in the model but provide basis for parameter settings of the simulation.

List of selected countries with variables describing user switching costs[a]:

| **Countries** | Market concentration (HHI[b]) | Mobile monthly ARPU[c] (USD) | MNP (length in days) | Churn rate (% monthly) | Cellular investment per capita per year (USD) | Price (USD per minute) | Fraction of prepaid subscriptions (%) |
|---|---|---|---|---|---|---|---|
| Australia | 0.3002 | 48 | 1 | 1.90 | 47.56 | 0.19 | 44 |
| Brazil | 0.2452 | 13 | 3 | 3.10 | 13.32 | 0.54 | 82 |
| Canada | 0.2916 | 52 | 0 | 1.60 | 79.97 | 0.34 | 21 |
| Chile | 0.3311 | 17 | 1 | 2.80 | 44.27 | 0.36 | 73 |
| China | 0.4456 | 10 | NA | 3.30 | 28.93 | 0.16 | 87 |
| Denmark | 0.3074 | 36 | 1 | 3.70 | 58.60 | 0.09 | 15 |
| Finland | 0.3320 | 32 | 5 | 1.60 | 34.33 | 0.14 | 10 |
| France | 0.3200 | 36 | 3 | 2.00 | 54,.21 | 0.36 | 27 |
| Germany | 0.2845 | 23 | 6 | 2.20 | 37,.02 | 0.31 | 56 |
| India | 0.1857 | 3 | 7 | 5.80 | 6.05 | 0.04 | 95 |
| Italy | 0.2920 | 23 | 3 | 2.10 | 67.44 | 0.29 | 85 |
| Japan | 0.3477 | 84 | NA | 0.60 | 134.49 | 0.63 | 1 |
| Korea | 0.3868 | 31 | NA | 3.10 | 61.22 | 0.32 | 2 |
| Mexico | 0.5539 | 16 | | 2.90 | 5.93 | 0.27 | 88 |
| Netherlands | 0.3890 | 39 | 3 | 2.40 | 56.22 | 0.36 | 39 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| New Zealand | 0.5162 | 21 | 1 | 2.40 | 27.99 | 0.40 | 66 |
| Spain | 0.3248 | 33 | 5 | 2.30 | 45.53 | 0.32 | 41 |
| Sweden | 0.3102 | 18 | 5 | 1.40 | 32.98 | 0.17 | 38 |
| United Kingdom | 0.1726 | 17 | 1 | 2.70 | 44.93 | 0.20 | 59 |
| United States | 0.2473 | 47 | 0 | 1.80 | 77.91 | 0.39 | 22 |

[a] Sources: OECD Communications Outlook, 2011 (OECD, 2011), ITU-D (2012), Global Wireless Matrix, 2011, ITU (2014a,b) and TRAI (2007).
[b] HHI index can be calculated as follows: HHI=s1\widehat2+s2\widehat2+s3\widehat2+…+*sn*\widehat2 (where *sn* is the market share of the *i*th firm).
[c] Average revenue per user.

List of selected countries with variables describing transaction costs.

| Countries | Separation of network and service operators | Termination rate (USD) | Number of MNOs | Technology neutrality | Reselling rights | Infra sharing (active elements) | Infra sharing (passive elements) | Number of MVNOs |
|---|---|---|---|---|---|---|---|---|
| Australia | No | 0.0930 | 3 | No | Yes | Yes | Yes | 40 |
| Brazil | No | 0.1839 | 5 | Yes | No | No | Yes | 2 |
| Canada | No | 0.0000 | 5 | Yes | Yes | Yes | Yes | 11 |
| Chile | No | 0.1650 | 4 | No | No | No | Yes | 6 |
| China | No | 0.0096 | 3 | Yes | No | No | Yes | 11 |
| Denmark | Yes | 0.0629 | 4 | Yes | Yes | No | Yes | 1 |
| Finland | Yes | 0.0625 | 3 | No | No | Yes | Yes | 1 |
| France | Yes | 0.0426 | 4 | No | Yes | No | Yes | 18 |
| Germany | Yes | 0.0477 | 4 | No | No | Yes | Yes | 2 |
| India | No | 0.0044 | 10 | Yes | No | No | Yes | 1 |
| Italy | Yes | 0.0938 | 4 | No | No | No | Yes | 15 |
| Japan | No | 0.1126 | 3 | Yes | No | No | No | 0 |
| Korea | No | 0.0285 | 3 | Yes | No | No | No | 0 |
| Mexico | No | 0.0327 | 5 | Yes | No | No | Yes | 0 |
| Netherlands | Yes | 0.0597 | 5 | No | Yes | No | Yes | 50 |
| New Zealand | No | 0.0570 | 3 | No | Yes | No | Yes | 7 |
| Spain | Yes | 0.0568 | 4 | No | Yes | Yes | Yes | 20 |
| Sweden | Yes | 0.0421 | 4 | No | Yes | Yes | Yes | 3 |
| United Kingdom | Yes | 0.0429 | 4 | No | Yes | Yes | Yes | 30 |
| United States | No | 0.0007 | 6 | Yes | Yes | No | Yes | 43 |

## *Appendix III*

This appendix shows a sensitivity analysis of the simulation model developed in this paper. Parameters that affect the increase in efficiency (i.e. number of users, number of MNOs and location of base stations) are varied with the intention of validating the obtained results and conclusions. The analysis is presented in Figs. 7–12.

Firstly, Fig. 7 depicts the obtained results for different number of end-users, while the cost parameters remain constant (low switching costs and high transaction costs). This figure shows that both served and unserved demand increase with the

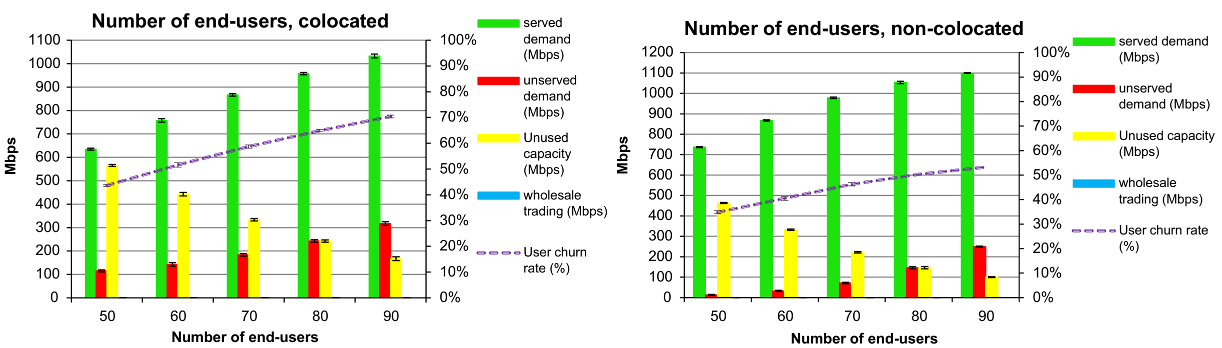


**Fig. 7.** Sensitivity analysis: number of users for low switching costs (multi-homing) and high transaction costs.

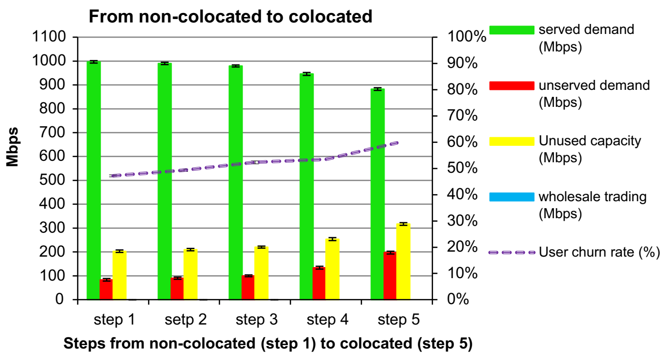


**Fig. 8.** Sensitivity analysis: location of base stations, from non-colocated to colocated.

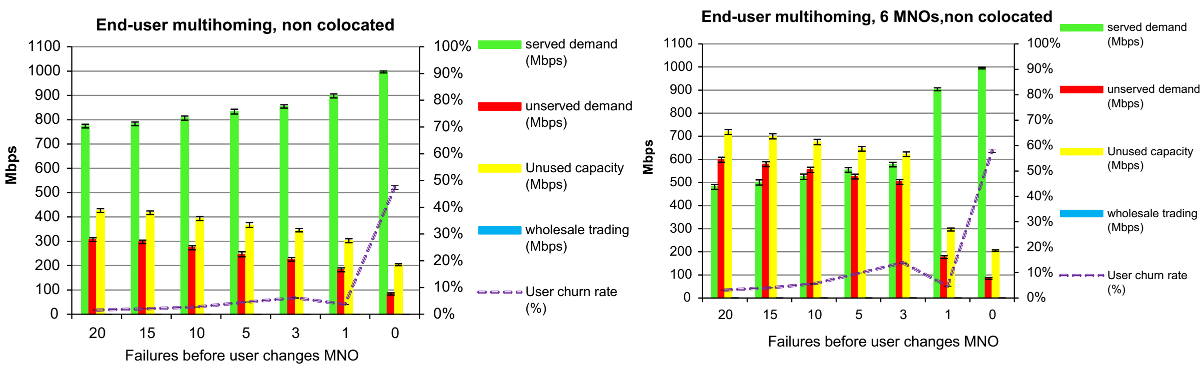


**Fig. 9.** Cost sensitivity analysis for end-user multihoming.

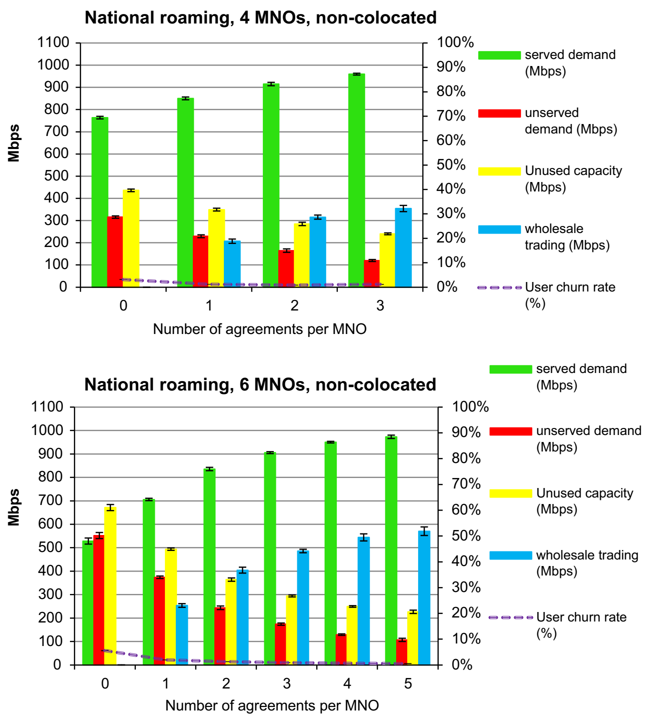


**Fig. 10.** Cost sensitivity analysis for national roaming.

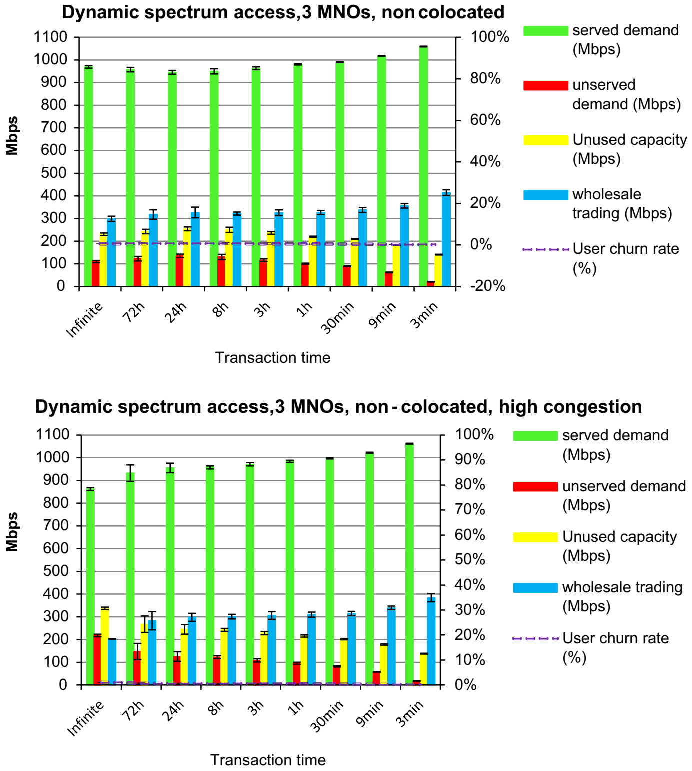


Fig. 11. Cost sensitivity analysis for dynamic spectrum access. Infinite means there is no transactions.

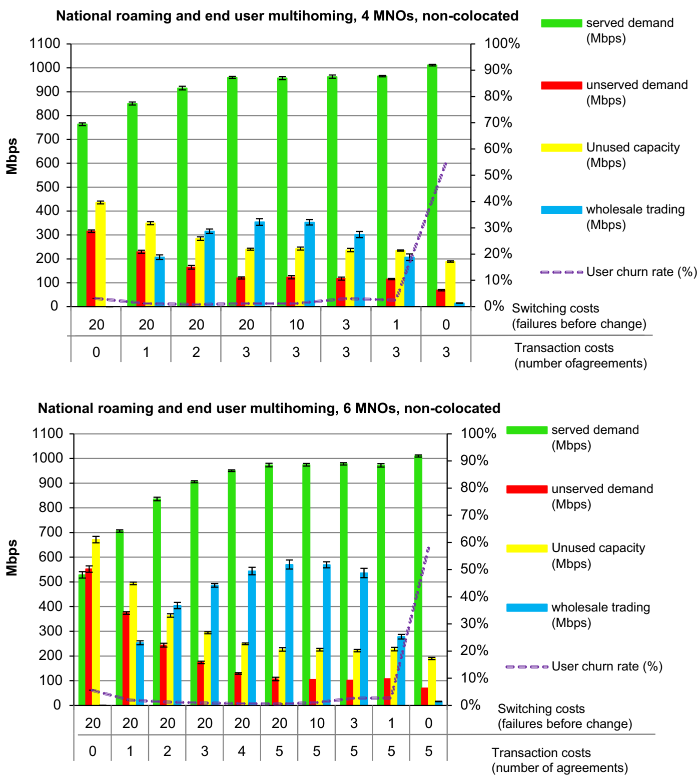


Fig. 12. Cost sensitivity analysis for national roaming and end-user multihoming.

number of end-users. While the optimal level of available capacity will depend on strategy decisions, this figure corroborates that the assumption of 72 end-users is a suitable number for allowing a sensitivity analysis of cost and other parameters.

Secondly, Fig. 8 shows a sensitivity analysis for the location of base stations, given that this parameter highly impact the performance of each mechanism. In this figure, base stations are gradually moved from a non-colocated setup to a collocated one, in five steps. The results provide further insights on the location criticality of base stations.

Figs. 9–11 perform a sensitivity analysis of cost parameters for each mechanism. Given that the non-colocated case showed higher variation, the following sensitivity analysis focuses on such case. Fig. 9 depicts the cost evolution for end-user multihoming, in which switching costs are measured by the number of failures after which the end-user changes from one MNO to another. From 20 to 3 failures, the end-user chooses a new MNO randomly. When number of failures equals 1, the end-user changes to the nearest base station, based on previous knowledge on the location of base stations. When the number of failures equals zero, the device constantly chooses the base station with lowest congestion. This figure evidences that end-user multihoming attains high efficiency when the end-user is able to decide on the network to access with high level of information and automation (i.e. 1 and 0). A random access does not provide high efficiency since the end-user is not aware on the quality of the network and on the location of base stations. The availability of information becomes more important when the mobile market is more fragmented (higher number of MNOs, such as illustrated by the figure) and the quality of the networks shows variations.

Fig. 10 illustrates a cost sensitivity analysis for national roaming. In this case, the involved transaction costs are described by the number of roaming agreement each MNO has. These costs change with the number of MNO in the market, and therefore Fig. 10 shows the results for four and six MNOs, each case maintaining the same number of base stations (and total network capacity). This analysis shows that while the benefits of national roaming are higher with a higher number of MNOs, decreasing the associated transaction costs is more demanding, since it requires higher coordination (i.e. more steps).

Fig. 11 presents a cost sensitivity analysis for dynamic spectrum access. In these graphs, indoor small-cellular networks require that base stations are open for all users; thus, the starting point, where transaction time is infinite, equals national roaming in allocative efficiency. This figure evidences that dynamic spectrum access is especially efficient with high congestion. Under a low congestion scenario, the benefits of this mechanism requires a short transaction time; in fact, when transaction time decreases to 8 h, the efficiency even lightly diminishes. For a high congestion scenario, the efficiency increases also with larger transaction times.

Finally, Fig. 12 illustrates a sensitivity analysis of cost parameters for the combination of national roaming and end-user multihoming; with four and six MNOs. Comparing with Fig. 5 (the base case with 3 MNOs), these results evidence that the higher the number of MNOs, the higher the impact these mechanisms have on allocative efficiency, since lowering transaction or switching costs provide end-users more access choices, especially to those belonging to a smaller MNO. Note that a high number of MNOs (e.g. 6) evidences high market fragmentation and therefore it demands higher coordination for decreasing transaction costs. In addition, this figure corroborates that these two mechanisms are not cumulative and that the most efficient mechanism drives the results.

This analysis may also be employed for applying to other cases; for instance, rural versus urban areas. However, this study is not intended to provide all possible combinations. The purpose of this paper is to show the main elements determining the efficiency of each mechanism. Additional simulation effort can emerge as future research.

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