PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE
SCHOOL OF ENGINEERING

ON THE DEADLINE MISS PROBABILITY OF ROUTING METRICS

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Thesis submitted to the Office of Research and Graduate Studies
in partial fulfillment of the requirements for the degree of
Master of Science in Engineering

Advisor:
CHRISTIAN OBERLI

Santiago de Chile, January 2021

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To my parents and grandparents

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ABSTRACT

Many time critical applications require that the measurements of a wireless sensor network (WSN) comply with a deadline requirement. Examples of these applications are early warning systems, where the measurements must arrive within a predefined time in order to be useful.

In this work, a model is presented to characterize the delay experienced by the measurements with focus on the role of the routing metric in those delays. Using the link delay statistics we are able to calculate path delay and node delay statistics. For the general case of networks that work with a deadline-aware routing table, an algorithm to calculate the end-to-end delay probability density function (PDF) of nodes is developed.

With this resources we are able to compare the performance, in terms of deadline miss probability, of a range of routing metrics. Although this work is focused on WSN, it can be applied to compare the performance of any type of network with costs associated to its edges.

Keywords: Mesh networks, Probability density function, Real time systems, Routing protocols, Wireless sensor networks.

RESUMEN

Muchas aplicaciones críticas de tiempo requieren que las medición realizadas por una Red Inalámbrica de Sensores (RIS) cumplan con un requerimiento de *deadline*. Ejemplos de estas aplicaciones son los sistemas de alerta temprana, donde las mediciones deben llegar dentro de un tiempo predefinido para ser útiles.

En este trabajo, se presenta un modelo para caracterizar los retardos experimentados por las mediciones con foco en el papel de la métrica de enrutamiento en estos retardos. Con las estadísticas de retardo de enlace podemos calcular estadísticas de retardo de los caminos y nodos. Para el caso general de redes que funcionan con una tabla de ruteo *deadline-aware*, se desarrolla un algoritmo para calcular la función de densidad de probabilidad (FDP) del retardo *end-to-end*.

Con estos recursos podemos comparar el desempeño, en términos de *deadline miss probability*, de una serie de métricas de ruteo. Pese a que este trabajo está enfocado en RIS, puede ser aplicado para comprar el desempeño de cualquier tipo de red con costos asociados a sus enlaces.

Palabras Claves: Redes, Función de densidad de Probabilidad, Sistemas en Tiempo Real, Protocolos de enrutamiento, Redes Inalámbricas de Sensores.

1. EXTENDED INTRODUCTION

1.1. Context

Wireless sensor networks (WSN) are often envisioned as a tool for monitoring distributed systems and environments. Data gathered at remote nodes is relayed in multiple hops across the network towards a sink node, which typically uploads the data to a server in the cloud where it is jointly processed (Figure 1.1).

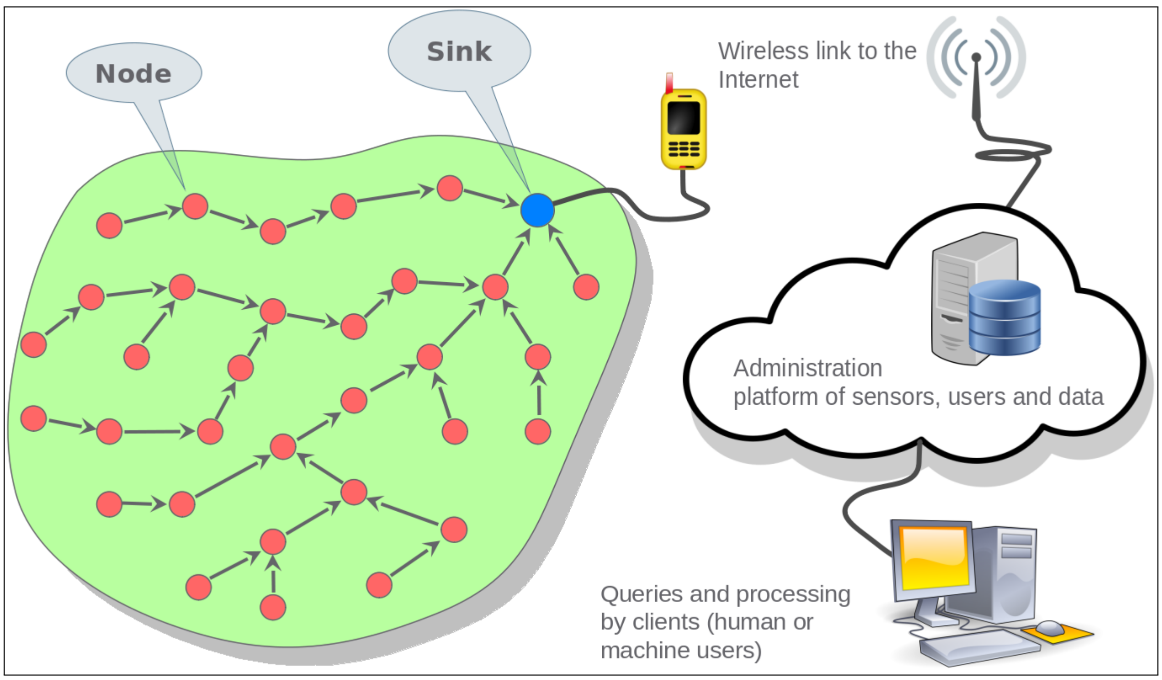

FIGURE 1.1. Diagram of a Wireless Sensor Network.

Real-time communication is in the heart of early warning systems of natural disasters, because it is about relaying observations from the place where conditions for a disaster build up (e.g. heavy rain in the mountains) to where predictions of the potential disaster, based on those observations, need to be known in advance (e.g. populated areas in the valley). This must happen in a shorter time than the propagation time of the disaster event itself, and therefore imposes deadline-type latency requirements on the communication component of the early warning system.

As an example, the Wireless Technology Laboratory of the Pontificia Universidad Católica de Chile (LatinaUC) has been operating a WSN for early monitoring of flash floods since 2014. The network is composed by 17 stations (Figure 1.2) located in the Quebrada de Ramón (QR) basin at the foothills of Santiago, Chile, at elevations between 878 and 2962 m.a.s.l (meter above sea level). The sensor nodes measure various hydro-meteorological variables every 10 minutes. The measurements are relayed over the network in multiple hops using the Sensorscope communication protocol stack (Barros, 2013; Barrenetxea et al., 2008; Ingelrest et al., 2010) to a sink node with cellular communications access that uploads the data to the cloud. In the QR network, measurements must reach the sink within 30 minutes to be useful for early warning.

FIGURE 1.2. WSN located in the Quebrada de Ramón (QR) basin at the foothills of Santiago, Chile.

Evidently, features in all layers of the protocol stack of a communication system impact a system's latency characteristics. However, careful thought allows for arguing that the design choices made in the first three layers —physical, data link control and networking layers (Haykin, 2001)— impact it the most. Assuming however that the physical medium and the medium access control mechanisms are restricted for cost reasons to radio devices that comply with some IoT standard (e.g. IEEE 802.15.4), then the networking layer is the only one left with a real offering of design choices for latency control.

1.2. Problem and motivation

We are interested in studying the probability of meeting or missing a deadline for data flowing from sensor nodes to a sink node. We will particularly focus on the role that the routing metric plays in this probability.

A number of routing metrics consider the goal of minimizing the mean end to end delay. This, however, does not ensure maximum probability of meeting a deadline. For example, a path P_1 may have a smaller expected delay than a path P_2, but a larger delay variance. This can cause that the probability of missing the deadline is larger for P_1 than for P_2 even though the expected delay of P_1 is smaller (Fig. 1.3).

Deadline-aware considers all routing policies that seek to deliver data from a source to a destination node within a deadline, maximizing the probability that the delay is below a given threshold. For this, it is key to consider the probability density functions of paths delays (illustrated in Fig. 1.3) for routing decisions.

In this work, a probabilistic model to characterize the delay experienced by measurements from sensing nodes to the sink node is proposed. With this model the end-to-end delay PDF of each node, and its Deadline Miss Probability (DMP), i.e. colored area in Figure 1.3, can be calculated. This probability will allow to compare the expected performance of different routing metrics in terms of percentage of measurements that miss the deadline.

1.3. Objectives

The general objective of this work is to study the delay experienced by the measurements from sensing nodes to the sink node and the influence of the routing metrics on those delays. The specific objectives are:

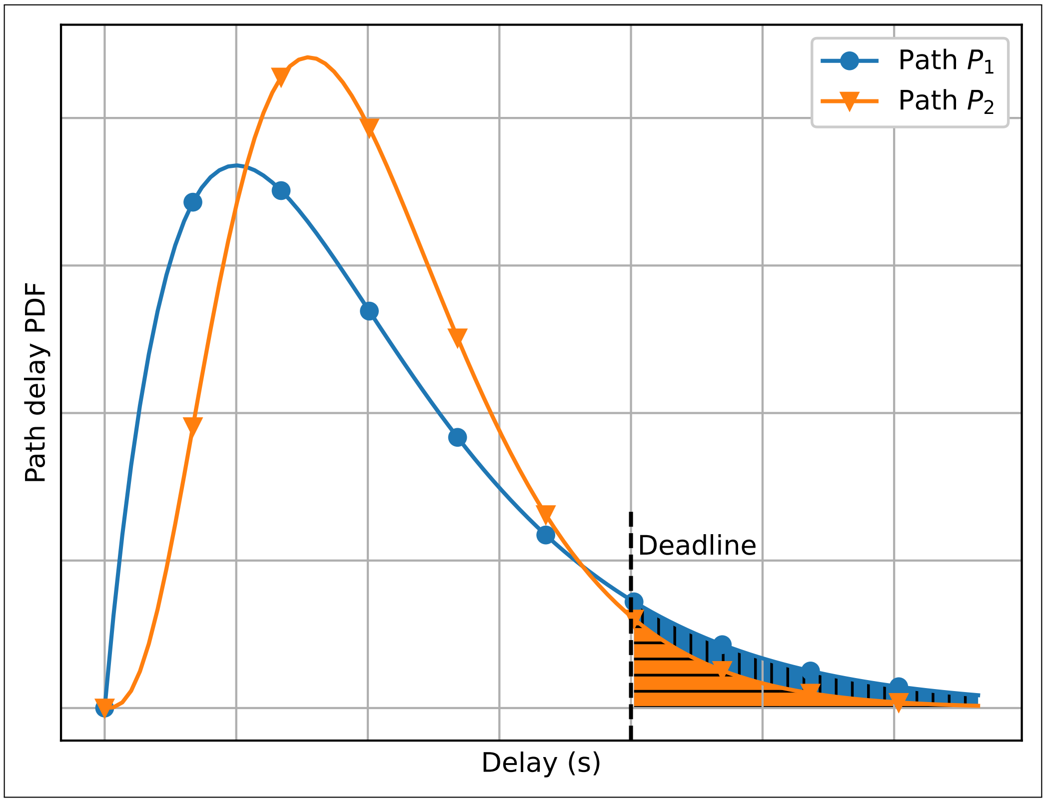

FIGURE 1.3. The Deadline Miss Probability (DMP) is larger for P_1 than for P_2 even though the expected delay of P_1 is smaller.

- Use link delay statistics to model the delay from the sensing nodes to the sink node.
- Apply this model to different routing metrics and compare their performance according to the deadline miss probability.

1.4. Related works

The following subsections present work related to this thesis. First a review of routing metrics applied to wireless sensor networks is made. Then, works related to delay modeling in wireless sensor networks are presented.

1.4.1. Routing metrics

The main task of the networking layer is to route traffic across a network according to given rules established in the *routing protocol*. Routing protocols for WSN, and their corresponding metrics, are a widely studied topic. The literature is vast and we do not attempt to cover it comprehensively here. Surveys (Al-Karaki & Kamal, 2004; Abdullah & Ehsan, 2014; Singh & Singh, 2016; Sarkar & Murugan, 2016; Echoukairi, Bourgba, & Ouzzif, 2016; Shabbir & Hassan, 2017; Arat & Demirci, 2020) provide a good overview about it.

Quality of service (QoS) plays a significant role in wireless sensor networks. Within the parameters that are used to study QoS we find: Energy efficiency, network lifetime, delay, network throughput, among others (Sarkar & Murugan, 2016). Classifications of routing protocols by their QoS can be found in (Sarkar & Murugan, 2016; Asif, Khan, Ahmad, Sohail, & Singh, 2017; Arat & Demirci, 2020). Due to distributed nature, dynamic topology and resources constraints of tiny sensing nodes satisfying the stringent QoS requirements is an open problem (Asif et al., 2017). Our interest is on routing policies that consider latency restrictions. More specifically, our interest is in minimizing the number of packets that do not meet their deadline. This metric is generally known as Deadline Miss Ratio (DMR). It is also worth noting that DMR is related to Measurement Delivery Ratio (MDR) in (Guerrero, 2020). Concretely, MDR and DMR are statistical complements, although DMR is measured at the network layer, whereas MDR includes statistics from sensors and hardware failure.

In general, *time-aware* routing approaches seek to find paths between two nodes whose average delay is minimized (or at least bounded) by some metric. Perhaps the simplest approach is to choose the paths with minimum hop-count to the destination, as a proxy for minimum path delay, because smaller hop counts certainly correlate with shorter path delays, but it is clearly no guarantee for it.

Couto et al. show in (De Couto, Aguayo, Bicket, & Morris, 2003) the poor performance, in terms of throughput, of the minimum hop-count metric and introduce the *expected transmission count* metric (ETX). ETX is the predicted number of transmissions (including re-transmissions) that must be made along a path until a packet is delivered successfully to the final destination. The ETX of a link is calculated using the forward and reverse delivery ratios of the links,

$$\mathrm{ETX} = \frac{1}{d_f \cdot d_r}, \tag{1.1}$$

where delivery ratios are estimated by counting the number of probes received from the total sent in a time window. For routing, the ETX metrics are accumulated link-by-link by flooding from the sink node into the network. Each node compares the cumulative ETX metrics received from its neighbours and uses them to determine the path to the sink along the neighbour with smallest cumulative ETX.

In similar fashion, Munir et al. propose in (Munir et al., 2010) to use statistics of failed vs. successfull transmissions in a time-slotted schedule in order to capture the burstiness of individual links (the $B_{\max}$ metric). A less bursty route is then associated with fewer re-transmissions, and a bound on the end-to-end average latency is established. This, in turn, is used for choosing low-delay routes. This metric routes considering the worst-case scenario. Although this way of routing delivers robust results, it is generally not the best choice between robustness and performance (Gürsu & Kellerer, 2017).

The term deadline-aware has been used in work on scheduling, e.g. for 5G (Monhof, Haferkamp, Sliwa, & Wietfeld, 2018) or Edge Computing (Meng, Tan, Li, Han, & Li, 2020). Similar ideas have been proposed for real-time traffic management in WSNs in order to prioritize and discard packets based on the remaining deadline and the probability of it being met (Karenos & Kalogeraki, 2006). However, not many works exploit the deadline-awareness for routing.

One of the most popular protocols that was designed to improve DMR (deadline-aware) is SPEED (Tian He, Stankovic, Chenyang Lu, & Abdelzaher, 2003). Real-time communication is achieved by maintaining a desired delivery speed across the sensor network through a combination of delay estimation scheme, feedback control and non-deterministic geographic forwarding (Tian He et al., 2003). The relay speed of the neighbour j of a node i is calculated as:

$$\text{Speed}_i^j(Destination) = \frac{L_i - L_j}{HopDelay_i^j}, \tag{1.2}$$

where L_i and L_j are the geographic distance from the i and j node, respectively, to the destination (e.g. the sink node). $HopDelay_i^j$, on the other hand, is the estimated delay between node i and j. Then, all neighbors who satisfy $\text{Speed}_i^j(Destination) > \text{S}_{\text{setpoint}}$ are selected as forwarding candidates, where $\text{S}_{\text{setpoint}}$ is a system parameter that depends on the communication capability of the nodes and desired traffic workload a sensor network should support. The forwarding node is chosen from this candidates, and the neighbor node with highest relay speed has a higher probability to be chosen as the forwarding node.

Though SPEED is a real-time protocol, the deadline is not used for the routing decision. Variants to this protocol have been proposed to use two-hop (Li, Chen, Song, Wang, & Sun, 2009) and multi-hop (Jung, Park, Lee, Oh, & Kim, 2010) information.

A deadline-aware protocol is proposed in (Bhuyan & Sarma, 2015), which uses the remaining deadline and the average delay of the links to choose the path used. The provided speed, V_{prov}, of a relay node is calculated for each neighbour node, similar to how it is calculated in SPEED. But in this case the required speed, V_{req}, is a function of the remaining deadline at each forwarding node:

$$V_{req} = \frac{d(n_i, Destination)}{t_l}, \tag{1.3}$$

where $d(n_i, Destination)$ is the geographical distance between the node and the destination and t_l is the time left to meet deadline. A neighbor node will be selected as a forwarding node if the provided speed, V_{prov}, is greater than or equal to required speed, V_{req}, and the forwarding node is closer to the destination with respect to the current node.

Several authors have modeled the wireless channel from a probabilistic perspective. In (Oliver & Fohler, 2009) Serna and Fohler model the distribution of latency of a link with mean and variance using an exponential weighted moving average. Applying the central limit theorem, they add these values to model the end-to-end delay distribution of a path as a Normal distribution. The work of Jang et al. (Byeong-Hoon Jang, Sunghwa Son, & Park, 2017) highlight the importance of modeling path latencies as *probability distributions* and not just as the sum of deterministic edge delays (or weights) along the path, as in classical graph theory. They propose that, applying this principle, is possible maximize the probability of packet arrival within the deadline.

As a convergence of the probabilistic perspective and deadline-aware routing, an approach called JLAT is presented in (Gürsu & Kellerer, 2017) by Murat and Kellerer. This metric seeks to be a midpoint between the ETX metric (De Couto et al., 2003) and $B_{\max}$ (Munir et al., 2010). The JLAT algorithm takes the Probability Density Functions (PDFs) of the links that form a path and generates the Joint LATency (JLAT) PDF of the entire path. The authors propose to select the path that has the largest probability of meeting a given deadline. Although JLAT is an interesting contribution towards achieving networks that meet deadlines, its model is unrefined and the idea is not fully exploited. Furthermore, while JLAT presents an interesting concept, its implementation in a WSN is difficult due to its centralized nature in contrast to the distributed algorithms that are preferred in these applications.

1.4.2. Delay models

Several works have been done to capture the delay statistics in a WSN. In (Chen, Peterson, Mainland, & Welsh, 2008) LiveNet, a set of tools and techniques for reconstructing complex dynamics of live sensor network deployments, is described. In (Abu Ali, Ekram, Eljasmy, & Shuaib, 2008) they made measurements of the link delay in a wireless network. They concluded that 90% of the times the best fit was obtained with a Gamma or Logistic distribution. In (Jurčík, Koubâa, Alves, Tovar, & Hanzálek, 2007) a simulation model for the IEEE 802.15.4 protocol is proposed for the evaluation of delay and throughput. In (Xie, Zhang, Su, Wang, & Zeng, 2014) simulations are run to estimate the network topology change, routing overhead and average packet End-to-End Delay of three routing protocols. In (Chaudhary & Waghmare, 2012) a mathematical model for end-to-end delay analysis is developed and the result are verified on NS-2.

Bianchi in (Bianchi, 2000) provides an analytical model to compute IEEE 802.11 throughput using a Markov chain. Raptist presents in (Raptis, Banchs, & Paparrizos, 2006) a delay distribution analysis for IEEE 802.11 based on the work of Bianchi. A generalized analysis of the IEEE 802.15.4 medium access control (MAC) protocol in terms of reliability, delay and energy consumption is presented in (Park, Di Marco, Soldati, Fischione, & Johansson, 2009). A similar analysis is performed in (Yang & Heinzelman, 2012) for duty-cycled MAC protocols.

With regard to an end-to-end delay analysis, (Y. Wang, Vuran, & Goddard, 2012) presents a generic cross-layer analysis of the end-to-end delay distribution. The model employs a stochastic queueing model, using Markov chains, in realistic channel environments and one-hop delay distributions are convolved to calculate the end-to-end delay distribution. In (J. Wang, Dong, Cao, & Liu, 2015) the performance in terms of delay in a large scale WSN is analysed. For this purpose, a lightweight delay measurement method for WSNs without time synchronization is introduced. A model to capture the factors that impact delay performance is proposed and validated. In (He, Liu, Zheng, & Yang, 2010) a calculus based on frequency domain analysis is developed to compute the end-to-end delay distribution. The main advantages of the proposed framework over the traditional time-domain approaches include the capability to capture higher order moments of system characteristics, scalability to analyze the reliability of complex systems, efficiency in calculation and practicability in simulation.

Despaux in (Despaux, 2015) propose a methodology to infer a Markov chain by analysing the execution traces of a given MAC protocol. Since this Markov chain is obtained by analysing the execution traces, factors like the impact of the underlying operating system are taken into account, an issue not considered in existing analytical models. This methodology is applicable to any underlying MAC protocols does not make any assumption regarding the distribution of the packet arrival. Hence, this approach allows to model the behavior of intermediate nodes without strong assumptions on the packet arrival distribution. Then using the model proposed in (He et al., 2010), the end-to-end delay distribution is composed. A generalization of this approach based on non-linear regression techniques that allows us to estimate the end to end delay for unknown arrival rates is also presented.

1.5. Contributions

In this work:

(i) We developed a mathematical model for the delay statistics of the end-to-end delay of nodes in a network.

(ii) We used this model for calculating the deadline miss probability of various routing metrics.

(iii) A general algorithm for calculating the delay statistics of deadline-aware metrics that use routing tables is presented.

(iv) A comparison of the performance of various routing metrics was made through a example.

1.6. Conclusion and future work

An analysis of the end-to-end delay of networks was made in this work. For this, a model to characterize those delays was developed. Also, an algorithm to calculate the end-to-end delay PDF of nodes that work with a routing table is presented. With this delay PDF, the deadline miss probability of several routing metrics can be calculated for comparison in time-critical applications.

Much work remains to be done with respect to time-critical networks. Some ideas for future work are briefly discussed below.

1.6.1. Development of a distributed routing metric to improve DMR

In this paper the performance of the JLAT metric was analyzed with respect to its DMP. Moreover, a version with optimal path updates was also analyzed, obtaining improvements of up to 5% of DMP in a toy example (Fig. 1.4).

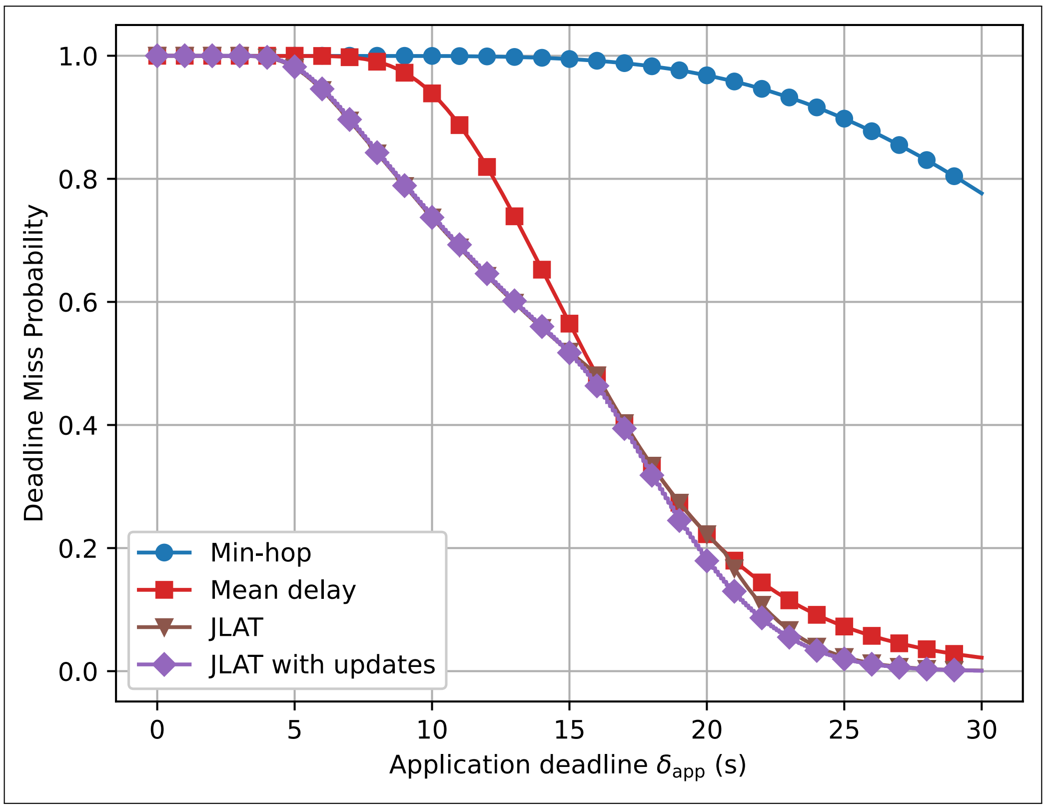

FIGURE 1.4. Deadline Miss Probability (DMP) in a toy example for each routing metric.

Although the performance of this metric is better than the average min-hop and delay, its implementation is challenging in practice and possibly unfeasible in a network with more than a few nodes. This is because the calculation of the metric does not occur in a distributed manner at each node. The development of a distributed version of JLAT would allow to achieve a good DMP with a feasible practical implementation.

1.6.2. Improvement of the model and algorithm

Another point of work is to extend the model presented in this work to consider statistical dependence of delays (inevitable in congested networks) and temporal variations of their statistics. This extended model could cover more cases than the current model. In fact, the model developed in this work would end up being a particular case where the link delays are independent and invariant in time.

Many questions about convergence, accuracy and practical implementation still need to be analyzed for the model and algorithm. Methods to estimate link delay PDFs, either through parameter estimation or histograms, must be studied and implemented to measure the accuracy of the model.

1.6.3. Apply the model to evaluate robustness

The model presented in this work allows to calculate the DMP of nodes in a network. This makes possible to evaluate families of network topologies and contrast the results. At the same time, as it was done in this work, it is possible to evaluate the performance of several routing metrics for a given network. This application of the model can lead to interesting results such as obtaining routing metrics that work better in certain families of networks than others, for example.

Also by slightly changing the topology of a network, for example by removing a link or a node, the variation in performance that this change produces could be evaluated. This exercise, again, could be performed for various network families and routing metrics. In this way, the robustness of these networks and metrics under connection failures could be evaluated.

1.6.4. Application of this work to other types of networks

Applications in other areas, such as operational research, could benefit from this work. For example, applying the concept of network with:

(i) nodes representing phases of a production process,

(ii) the sink representing the successfully completed process and

(iii) the links representing some random cost (e.g. man-hours).

With our model applied to the network described above, an analysis of costs and which path (i.e. production process) provides the smallest probability of exceeding the budget could be obtained. Many other applications to different areas can be explored and exemplified in future work.

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On the Deadline Miss Probability of Various Routing Policies in Mesh Networks

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ABSTRACT Moving data or goods across networks is often subject to deadline requirements. Examples are delivering people or goods at a destination location by a given time, and early warning for disasters of natural origin, where sensor measurements at the disaster location must be communicated across a network within a predefined maximum delay in order for a consequent warning to be timely. In this work, we present a probabilistic model that allows for characterizing the delay experienced from source to sink by the transported goods in a network depending upon the routing metric used for directing the goods through the network. Using link delay probability distributions and the probabilities of following different paths to the sink, source-to-sink delay distributions are found for routing policies based on minimum hop-count, minimum mean delay and the JLAT protocol. For the general case of networks that use routing tables whose input for routing decisions is the remaining time-to-deadline, an algorithm for calculating the end-to-end source to sink delay probability density function (PDF) is presented. With these results we illustrate the deadline miss probability of the various routing approaches by means of an example. This work provides a general tool for routing policy analysis that allows for comparison of the deadline miss probability of various routing policies.

INDEX TERMS Mesh networks, Probability density function, Real time systems, Routing protocols, Wireless sensor networks.

I. INTRODUCTION

CONSIDER a mesh network with nodes connected by edges. All nodes may be sources of goods, which are relayed from node to node in multihop fashion along the edges with the goal of moving the goods from their respective source nodes to destination nodes. Any node may be a destination node, but for simplicity and without loss of generality we will focus on delivering the goods to one specific *sink node*. The goods must reach the goods by a deadline. We are interested in the probability of missing the deadline.

It is evident that the deadline miss probability (DMP) depends on whichever policy is used for taking routing decisions for the goods. These decisions are often based on the value of some *routing metric*. We will focus on the role that routing metrics play on the DMP.

Application cases of the presented scenario can be found in numerous disciplines, such as logistics, transport and digital communication networks. The sequel provides a motivational example from the realm of wireless sensor networks. We will use this case throughout the article in order to frame the work within a concrete context and use case, but the results are directly applicable to other contexts as well.

Wireless sensor networks (WSN) are a tool for monitoring distributed systems and environments. Data gathered at remote nodes is relayed in multiple hops across the network towards a sink node, which typically uploads the data to a

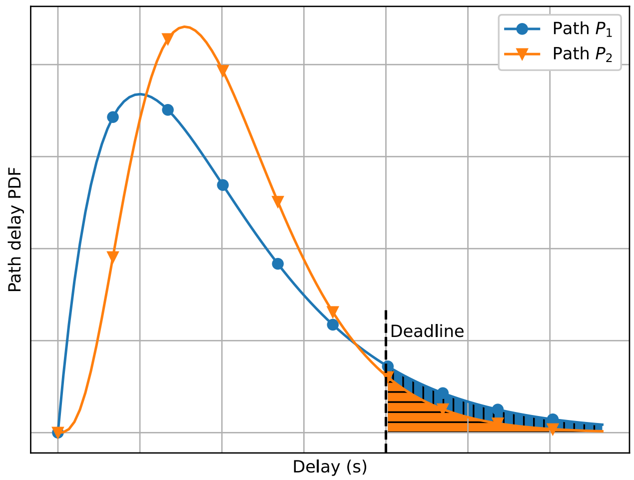

FIGURE 1. The probability of missing the deadline is larger for path P_1 than for path P_2 even though the expected delay of P_1 is smaller. Recreated from [4].

server in the Cloud, where the data is jointly processed.

A time-critical application of WSN is early warning of flash floods. To this end, the authors have been operating a WSN for early warning of flash floods since 2014. The network is composed of 17 stations located in the Quebrada de Ramón (QR) basin at the foothills of Santiago, Chile, at elevations between 878 and 2962 meters above sea level. The sensor nodes measure various hydro-meteorological variables every 10 minutes. The measurements are relayed over the network in multiple hops using the Sensorscope communication protocol stack [1]–[3] to a sink node with cellular access to the Internet, by which the data is uploaded to a server in the Cloud. In the QR network, measurements must reach the sink within 30 minutes to be useful for early warning.

A number of communication routing metrics seek the goal of minimizing the end-to-end delay from source to sink *on average*. This, however, does not ensure that the probability of meeting a deadline is maximized. In effect, a path P_1 across the network may have a smaller expected delay than a path P_2, but a larger delay variance. This can cause that the probability of missing the deadline is larger for P_1 than for P_2 even though the expected delay of P_1 is smaller (Fig. 1, recreated from [4]).

From this example, it is compelling to consider the probability density functions of paths delays (Fig. 1) for routing decisions, rather than using the mean value of those distributions.

In this paper we develop a mathematical model for the probability distributions of the end-to-end delays in a WSN and use it for calculating the DMP of various known routing methods.

This paper is organized as follows: Section II presents a general model for calculating the delay probability distributions of paths and the DMP from a given node to the sink. In Section III the DMP of the routing metrics min-hop, minimum mean delay and JLAT is analyzed. A general algorithm for calculating the delay probability distributions of routing approaches based on deadline-aware routing tables is presented in Section IV. Finally, Section V presents the conclusions of our work.

II. GENERAL MODEL

Our aim is to study the probability of achieving or missing a deadline by data flowing from sensor nodes to a sink node in a WSN. By *data value* or *measurement* we mean an indivisible data unit composed by a *sensor ID*, a *source node ID*, a *measured value* and a *measurement timestamp*.

Once a data value is acquired by a sensor node, it begins a multi-hop journey across the network towards the sink node. Along the way it encounters numerous delays, caused by transmission queues, channel access delays, propagation delays, protocol stack processing delays, etc. [5]. These delays repeat for each new hop the data takes from one node to the next along its route toward the sink. One-hop delays add up over time to a *time en route* value and subtract time left until the *deadline* (time-to-deadline). The deadline itself is the maximum time that a data value acquired by a sensor node can take to reach the sink in order to be useful for an application (e.g. an early warning application) [6].

For each hop, measurements may be forwarded individually or be aggregated by the network layer at each node into a *packet* to be passed down to the node's MAC layer and transmitted over the physical medium. We assume that the network layer has, if needed, the capability of inspecting the measurement timestamp of each data value in order to assist routing decisions for each one of them. Thus, upon downstream reception of a packet, the receiving network layer may separate the measurements carried by it and re-package them into different packets in order to route measurements along different next-hop edges, depending on the time left for each measurement to fulfill its deadline.

The end-to-end delay realization of each measurement for reaching the sink depends on the route followed and hence on the metrics used to make the routing decisions. A priori, the delay from node u to the sink is a random variable which we denote $D_N^{(u)}$. The probability of missing a deadline, henceforth called DMP (Deadline Miss Probability), for a given time-to-deadline δ and source node u is then

$$\begin{aligned} \mathrm{DMP}_N^{(u)}(\delta) &= \mathbb{P}\left\{D_N^{(u)} > \delta\right\} \\ &= \int_\delta^\infty f_N^{(u)}(d)\,\mathrm{d}d, \end{aligned} \tag{1}$$

where $f_N^{(u)}(d)$ is the probability density function (PDF) of $D_N^{(u)}$.

It is to be noted that (1) is related to the metric Deadline Miss Ratio (DMR) for node u discussed e.g. in [7]–[9]. DMR is an estimator of the DMP. It is also worth noting that DMR is related to the Measurement Delivery Ratio (MDR) studied in [10]. MDR and DMR are in fact statistical complements, although DMR is measured at the network layer, whereas MDR includes statistics about sensors and hardware failure.

The random properties of $D_N^{(u)}$ depend on a number of aspects. In order to study $D_N^{(u)}$, we turn our attention to a few concepts from graph theory in the sequel.

We define a *path* as a sequence of edges that connect a node u with the sink. We assume that every node has at least one path to the sink node and that all nodes on a path are distinct, ruling therefore out paths with cycles. Furthermore, we assume that edges may be bi-directional. Therefore some paths may follow links in opposite direction than other paths. We denote by $\mathcal{P}_u$ the set of all paths from node u to the sink. $P^{(k,u)} \in \mathcal{P}_u$ is the k-th path from node u to the sink, enumerated by k in no particular order.

Paths are sequences of links. Traffic across link (u, v) experiences a random delay $D_L^{(u,v)}$ whose PDF is denoted by $f_L^{(u,v)}(d)$. We define $D_L^{(u,v)}$ as the time elapsed from the moment of reception of a measurement within a packet by node u, until the time at which that measurement, possibly carried by a different packet, is acknowledged to have been successfully received by node v one hop later.

Several works have been done to capture the link statistics, either by measurement [5], [11], [12]; simulation [13]–[15] or analytical models [5], [15]–[21].

We assume that the network topology and link PDFs are known and static. We also assume that link delays are independent random variables.

For path $P^{(k,u)}$, the end-to-end delay is given by

$$D_P^{(k,u)} = \sum_{(v_1,v_2)\in\mathcal{E}^{(k,u)}} D_L^{(v_1,v_2)}. \quad (2)$$

Because link delays are assumed independent, the path delay PDFs can be obtained as follows [6], [22]:

$$f_P^{(k,u)}(d) = \left(f_L^{(u,v_1)} * f_L^{(v_1,v_2)} * \cdots * f_L^{(v_n,s)}\right)(d), \quad (3)$$

where $*$ denotes the convolution operation of functions.

From (3) we can see that the delay PDF of a path can be determined from each link PDF that forms the path.

Node PDFs introduced in (1) and path PDFs introduced in (3) are related but not the same. For a source node u, the former represents the combined a priori node-to-sink delay considering that any path in $\mathcal{P}_n$ can be taken, while the latter is the specific delay PDF of path k. However, it is to be pointed out that, we may speak of a DMP of a path just as much it was defined in (1) for nodes, as follows:

$$\mathrm{DMP}_P^{(k,u)}(\delta) = \int_\delta^\infty f_P^{(k,u)}(d)\,\mathrm{d}d. \quad (4)$$

The notation introduced above is summarized in Table 1, along with further definitions that will be introduced later.

The concepts introduced above are used in the next section for analysing the deadline miss probability of various known routing metrics for communications networks.

TABLE 1. Notation

u, v, w	Denote nodes in unique fashion.
s	Denotes the sink node.
n, m	Integer index that enumerates nodes.
k	Integer index that enumerates paths.
d	A delay in seconds.
$\mathcal{P}_u$	Set of all paths between a node u and the sink.
$P^{(k,u)}$	k-th path from node u to sink.
$P^{(\hat{k},u)}$	Chosen path from node u to sink (by some criterion).
$(u, \ldots, v_n)$	Route starting at u and ending at v_n.
$D_L^{(u,v)}$	Delay of link (u, v), with PDF $f_L^{(u,v)}(d)$.
$D_P^{(k,u)}$	Delay of path $P^{(k,u)}$, with PDF $f_P^{(k,u)}(d)$.
$D_N^{(u)}$	Delay of node u to sink, with PDF $f_N^{(u)}(d)$.
$D_R^{(u,\ldots,v_n)}$	Time en route of route $(u, \ldots, v_n)$, with PDF $f_R^{(u,\ldots,v_n)}(d)$.
$f_L^{(u,v)}(d)$	PDF of the link delay $D_L^{(u,v)}$.
$f_P^{(k,u)}(d)$	PDF of the path delay $D_P^{(k,u)}$.
$f_N^{(u)}(d)$	PDF of the node delay $D_N^{(u)}$.
$f_R^{(u,\ldots,v_n)}(d)$	PDF of time en route $D_R^{(u,\ldots,v_n)}$.
$f_{R\|E}^{(u,\ldots,v_n)}(d\|E)$	Conditional PDF of time en route given event E.
$\mathrm{DMP}_N^{(u)}(d)$	Deadline Miss Probability of node u.
$\mathrm{DMP}_P^{(k,u)}$	Deadline Miss Probability of path $P^{(k,u)}$.
δ	Time-to-deadline.
$\mathrm{NH}_{v_n}(\delta)$	Next hop from node v_n for time-to-deadline δ.
M_{v_n}	Number of entries in the routing table of node v_n.
Δ_{v_n}	Random variable of the time-to-deadline at node v_n.
δ_{app}	Application deadline that measurements must meet.

III. DMP OF SOME KNOWN ROUTING PROTOCOLS

Routing protocols for WSNs have been proposed in quite vast number and variety [23]–[25]. Routing aims at determining to which node data should be transmitted next and which path to the sink shall be followed. Routing decisions are generally taken based on some metric, such as min-hop [1]–[3], minimum mean delay and JLAT [6]. We next analyze the DMP performance of these routing algorithms using the model introduced in the previous section.

A. MINIMUM HOP-COUNT (MIN-HOP)

This metric minimizes the number of hops used to reach the sink. The optimal path $P^{(\hat{k},u)}$ for a node u chosen under this metric is one with value $\hat{k}$ chosen typically at random (or otherwise by some secondary decision criterion) among the set of all values of k that correspond to paths in $\mathcal{P}_u$ with minimum hop-count, as follows:

$$P^{(\hat{k},u)} : \hat{k} \in \operatorname*{argmin}_k \left|\mathcal{E}^{(k,u)}\right|, \quad (5)$$

where $|\cdot|$ denotes the cardinality of a set.

For this routing metric, the chosen path depends only on the topology and remains the same as long as the topology does not change. Therefore, the delay PDF for a node u is:

$$f_N^{(u)}(d) = f_P^{(\hat{k},u)}(d), \quad (6)$$

where $f_P^{(\hat{k},u)}(d)$ is the PDF that corresponds to the optimal path $P^{(\hat{k},u)}$ chosen by (5). The DMP is given by (1) and (6).

B. MINIMUM MEAN DELAY

Another interesting metric to analyze is the minimum mean delay (MMD). This metric seeks to minimize the mean delay of the measurements and corresponds to the example given in Fig. 1. Mathematically, the path chosen by node u using MMD as routing metric is given by:

$$P^{(\hat{k},u)}: \hat{k} = \underset{k}{\operatorname{argmin}} \, \mathbb{E}\left\{D_P^{(k,u)}\right\} = \underset{k}{\operatorname{argmin}} \sum_{(v_1,v_2)\in\mathcal{E}^{(k,u)}} \mathbb{E}\left\{D_L^{(v_1,v_2)}\right\}. \tag{7}$$

As with min-hop, the chosen path by MMD is fully defined by link statistics and the topology. Therefore, the DMP of node u for a deadline δ is again given by (1) and (6).

MMD may be impractical for implementation. To this end, it is worth mentioning that a practical routing metric with similarities to the MMD metric is the *expected transmission count* metric (ETX) [26]. ETX is a statistic kept by every node about its links to all its neighbours on the average number of transmission attempts (including retransmissions) over the link until a reception acknowledgment is received. For routing, the ETX metrics are accumulated link-by-link into the network by flooding from the sink node. Each node compares the cumulative ETX metrics received from its neighbours and determines the path to the sink by the neighbour with smallest cumulative ETX.

C. JOINT LATENCY (JLAT) PROBABILITY ROUTING

The JLAT algorithm [6] uses discrete versions of the $f_P^{(k,u)}(d)$ densities and accumulates their probability up to an *application deadline* (system parameter δ_{app}) in order to calculate, for every path, the probability of meeting the application deadline, as follows (JLAT metric):

$$C_P^{(k,u)} = \sum_{d=1}^{\delta_{\text{app}}} f_P^{(k,u)}[d], \tag{8}$$

where δ_{app} and d in [6] are specified in discrete time. Each node then routes its measurements along the path with maximum $C_P^{(k,u)}$. In terms of our continuous-time notation, the path chosen by a node u given an application deadline δ_{app} in seconds is determined as

$$P^{(\hat{k},u)}(\delta_{\text{app}}): \hat{k} = \underset{k}{\operatorname{argmin}} \, \text{DMP}_P^{(k,u)}(\delta_{\text{app}}), \tag{9}$$

where $\text{DMP}_P^{(k,u)}(\delta_{\text{app}})$ is given by (4) and (3).

One challenging aspect of the algorithm proposed in [6] for using $\text{DMP}_P^{(k,u)}(\delta_{\text{app}})$ for routing is that every node must know all path PDFs $f_P^{(k,u)}(d)$ of all possible paths to the sink, which by (3) implies also knowing many —if not all $f_L^{(u,v)}(d)$— densities of the network. This is challenging in practice and possibly unfeasible for networks with more than a few nodes.

The path chosen using the JLAT metric is established at the source node and stays fixed from there on. Therefore, the node PDF can again be obtained using (6). We point out, however, that in contrast to routing by min-hop or MMD, it is apparent from (9) that the optimal path $\hat{k}$ now depends on the specified application deadline δ_{app}, and therefore the optimal path in (9) and the corresponding path delay PDF $f_P^{(\hat{k},u)}(d)$ from (5) may vary if the application deadline changes. The DMP is, however, still given by (1), which in this case may also be expressed as:

$$\text{DMP}_N^{(u)}(\delta_{\text{app}}) = \min_k \text{DMP}_P^{(k,u)}(\delta_{\text{app}}). \tag{10}$$

D. JLAT WITH UPDATES

In practice, as the time-to-deadline shortens as time goes by, the optimal JLAT path that each relay node would pick may be different than the path chosen by the source node at the beginning of the journey. It is evident that the idea of updating the optimum path at each hop by performing a new JLAT calculation at each node visited by the measurement along its journey to the sink should be considered. It is clear that the deadline miss performance of this *JLAT with updates* approach is smaller or equal than that of the standard/original JLAT method.

In JLAT with updates, the path that a measurement eventually follows is unknown a priori and the route finally followed (a posteriori) may actually contain cycles. This is so because the optimum next hop chosen by each visited node is based on the remaining time-to-deadline and it may, under given circumstances, send the data back to a previous node. As a consequence, a node's delay statistics $f_N^{(u)}(d)$ do not correspond anymore to those of a specific path, as was the case with the other metrics, and (6) no longer applies.

A methodology for calculating $f_N^{(u)}(d)$ under these conditions is presented in the following section.

IV. DMP OF METRICS BASED ON ROUTING TABLES

A. ROUTING TABLES AND ROUTES

Consider a network in which forwarding at each node is performed based on a deadline-aware routing table. Input to the table is the time-to-deadline of the measurement that is to be forwarded. The table output is the next-hop neighbour.

Concretely, the routing table of a node v_n is a collection of entries as follows:

$$\text{NH}_{v_n}(\delta) = \begin{cases} w_1, & \text{if } \delta \in [\delta^1_{v_n,w_1}, \delta^2_{v_n,w_1}) \\ \vdots & \quad \vdots \\ w_m, & \text{if } \delta \in [\delta^1_{v_n,w_m}, \delta^2_{v_n,w_m}) \\ \vdots & \quad \vdots \\ w_{M_{v_n}}, & \text{if } \delta \in [\delta^1_{v_n,w_{M_{v_n}}}, \delta^2_{v_n,w_{M_{v_n}}}). \end{cases} \tag{11}$$

Above, when the time-to-deadline δ is in the range $[\delta^1_{v_n,w_m}, \delta^2_{v_n,w_m})$, then node w_m will be chosen by node v_n as the next-hop (NH). M_{v_n} is the number of entries in the routing table of node v_n.

The routing tables (11) may be constructed by any suitable means, for instance using (9) and varying δ_{app} over the entire range of possible time-to-deadline values, thus finding the optimum path and next hop (routing table (11)) for every time-to-deadline.

By the above routing policy, each new hop of any given measurement depends on the link delays it experienced on all previous hops. Every measurement therefore follows its own trajectory through the network. We call them *routes* and they grow with each new hop. Each time a hop is added to the tail of a route, then the original route is defined as the parent route. For example, route (u, v_1) is the parent route of route (u, v_1, v_2).

The *time en route* is the time elapsed from the moment a measurement was taken at its source node until the time the data packet carrying the measurement reaches the end node of a given route. The time en route is a random variable. For a route $(u, v_1, \ldots, v_n)$, we represent it by $D_R^{(u,v_1,\ldots,v_n)}$ and its PDF is $f_R^{(u,v_1,\ldots,v_n)}(d)$.

The *time-to-deadline* for a data unit to reach the desired destination (typically the sink) when the data is at the last node of a route, v_n, is given by:

$$\Delta_{v_n} = \delta_{\text{app}} - D_R^{(u,v_1,\ldots,v_n)}. \tag{12}$$

The time-to-deadline is a random variable. At any given node v_n, the realizations δ_{v_n} of Δ_{v_n}, observed by v_n each time a new measurement passes it, are used as input to the node's routing table in order to determine the next-hop node.

The probability of following route $(u, \ldots, v_n, w)$ can be expressed in terms of the probability of following its parent route, as follows:

$$\begin{aligned} &\mathbb{P}\left\{(u, \ldots, v_n, w)\right\} \\ &= \mathbb{P}\left\{(u, \ldots, v_n, w) \cap (u, \ldots, v_n)\right\} \\ &= \mathbb{P}\left\{(u, \ldots, v_n, w) | (u, \ldots, v_n)\right\} \cdot \mathbb{P}\left\{(u, \ldots, v_n)\right\} \\ &= \mathbb{P}\left\{\text{NH} = w | (u, \ldots, v_n)\right\} \cdot \mathbb{P}\left\{(u, \ldots, v_n)\right\}, \end{aligned} \tag{13}$$

where

$$\begin{aligned} &\mathbb{P}\left\{\text{NH} = w | (u, \ldots, v_n)\right\} \\ &= \mathbb{P}\left\{D_R^{(u,\ldots,v_n)} \in (\delta_{\text{app}} - \delta^2_{v_n,w}, \delta_{\text{app}} - \delta^1_{v_n,w}]\right\} \\ &= \int_{\delta_{\text{app}} - \delta^2_{v_n,w}}^{\delta_{\text{app}} - \delta^1_{v_n,w}} f_R^{(u,\ldots,v_n)}(d)\, \mathrm{d}d, \end{aligned} \tag{14}$$

represents the probability of selecting w as next-hop given that route $(u, \ldots, v_n)$ has been followed.

It is to be noted that min-hop, MMD and (standard) JLAT can be modeled as particular cases of this routing mechanism. In effect, since these routing methods determine and fix the path at the source node, the routing table at each node along the path is simply such that the same fixed next-hop neighbour is returned regardless of the remaining time-to-deadline (in the case of JLAT, however,the routing tables vary with δ_{app}).

B. PDF OF TIME EN ROUTE

Consider starting at the source node u. Because the time en route at the source node is zero, the remaining time to deadline is equal to the application deadline. The source node forwards its measurements according to its routing table (11) evaluated with $\delta = \delta_{\text{app}}$. Therefore, the routing at the source node is always the same. The time en route at the first hop v_1, $D_R^{(u,v_1)}$, is therefore

$$D_R^{(u,v_1)} = D_L^{(u,v_1)}, \tag{15}$$

and has a PDF given by:

$$f_R^{(u,v_1)}(d) = f_L^{(u,v_1)}(d). \tag{16}$$

Consider now the second hop. Node v_1 inspects the time en route and calculates the realization δ_{v_1} of Δ_{v_1} using (12). Then, entering the routing table (11) with δ_{v_1}, the next hop node w is determined and the data is forwarded accordingly.

Using the law of total probability, $f_R^{(u,v_1)}(d)$ can be expressed in terms of conditional probabilities as:

$$\begin{aligned} f_R^{(u,v_1)}(d) = \sum_{m=1}^{M_{v_1}} [f_{R|\text{NH}}^{(u,v_1)}(d | \text{NH} = w_m) \cdot \\ \mathbb{P}\left\{\text{NH} = w_m | (u, v_1)\right\}], \end{aligned} \tag{17}$$

where $f_{R|\text{NH}}^{(u,v_1)}(d|\text{NH} = w)$ is the conditional PDF of $D_R^{(u,v_1)}$ given that the next hop shall be w, that is, given that $\Delta_{v_1} \in [\delta^1_{v_1,w}, \delta^2_{v_1,w})$; and $\mathbb{P}\left\{\text{NH} = w|(u, v_1)\right\}$ is given by (14).

The choice of a given next-hop node w using (11) implies that the time en route up to the current hop v_1 is, by (12), in the range

$$D_R^{(u,v_1)} \in (\delta_{\text{app}} - \delta^2_{v_1,w}, \delta_{\text{app}} - \delta^1_{v_1,w}]. \tag{18}$$

Furthermore, it is to be noted in (17) that because of (11) all conditions $\text{NH} = w_m$ are disjoint events in m. For this reason, each addend in (17) provides the definition of $f_R^{(u,v_1)}(d)$ for the corresponding range given by (18). We may therefore and, in general, state that

$$f_R^{(u,v_1)}(d) = f_{R|\text{NH}}^{(u,v_1)}(d|\text{NH} = w) \cdot \mathbb{P}\left\{\text{NH} = w|(u, v_1)\right\}, \tag{19}$$

keeping in mind that w varies with d. Focusing on hopping next to a given node w and therefore on the range $d \in (\delta_{\text{app}} - \delta^2_{v_1,w}, \delta_{\text{app}} - \delta^1_{v_1,w}]$, we may solve for the conditional PDF in (19) and use (14) to obtain:

$$f_{R|\text{NH}}^{(u,v_1)}(d|\text{NH} = w) = \frac{f_R^{(u,v_1)}(d)}{\int_{\delta_{\text{app}} - \delta^2_{v_1,w}}^{\delta_{\text{app}} - \delta^1_{v_1,w}} f_R^{(u,v_1)}(d)\, \mathrm{d}d}. \tag{20}$$

The above PDF is non-zero only for the range of d indicated above, and 0 otherwise.

Using (20), the PDF of the time en route from source node u to a given node w is then obtained as

$$f_R^{(u,v_1,w)}(d) = f_{R|\text{NH}}^{(u,v_1)}(d|\text{NH} = w) * f_L^{(v_1,w)}(d). \tag{21}$$

We shall also point out that by (20), $f_R^{(u,v_1,w)(d)}$ in (21) depends in fact solely on $f_R^{(u,v_1)}(d)$ and on $f_L^{(v_1,w)}(d)$.

The calculation of $f_R^{(u,v_1,w)}(d)$ in (21) must be performed for all neighbours w of v_1 to which v_1 could route with time-to-deadline values in the range $\Delta_{v_1} \in [0, \delta_{\text{app}}]$, according to the routing table (11).

In general, for the n-th hop node v_n of a route, the conditional PDF of time en route is

$$f_{R|\mathrm{NH}}^{(u,\ldots,v_n)}(d|\mathrm{NH}=w) = \frac{f_R^{(u,\ldots,v_n)}(d)}{\int_{\delta_{\mathrm{app}}-\delta^2_{v_n,w}}^{\delta_{\mathrm{app}}-\delta^1_{v_n,w}} f_R^{(u,\ldots,v_n)}(d)\,\mathrm{d}d}, \tag{22}$$

for $d \in (\delta_{\mathrm{app}} - \delta^2_{v_n,w}, \delta_{\mathrm{app}} - \delta^1_{v_n,w}]$ and 0 otherwise, and the time en route to a given next hop node w is:

$$f_R^{(u,\ldots,v_n,w)}(d) = f_{R|\mathrm{NH}}^{(u,\ldots,v_n)}(d|\mathrm{NH}=w) * f_L^{(v_n,w)}(d). \tag{23}$$

Once $f_R^{(u,\ldots,v_n,w)}(d)$ is calculated, the node w becomes the last node of the child route and the following hop PDFs of the time en route can be calculated by assigning $n \leftarrow n+1$ and $v_n \leftarrow w$, then repeating (22) and (23).

The above procedure can be performed in tree-like fashion, following all possible routes from a source node u and determining the route delay PDF for each one of them. This notion is the base of an iterative algorithm for finding the end-to-end delay PDF from any given source node u to the sink, described next.

C. ITERATIVE ALGORITHM FOR FINDING $f_N^{(u)}(d)$

Starting from any node u, the steps described in the previous subsection can be followed to every neighbor of u (the first hop however is always the same, as noted), and again from each one of them to their neighbours. The corresponding route PDFs are calculated each time using (22) and (23). Hops back to a previously visited node can occur. This flooding procedure shall continue into the network, following all possible routes. Each time a hop is added to the tail of a route, the resulting new route is tested for its probability to reach the sink by the deadline by evaluating the DMP of the route, as follows:

$$\begin{aligned}\mathrm{DMP}_R^{(u,\ldots,v_n)}(\delta_{\mathrm{app}}) &= \mathbb{P}\left\{D_R^{(u,\ldots,v_n)} > \delta_{\mathrm{app}}\right\} \\ &= \int_{\delta_{\mathrm{app}}}^{\infty} f_R^{(u,\ldots,v_n)}(d)\,\mathrm{d}d,\end{aligned} \tag{24}$$

The test may yield two outcomes, namely:

1) The DMP of the route is 1, thus indicating that the sink cannot be reached anymore by the deadline along this route. In this case, this route is unviable and shall be discarded.
2) The sink is reached (with $\mathrm{DMP}_R^{(u,\ldots,v_n)}(\delta_{\mathrm{app}}) < 1$). In this case, the route followed is a viable route for reaching the sink by the deadline.

Once no more routes are left to be explored, the accumulated statistics of each route that reached the sink are weighted by the probability of taking that route, thus obtaining the end-to-end delay PDF as follows:

$$f_N^{(u)}(d) = \sum_{\forall(u,\ldots,s)} \mathbb{P}\left\{(u,\ldots,s)\right\} \cdot f_R^{(u,\ldots,s)}(d), \tag{25}$$

where $\mathbb{P}\left\{(u,\ldots,s)\right\}$ is given by (13).

It is to be noted that reaching condition 1 above may be impractical because the number of routes to be explored might be very large. Discarding routes with a criterion $\mathrm{DMP}_R^{(u,\ldots,v_n)}(\delta) > 1-\epsilon$, with ϵ a small probability is a practical alternative. Larger values of ϵ prune routes sooner and shorten the search, but also tend to limit the accuracy of the result because (13) becomes less accurate.

Algorithms 1 and 2 detail the procedure for calculating the end-to-end delay PDF $f_N^{(u)}(d)$.

Algorithm 1 Calculation of end-to-end delay PDF $f_N^{(u)}(d)$.

Input: u: Source node,
δ_{app}: Application deadline.
Output: $f_N^{(u)}(d)$: End-to-end delay PDF of node u.
$v_1 = \mathrm{NH}_u(\delta_{\mathrm{app}}) \leftarrow$ From routing table in (11).
$f_R^{(u,v_1)}(d) = f_L^{(u,v_1)}(d) \leftarrow$ From (16).
$\mathrm{VRL} = [\,] \leftarrow$ Create an empty Valid Routes List.
Call the Recursive Calculation (RC) of routes (Algorithm 2),
$\mathrm{VRL} = \mathrm{RC}(v_1, f_R^{(u,v_1)}(d), 1, \mathrm{VRL})$.
$f_N^{(u)}(d) \leftarrow$ From (25) with the entries of VRL.
return $f_N^{(u)}(d)$.

Algorithm 2 RC: Recursive Calculation (RC) of the valid routes list (VRL).

Input: v_n: Last node of the route,
$f_R^{(u,\ldots,v_n)}(d)$: Time en route PDF,
$\mathbb{P}\left\{(u,\ldots,v_n)\right\}$: Probability of following the route.
VRL: Valid Routes List.
Output: VRL: Updated Valid Routes List.
if the probability of reaching the sink along the followed route by the deadline becomes negligible, i.e. $\int_0^{\delta_{\mathrm{app}}} f_R^{(u,\ldots,v_n)}(d)\,\mathrm{d}d < \epsilon$, **then**
  return VRL.
else if v_n is the sink, i.e. $v_n = s$, **then**
  Add $\left\{\mathbb{P}\left\{(u,\ldots,s)\right\}, f_R^{(u,\ldots,s)}(d)\right\}$ to VRL.
  return VRL.
end if
{If none of the stopping conditions is met, Algorithm 2 is called for every possible next-hop node.}
for all w in routing table (11) for node v_n **do**
  Find $\delta^1_{v_n,w}, \delta^2_{v_n,w}$.
  $\mathbb{P}\left\{\mathrm{NH}=w|(u,\ldots,v_n)\right\} \leftarrow$ From (14).
  $\mathbb{P}\left\{(u,\ldots,v_n,w)\right\} \leftarrow$ From (13).
  $f_{R|\mathrm{NH}}^{(u,\ldots,v_n)}(d|\mathrm{NH}=w) \leftarrow$ From (22).
  $f_R^{(u,\ldots,v_n,w)}(d) \leftarrow$ From (23).
  RC is called with node w,
  $\mathrm{VRL} = \mathrm{RC}(w, f_R^{(u,\ldots,v_n,w)}(d), \mathbb{P}\left\{(u,\ldots,v_n,w)\right\}, \mathrm{VRL})$.
end for
return VRL.

Note that because the time-to-deadline is calculated as a function of the application deadline (12), the end-to-end

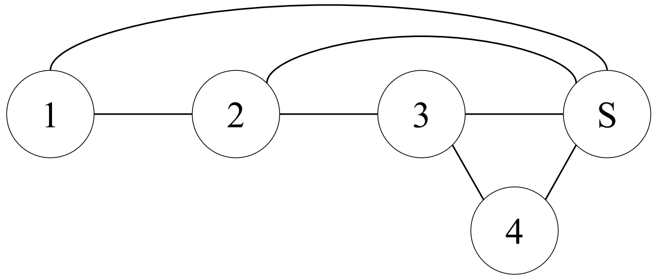

FIGURE 2. Example network.

delay PDF $f_N^{(u)}(d)$ obtained is only valid for a specific δ_{app} chosen. Algorithm 1 must therefore be run for each different value of δ_{app}.

Once $f_N^{(u)}(d)$ has been obtained by Algorithm 1, the DMP is calculated using (1) with $\delta = \delta_{\text{app}}$.

A numerical example is presented in the Appendix in order to illustrate the model and algorithm presented in this work.

V. CONCLUSION

In this work we analyze and model the probability distribution of the end-to-end delay of goods moving in delay-aware networks. Our works yields an algorithm that allows for determining the end-to-end delay PDF of routing policies based on routing tables whose input is the time-to-deadline of the transported goods. With this delay PDF, the deadline miss probability of several routing metrics can be calculated for comparison in deadline-limited networking applications.

APPENDIX. EXAMPLE

In the sequel we illustrate the use of the model and algorithm presented in this work by means of the example network shown in Fig. 2.

All nodes have four paths without cycles to reach node s, the sink. Focusing arbitrarily on node 1, for each of its four paths, the delay (2) is given by:

$$D_P^{(1,1)} = D_L^{(1,s)} \tag{26}$$
$$D_P^{(2,1)} = D_L^{(1,2)} + D_L^{(2,s)} \tag{27}$$
$$D_P^{(3,1)} = D_L^{(1,2)} + D_L^{(2,3)} + D_L^{(3,s)} \tag{28}$$
$$D_P^{(4,1)} = D_L^{(1,2)} + D_L^{(2,3)} + D_L^{(3,4)} + D_L^{(4,s)}. \tag{29}$$

Knowing the PDF of each of the links, we can calculate the delay PDF of each path using (3). These are:

$$f_P^{(1,1)}(d) = f_L^{(1,s)}(d) \tag{30}$$
$$f_P^{(2,1)}(d) = \left(f_L^{(1,2)} * f_L^{(2,s)}\right)(d) \tag{31}$$
$$f_P^{(3,1)}(d) = \left(f_L^{(1,2)} * f_L^{(2,3)} * f_L^{(3,s)}\right)(d) \tag{32}$$
$$f_P^{(4,1)}(d) = \left(f_L^{(1,2)} * f_L^{(2,3)} * f_L^{(3,4)} * f_L^{(4,s)}\right)(d). \tag{33}$$

In [12], the authors made measurements of the link delay in a wireless network. They concluded that 90% of the times the best fit for the link PDF was obtained with a Gamma or Logistic distribution. For this reason, we will assume for our example that the links have delays $D_L^{(u,v)} \sim \text{Gamma}(\alpha_{uv}, \beta_{uv})$, where α_{uv} is a shape parameter and β_{uv} is a rate parameter (or inverse scale parameter), although our method can take PDFs of any nature. The values chosen arbitrarily for these parameters for this example are shown in Table 2. The corresponding PDFs are illustrated in Fig. 3.

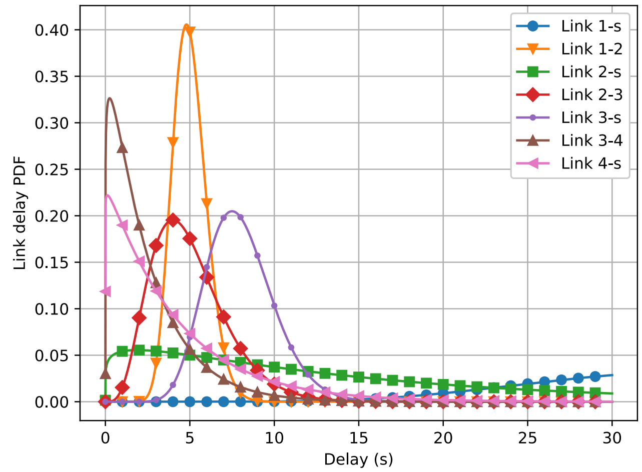

FIGURE 3. Link delay PDF, $f_L^{(v_1,v_2)}(d)$, used in the example network.

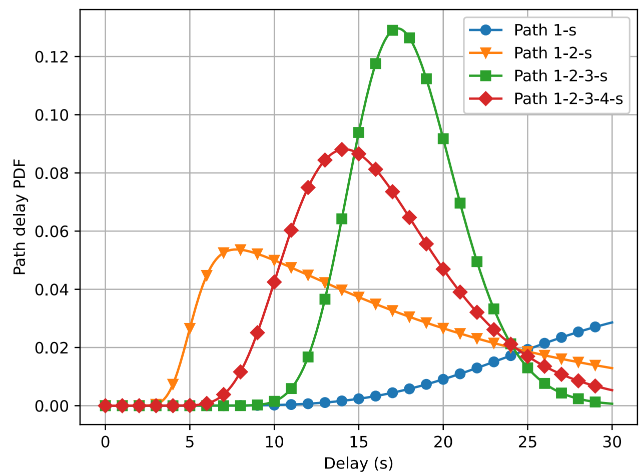

FIGURE 4. Delay PDF $f_P^{(k,u)}(d)$, given by (3), of the paths from node 1 to the sink node.

The convolutions (31), (32) and (33) were evaluated numerically because there are no closed-form expressions for them. The resulting delay PDFs for all paths from node 1 to the sink obtained by (3) are shown in Fig. 4. The corresponding path DMPs obtained by (4) are shown in Fig. 5.

In order to determine the statistics of the JLAT with updates routing method, the routing tables (11) must be known. We chose to determine them using (9) as explained in Section IV-A. The resulting routing tables are presented graphically in Figs. 6 through 9. Finally, Algorithm 1 run for

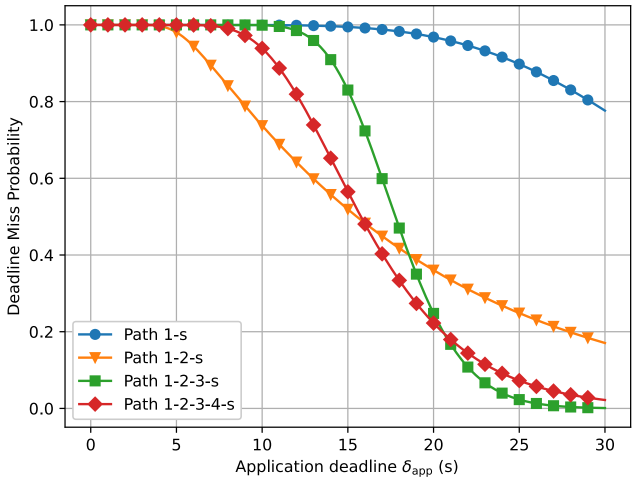

FIGURE 5. Deadline Miss Probability of the paths from node 1 to the sink, given by (4).

TABLE 2. Example parameters.

Parameter	α_{1s}	α_{12}	α_{2s}	α_{23}	α_{3s}	α_{34}	α_{4s}
Value	10	25	1.15	5	16	1.11	1.03

Parameter	β_{1s}	β_{12}	β_{2s}	β_{23}	β_{3s}	β_{34}	β_{4s}
Value	0.25	5	0.08	1	2	0.44	0.25

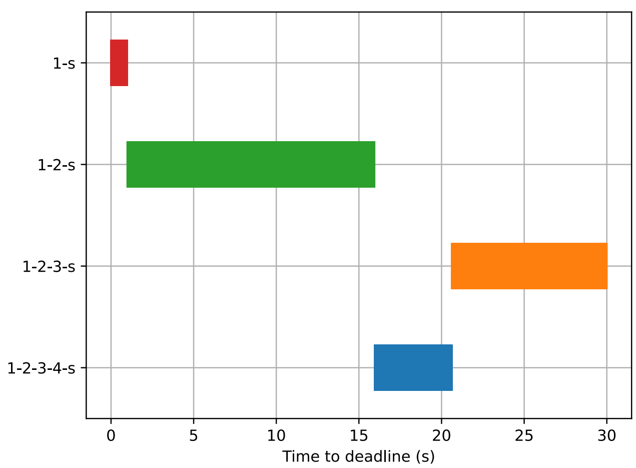

FIGURE 6. Paths used from node 1 toward node s by JLAT metric, obtained with (9).

node 1 yields its end-to-end PDF (25).

The delay PDFs of node 1 for min-hop, MMD, standard JLAT and JLAT with updates are presented in Fig. 10. An application deadline $\delta_{\text{app}} = 24$ seconds was used. Specifying a different application deadline may result in different delay PDFs for both JLAT cases.

Finally, the DMP (1) for node 1 and all four studied routing metrics is shown in Fig. 11. It is to be noted that the abscissa shows application deadline (δ_{app}), which takes values from 0 to 30 s. It can be seen that the path used by min-hop is 1-s, as expected. On the other hand, the path used by MMD is

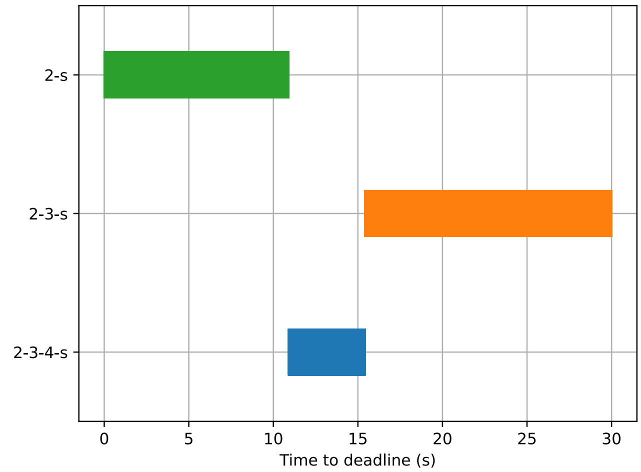

FIGURE 7. Paths used from node 2 toward node s by JLAT metric, obtained with (9).

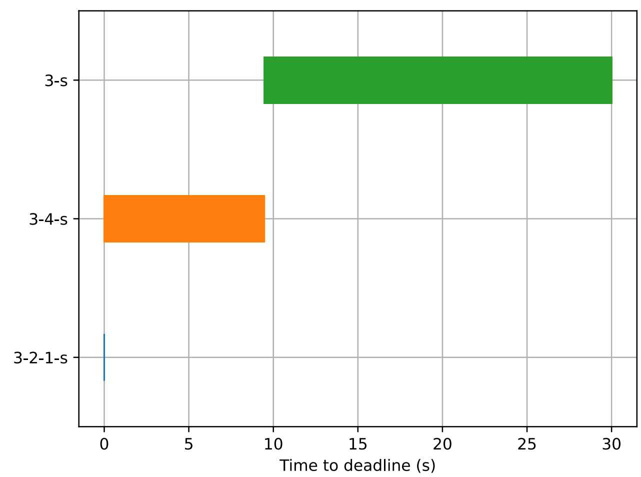

FIGURE 8. Paths used from node 3 toward node s by JLAT metric, obtained with (9).

1-2-3-4-s. Comparing Figs. 5 and 11, we observe that JLAT uses either path 1-2-s, 1-2-3-s or 1-2-3-4-s, depending on the specified value of δ_{app}. Lastly, JLAT with updates has equal or better performance than (standard) JLAT.

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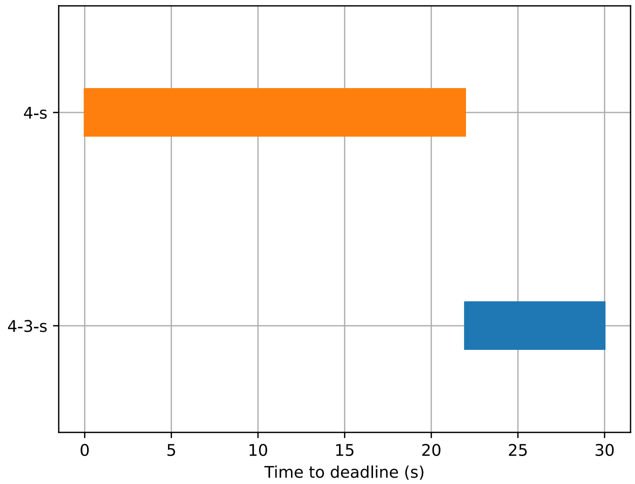

FIGURE 9. Paths used from node 4 toward node s by JLAT metric, obtained with (9).

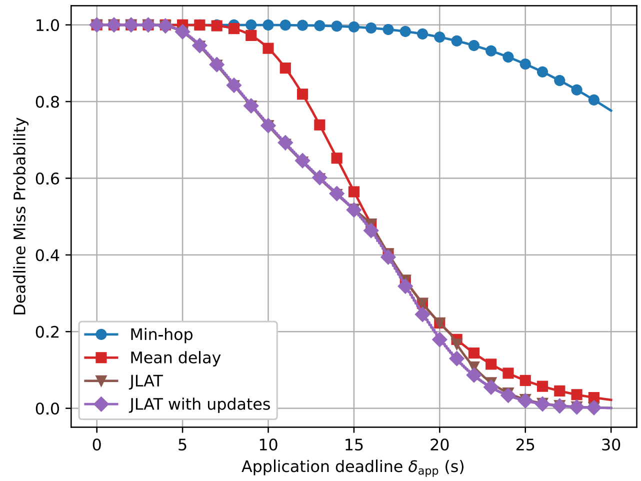

FIGURE 11. Deadline Miss Probability, given by (1), from node 1 to the sink for each metric.

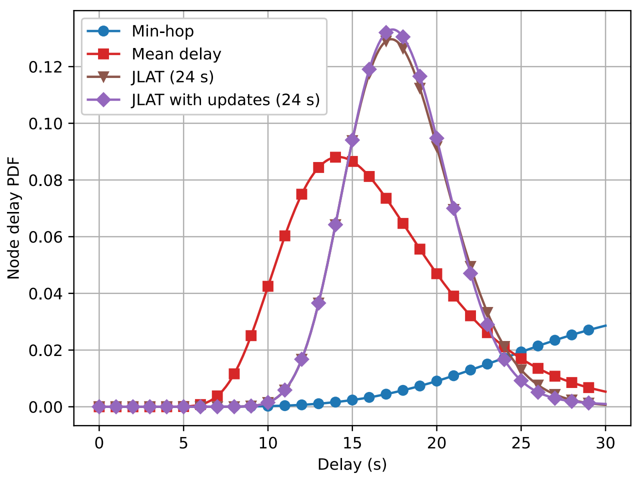

FIGURE 10. Delay PDF of node 1, $f_N^{(1)}(d)$, under different routing metrics with $\delta_{\mathrm{app}} = 24$ s. Obtained with (6) for min-hop, MMD and JLAT; and (25) with Algorithm 1 for JLAT with updates.

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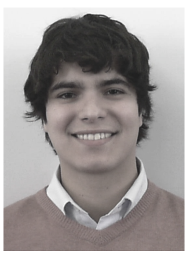

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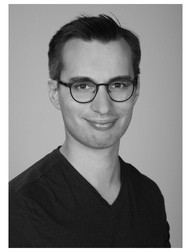

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