A Stochastic Network Calculus Model for TSCH Schedulers

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***Abstract*—Low-power wireless Internet of Things (IoT) devices employ *Time Slotted Channel Hopping* (TSCH) *Medium Access Control* to achieve predictable timing behaviour. TSCH aims at collision-free scheduling by exploiting diversity over time (slots) and frequency (channels). However, existing works on performance and worst-case analysis are based on deterministic models, which lead to rather pessimistic non-realistic results, i.e. tools for probabilistic performance analysis of TSCH schedulers are still lacking. In this context, we devised a *Stochastic Network Calculus* model that enables to calculate end-to-end delays for specific traffic flows and (deadline) violation probability, building on *Moment Generating Functions*. We instantiate this SNC model and provide bounds for three widely used TSCH schedulers, namely *Minimal Scheduling Function*, Orchestra, and a custom collision-free scheduler, with different parameters such as radio duty-cycle, radio link quality, and traffic arrival rate. We demonstrate that our proposed model closely follows the simulation results, under different network scenarios.**

***Index Terms*—Internet-of-Things (IoT); wireless sensor networks; 6loWPAN; 6TiSCH; RPL; stochastic network calculus; performance analysis; simulation; schedulers; Contiki; COOJA**

I. Introduction

Emerging IoT applications require time-bounded communication delays, which is challenging to achieve in wireless networks populated by resource-constrained devices. The *Time Slotted Channel Hopping* (TSCH) MAC of the IEEE 802.15.4-2015 standard protocol [1] is tailored to meet these requirements. TSCH involves nodes synchronizing and dividing time into equal slots. Within each timeslot (typically 10 ms), nodes can operate in receiving, transmitting, or idle mode. Schedulers determine a tuple consisting of timeslot offset and channel offset, referred to as *cells*, where specific nodes are expected to transmit or receive packets. The scheduling mechanism determines how the flows access the wireless link.

The *Internet Engineering Task Force* (IETF) proposed IPv6 over Time Slotted Channel Hopping (6TiSCH) [2] that integrates the *Routing Protocol for Low-Power and Lossy Networks* (RPL) and IPv6 over Low-Power Wireless Personal Area Networks (6LoWPAN). The incorporation of these upper-layer protocols into TSCH necessitates schedulers to allocate cells for routing packets, typically broadcast, alongside data transmissions. Schedulers also bear the responsibility of allocating cells in a manner that prevents collisions between transmissions from neighboring nodes. This collision avoidance can be ensured through centralized or distributed negotiations. Alternatively, if a certain amount of collisions is deemed acceptable, schedulers may opt for simpler approaches to avoid negotiation overhead.

Analyzing the performance of different schedulers is usually performed through simulation, as existing analytical models fail to capture some important aspects of the schedulers. Existing models either lack the flexibility of network calculus or disregard the stochastic nature of wireless links and build on Deterministic Network Calculus. In this paper, we develop an analytical model based on *Stochastic Network Calculus* (SNC) [3], [4], for its flexibility to model various arrival and service bounds (also inherent to the deterministic versions) and for achieving a less pessimistic prediction of "worst-case" communication delays. Using *Moment Generating Function* (MGF)-based SNC, we model performance bounds and the violation probabilities. These bounds can prove useful for optimizing scheduling parameters as well as designing new schedulers. The main contributions of this paper are summarized below.

- We propose a stochastic analytical model to obtain probabilistic performance bounds for a TSCH network for 3 different scheduling policies: collision-free, Minimal Scheduling (RFC 8180) and Orchestra [5]. For Orchestra, we extend the basic theorems of network calculus.
- We analyze the impact of key network parameters on its performance, namely slotframe duration, arrival rate, and wireless link reliability.
- We evaluate the tightness of the analytical bounds by comparing them with simulations (using Contiki/COOJA) and empirical results[1].

The remainder of the paper is structured as follows. Section II presents the basics and definitions of TSCH schedulers. Then, we overview the fundamentals of SNC in Section III and present our SNC-based model in Section IV. Section V presents a comparative performance analysis between the

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[1] https://github.com/iliar-rabet/NetCal-TSCH

proposed SNC model and simulations for the three aforementioned scheduling policies. We finalize the paper with some considerations about related work (Section VI and final remarks (Section VII).

II. TSCH SCHEDULING

This section describes the 3 scheduling policies we consider in the rest of the paper, as well as the rationale for their selection. TSCH schedulers are commonly classified based on the process of negotiation, such as centralized, distributed, and autonomous schedulers. However, we approach this differently and select schedulers based on their robustness against collisions and analyze the following schedulers.

A. Minimal scheduling

The 6TiSCH minimal configuration (RFC8180) defines a schedule where all nodes communicate using a single shared cell, eliminating the need for negotiation. As depicted in Figure 1(a), this "minimal cell" is a solitary shared cell designated for all types of traffic from all nodes, leaving the remaining cells unused. This simplified scheduling approach can lead to collisions within a node's control and data packets and among nodes within the same radio range.

B. Collision-free scheduling

In contrast, Figure 1(b) depicts a collision-free schedule for a pair of nodes. In the schedule, we have a shared cell for EB and broadcast packets, while data packets have reserved cells for both upward and downward directions. This guarantees that data packets will not collide with the control packets. The process for achieving such schedule usually involves a centralized controller and brings extra communication overhead [6].

C. Orchestra

Orchestra [5] introduced the concept of "autonomous scheduling", where nodes determine the schedule without any negotiation. Orchestra significantly reduces the number of required control packets, while relying only on nodes local information (e.g. MAC address) to schedule packet transmission. Nodes apply a hash function to the MAC address of the receiver or sender (two modes) to determine which timeslot to send or receive data. In this paper, we analyze the receiver-based Orchestra that applies the hash to the MAC address of the receiver node. Figure 2 exemplifies an Orchestra schedule and its 3 slotframes. We see that the number of collisions between the EB, broadcast, and data packets in Orchestra can be estimated once we know the length of the 3 slotframes.

To enable different traffic classes, each orchestra node is assigned three slotframes (with different sizes), in a predetermined order of priority:

1) For synchronization and discovering the gateway, all nodes send *Enhanced Beacons* (EB). *One* slot is assigned for EBs in a slotframe with a length of L_{SF}^{EB}. Let $t^{EB}(k)$ denote the time offset of the EB cell associated with node k can be determined by applying a hash function ($Hash()$) to the MAC address of node ($MAC(k)$) [7]. The hash function is implementation-dependent and not specified by the standard.
$$t^{EB}(k) = Hash(MAC(k)) \mod L_{SF}^{EB} \quad (1)$$
2) For *Broadcast* (BC) packets that are mostly used for sending routing packets, each node is assigned *one* slot in a slotframe with an arbitrary length L_{SF}^{BC}. Its time offset is given by:
$$t^{BC}(k) = Hash(MAC(k)) \mod L_{SF}^{BC} \quad (2)$$
3) For the *Unicast* (UC) packets, which contain the actual data, one dedicated slot is assigned per receiver node that is present in the routing table at intervals of L_{SF}^{UC}. The time offset is given by:
$$t^{UC}(k) = Hash(MAC(k)) \mod L_{SF}^{UC} \quad (3)$$

The length of these 3 slotframes is selected to be mutually prime to make sure that if two slots overlap, this will not happen again in the next slotframe. The slotframe length determines the traffic capacity, latency, and energy consumption of the nodes, as shorter slotframes means that cells are reserved more often.

III. BASICS ON STOCHASTIC NETWORK CALCULUS

This section reviews the basics of *Moment-Generated Functions* (MGF)-based *Stochastic Network Calculus* (SNC) theory. Interested readers can find comprehensive material in [8]–[10].

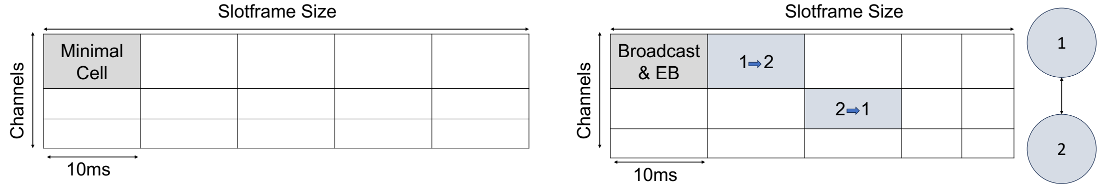
A. Arrival and service bounds

The core idea behind SNC is to relax deterministic delay bounds by allowing a certain probability of deadline violation, thus achieving smaller, less pessimistic bounds. Modeling the network is based on bivariate random processes that describe the packet arrival and service functions/curves inherent to the communication protocol. Let cumulative arrival, departure, and service in the time interval $(s, t]$ be described respectively by $A(\tau, t)$, $D(\tau, t)$, and $S(\tau, t)$.

For studying the statistical characteristics of random arrival and service processes, we resort to their MGFs. For a random variable X, MGF can be defined as $M_X(\theta) = E[e^{\theta X}]$ with $\theta > 0$ being a free parameter. The bounds presented by MGF-based calculus [8] are based on the Chernoff bound, which states that for all $\theta > 0$, we have:
$$P[X \geq x] \leq e^{-\theta x} M_X(\theta) \quad (4)$$
This means that MGF characterizes the tail distribution of the underlying random process through its moments. Hence we can employ certain operations on the MGF of arrival and service processes to determine the performance bounds.

Definition 1: (ρ_A, σ_A) constrained arrival and service Arrival process $A(s, t)$ is (ρ_A, σ_A)-constrained if for all $t \geq s \geq 0$ we have:
$$E[e^{\theta A(s,t)}] \leq e^{\theta(\rho_A(\theta).(t-s)+\sigma_A(\theta))} \quad (5)$$

Alternatively, for the service process:
$$E[e^{-\theta S(s,t)}] \leq e^{-\theta(\rho_S(-\theta).(t-s)+\sigma_S(-\theta))} \quad (6)$$



(a) Minimal scheduling example

(b) Collision-free scheduling example

Fig. 1. In the "minimal" scheduler (a), there is a shared cell that is used for all transmissions. In the custom collision-free scheduler (b), each node has its reserved cell for upward and downward traffic, and control packets (EB and broadcast) are sent in a separate cell.

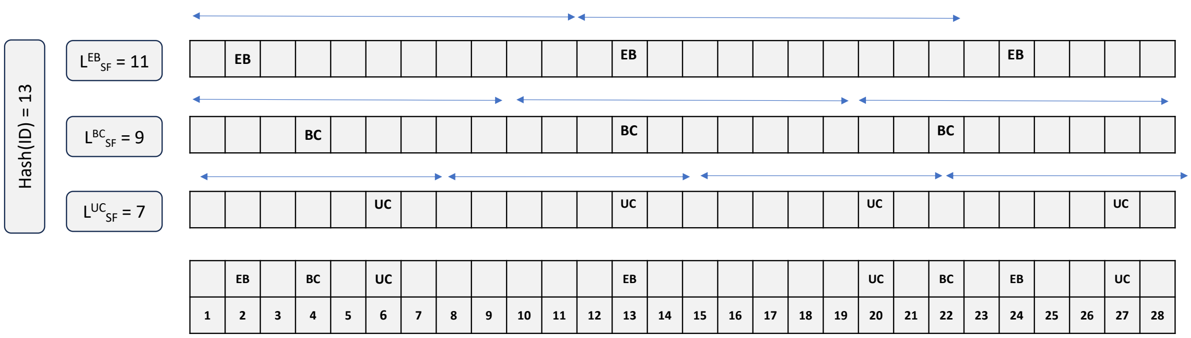


Fig. 2. An example of Orchestra scheduler with 3 repeating slotframes, with EB having the highest priority. Assuming the hash of node ID is 13, transmission of EB happens in the 2^{nd} timeslot and is repeated every 11 timeslots after that. If the transmission EB, BC and UC collide, the node transmits the higher-priority packet which is EB as in the 13^{th} slotframe. If a collision happens between EB and UC at t, the next collision will happen at $t + L_{SF}^{EB} \times L_{SF}^{UC}$.

B. Basic operations of SNC

The (min,+)-algebra is the underlying basis for SNC. It defines the convolution ($\otimes$) and deconvolution ($\oslash$) operators using minimum and addition operations which are later used to devise the performance bounds.

Definition 2: (min,+) convolution and deconvolution For two bivariate functions $x(s,t)$ and $y(s,t)$, the (min,+) convolution and deconvolution are respectively defined as:

$$(x \otimes y)(s,t) = \inf_{\tau \in [s,t]} [x(s,\tau) + y(\tau,t)]$$

$$(x \oslash y)(s,t) = \sup_{\tau \in [0,s]} [x(\tau,t) - y(\tau,s)]$$

Definition 3: Dynamic server
Let A(0,t) and D(0,t) be the arrival and departure process of a server. Then the server is defined as a dynamic server [3] if, for any sample path, we have:

$$D(0,t) \geq (A \otimes S)(0,t)$$

for all $t \geq 0$

We aim at deriving a bound on the delay in the form of $\mathbb{P}(d(t) > \omega) \leq \varepsilon$ where ε is the *delay violation probability* associated with the delay bound.

Theorem 1. *Suppose we have a (ρ_A, σ_A)-constrained dynamic service and arrival. Under the stability condition that $\rho_A < \rho_S$, the violation probability of a given delay $\omega \geq 0$ at time $t \geq 0$ is bounded by:*

$$P[d(t) > \omega] \leq e^{-\theta \rho_S(-\theta)\omega} \frac{e^{\theta(\sigma_A(\theta)+\sigma_S(-\theta))}}{\theta(\rho_S(-\theta) - \rho_A(\theta))} \tag{7}$$

By reordering Eq. 7, given the violation probability the delay that can be guaranteed :

$$\omega < \frac{\log(\frac{\varepsilon\theta(\rho_S(-\theta)-\rho_A(\theta))}{e^{\theta(\sigma_A(\theta)+\sigma_S(-\theta))}})}{-\theta\rho_S(-\theta)}$$

For proof see: [10]

C. Modeling the cross traffic

The concept of leftover service can be used to model multiple flows that share a server. If no information is known about how the scheduling is performed, a pessimistic bound can be derived for the service using the concept of blind multiplexing. In blind multiplexing, the assumption is that the whole available service (ρ_S, σ_S) is first offered to the cross traffic, which is (ρ_{cr}, σ_{cr})-constrained. The remaining (leftover) service is proved [3] to be (ρ_{lo}, σ_{lo})-constrained where:

$$\rho_{lo} = \rho_S - \rho_{cr} \text{ and } \sigma_{lo} = \sigma_S + \sigma_{cr} \tag{8}$$

This results in very conservative bounds as the assumptions are pessimistic and the bounds can be improved for the schedulers such as Orchestra, or collision-free by exploiting the knowledge about the schedulers.

IV. SNC MODEL FOR TSCH SCHEDULERS

This section describes the proposed SNC-based model for a 6TiSCH network and the probabilistic performance bounds. We assume a Markov On-Off service model for the wireless link behaviour. This section addresses how classic network calculus tools can be used to model collision-free and Minimal schedulers. For Orchestra, we present a theorem that takes as input a set of parameters, including slotframes size, and gives the service curve as output.

A. Arrival

We consider the following two models for the arrivals:

1) Periodic traffic: Assume we have a source of data that generates packets of size α with a deterministic time interval (period) of τ. Then the MGF of the arrival is bounded: [3]

$$E[e^{\theta A(s,t)}] \leq e^{\theta\alpha/\tau.(t-s)+\theta\alpha}$$

Based on definition of (ρ, σ)-constrained arrival we have: $\sigma_A(\theta) = \alpha$ and $\rho_A(\theta) = \frac{\alpha}{\tau}$

2) Poisson traffic: Assume the counting process associated with the arriving packets is Poisson with rate λ and the packet size α. Then the MGF of the arrival is given by equation below [9]:

$$E[e^{\theta A(s,t)}] \leq e^{\lambda(t-s)(e^{\theta\alpha}-1)}$$

Then, based on definition of (ρ, σ)-constrained arrival we have: $\sigma_A(\theta) = 0$ and $\rho_A(\theta) = \frac{\lambda(e^{\theta\alpha}-1)}{\theta}$

B. Service Curve

Considering the 3 selected schedulers, for Minimal and collision-free scheduling, we use existing theorems from network calculus; for Orchestra, we prove the performance bounds.

1) Modeling collision-free schedule: Suppose nodes are scheduled in a way that there is no collision between data (UC) packets and control packets (EB and BC). Also, the ν^{th} slotframe contains a set of 10ms slots. The service process between τ and t can be described by a sum of increments:

$$S(\tau, t) = \sum_{\nu=\tau+1}^{t} X(\nu)$$

For the case of a Markov On-Off process, the incremental process (X) describes the number of bits served at ν^{th} slotframe and constitutes i.i.d Bernoulli trials with the probability mass function $p_X(x)$. The packets of size r are either received successfully (with probability P_{on}) or dropped. Retransmission is not allowed during the same timeslot (if the packet gets lost). We assume the link quality is stable during the 10ms timeslot.

$$p_X(x) = \begin{cases} P_{on} & x = r \\ 1 - P_{on} & x = 0 \end{cases} \tag{9}$$

The MGF of a sum of independent random variables is the product of their individual MGFs. Hence the MGF of the service process can be described as follows:

$$M_S(-\theta, t) = (M_X(-\theta))^t = \\ (\sum_x e^{-\theta x} p_X(r))^t = (P_{on}e^{-\theta r} + 1 - P_{on})^t \tag{10}$$

Therefore, for a single TSCH node with a collision-free schedule, we have (ρ, σ)-constrained service envelope with $\sigma_S = 0$ and

$$\rho_S = \frac{\ln(P_{on}e^{-\theta r} + 1 - P_{on})}{-\theta} \tag{11}$$

2) Modeling Minimal scheduling: As we explained in section II, Minimal scheduling leads to a high level of contention between the control and data packets and collision between neighboring nodes. We can only use the pessimistic bounds of Blind Multiplexing (BMUX). Consider three (ρ, σ)-constrained arrival processes A_{UC}, A_{EB} and A_{BC}. According to a BMUX scheduler, the leftover service for data packets $(S_{UC}(s,t))$ is given by:

$$S_{UC}(s,t) = [S(s,t) - A_{EB}(s,t) - A_{BC}(s,t)]^+$$

Thus, the leftover service is also (ρ, σ)-constrained with:

$$\rho_{UC}(-\theta) = \rho_S(-\theta) - \rho_{EB}(-\theta) - \rho_{BC}(-\theta)$$

$$\sigma_{UC}(-\theta) = \sigma_S(-\theta) + \sigma_{EB}(-\theta) + \sigma_{BC}(-\theta)$$

Throughout our analysis, all the broadcast packets consist of RPL packets, and the Trickle algorithm determines their rate. Trickle adapts the interval of routing packets to the dynamism of the network but the minimum (I_{min}) interval can be configured. Therefore, the arrival process of broadcast packets can be modeled as periodic traffic with a rate of $1/I_{min}$.

3) Modeling Orchestra: The following theorem exploits the existing knowledge about the scheduling mechanism in the autonomous schedulers to achieve tighter bounds.

Theorem 2. *Assume we have a pair of Orchestra nodes with three slotframes with length L_{SF}^{EB}, L_{SF}^{BC}, and L_{SF}^{UC}.*

Then the service that is given to the UC is (ρ_{UC}, σ_{UC})-bounded

$$\rho_{UC} = \rho_S - \rho_C \text{ and } \sigma_{UC} = \sigma_S + \sigma_C$$

where $C(s,t)$ represents the collisions between UC and other traffic classes. $C(s,t)$ is bounded by:

$$\rho_C = r(\frac{1}{L_{SF}^{EB}} + \frac{1}{L_{SF}^{BC}} - \frac{1}{L_{SF}^{EB}L_{SF}^{BC}}) \text{ and } \sigma_C = r \tag{12}$$

Proof. According to the functionality of Orchestra, we have:

$$S_{UC}(s,t) = [S(s,t) - C(s,t) \times r]_+ \tag{13}$$

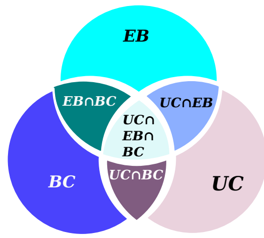


Fig. 3. A Venn diagram of the sets of timeslots associated with each traffic class. The set of slots that are guaranteed (no collision with higher priority traffic) for unicast is $UC - EB - BC$.

where r is the size of packets (we assume 1 bit), and $C(s,t)$ is the number of times collisions stop a UC packet from being transmitted.

Let UC, EB, and BC be the sets containing the timeslots that Orchestra allocates for each traffic class. Since UC is the lowest priority traffic class, we need to account for $|UC - EB - BC|$. The principle of inclusion-exclusion states that to find the cardinality (number of elements) of the union of two sets A and B, you can sum the cardinalities of each set and subtract the cardinality of their intersection. As illustrated in Figure 3, the number of timeslots that are reserved for UC and have no collision with other traffic classes can be formulated as:

$$|UC - EB - BC| = |UC| - |EB \cap UC| - |BC \cap UC| + |EB \cap BC \cap UC| \quad (14)$$

Now, we need to calculate the cardinality of the set of unions (the number of collisions). Let m_1 and m_2 be coprime integers (corresponds to the size of slotframe for different traffics in this problem) and arbitrary integers a_1, a_2 (the hash of MAC address). The Chinese remainder theorem [11] states that the following system of congruences:
$a_1 \mod m_1 = x$ and $a_2 \mod m_2 = x$
has a unique solution modulo $m_1 m_2$. In other words, if, for example, UC and EB collide at time slot x, then the next collision happens at $x + L_{SF}^{UC} \times L_{SF}^{EB}$. *Chinese remainder theorem can also be extended to 3 or more congruences [11].*

Let t' be the time interval defined as the number of slotframes of size L_{SF}^{UC}. According to the Chinese remainder theorem, during an interval of t', the collisions between EB and UC slots are bounded (same is valid for BC and UC):

$$\lfloor \frac{t'}{L_{SF}^{UC} \times L_{SF}^{EB}} \rfloor \leq |UC \cap EB| \leq \lfloor \frac{t'}{L_{SF}^{UC} \times L_{SF}^{EB}} \rfloor + 1 \quad (15)$$

$N^{UC}(t')$ the number of timeslots that each node has reserved for UC during an interval of t' is bounded by:

$$N^{UC}(t') < \lfloor t'/L_{SF}^{UC} \rfloor - \lfloor \frac{t'}{L_{SF}^{UC} \times L_{SF}^{EB}} \rfloor - \lfloor \frac{t'}{L_{SF}^{UC} \times L_{SF}^{BC}} \rfloor + \lfloor \frac{t}{L_{SF}^{UC} \times L_{SF}^{BC} \times L_{SF}^{EB}} \rfloor + 1 \quad (16)$$

Now if we consider the slotframes between s and t, the collisions during the interval $t - s = \lfloor t'/L_{SF}^{UC} \rfloor$ would be upper-bounded by $C(s,t)$:

$$C(s,t) < \frac{(t-s)}{L_{SF}^{EB}} + \frac{(t-s)}{L_{SF}^{BC}} - \frac{(t-s)}{L_{SF}^{EB} L_{SF}^{BC}} + 1$$

We want to calculate a (ρ, σ)-constrained service for the Orchestra scheduler. Under the assumption that $S(s,t)$ and $C(s,t)$ are independent, it follows that the MGF of the leftover service for UC is:

$$E[e^{-\theta S_{UC}(s,t)}] \leq E[e^{-\theta S(s,t)}] E[e^{\theta r C(s,t)}] \quad (17)$$

The MGF of collisions is (ρ, σ)-constrained with

$$\rho_C = r(\frac{1}{L_{SF}^{EB}} + \frac{1}{L_{SF}^{BC}} - \frac{1}{L_{SF}^{EB} L_{SF}^{BC}}) \quad (18)$$

and $\sigma_C = r$ By substituting this in (17), we have:

$$E[e^{-\theta S_{UC}(s,t)}] \leq e^{-\theta(\rho_S - \rho_C)(t-s)} + e^{-\theta(\sigma_S + \sigma_C)} \quad (19)$$

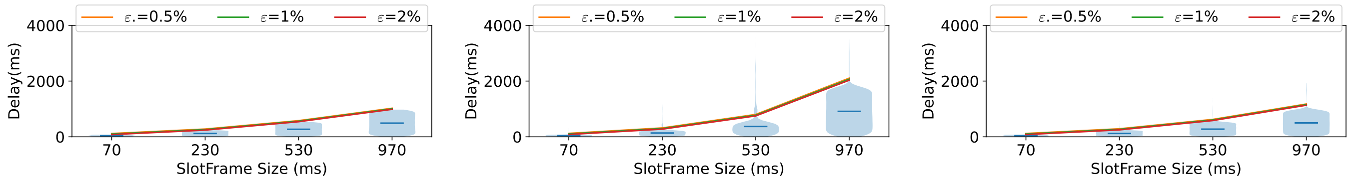
which proves the theorem. □

V. Evaluation

In order to compare the proposed SNC model with the actual performance of the system, we conducted extensive simulations using Contiki-NG/Cooja for different network scenarios and configurations. We implement our SNC toolbox using Python, extending some existing libraries [10]. Each simulation is repeated 50 times for a duration of 10 minutes each, and we measured the end-to-end delay for the aforementioned schedulers and compared it with our SNC model. We evaluated the model under different (i) slotframe sizes, (ii) wireless link *Packet Reception Ratio* (PRR), and (iii) arrival rates (for periodic and Poisson traffic patterns). The simulation results as shown with the violin plots while we plot the delay bound (calculated according to Eq. 1) with 3 different violation probabilities (ε) with solid lines.

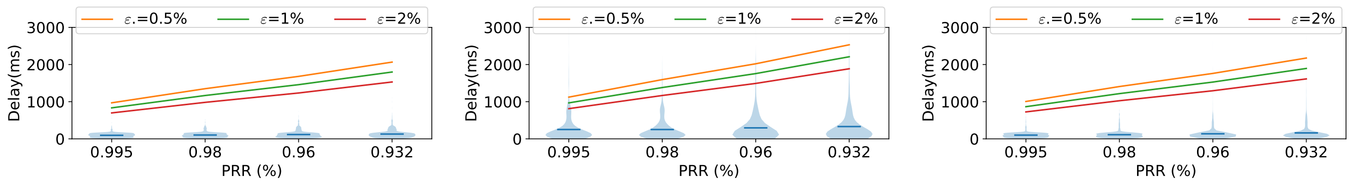
Due to size restrictions, in this paper we limit the evaluation to a network scenario with just two nodes: a transmitter and a receiver. The transmitter sends one data packet (UC) every 2 seconds, while the receiver only transmits control packets. A periodic traffic arrival with inter-packet arrival of 2 s is considered, unless stated otherwise. The radio link between the nodes is assumed to be ideal except for the results associated with Figure 5.

First, as illustrated in Figure 4, we evaluate the impact of slotframe size on the delay. For Orchestra, we refer to the UC slotframe in this chart, and the other two slotframes are configured to their default value (970 and 3970 ms for BC and EB, respectively). As Figure 4 shows, we expect higher delays for longer slotframe sizes. Both delays computed by the SMC model and resulting from simulation increase with slotframe length. We also observe that if a higher violation probability is acceptable, the SNC model expects a lower delay. Comparing the 3 schedulers also shows that Minimal scheduling leads to the highest contention between control and data packets, thus yielding higher delays. We see that the contention is



(a) (b) (c)

Fig. 4. Delay relative to slotframe size for various schedulers: (a) collision-free, (b) Minimal, and (c) Orchestra. The delay bound according to the model is shown with solid lines, while simulations are plotted using a violin chart.



(a) (b) (c)

Fig. 5. Delay relative to Packet Reception Ratio for various schedulers: (a) collision-free, (b) Minimal, and (c) Orchestra.

much lower in Orchestra and non-existent for the collision-free scheduler.

Figure 5 shows longer delays when PRR decreases. In this experiment, the slotframe size for the collision-free, Minimal schedulers and UC Orchestra were set to 170 ms.

The next set of results (Figures 6 and 7) focuses on the characteristics of Periodic and Poission traffic arrival patterns. With a periodic arrival, the inter-packet interval is constant; thus, the delay is not as volatile as for Poisson arrival. However, Minimal scheduling still suffers from the collision between data packets (BC) and control packets (EB), which leads to an "explosion" when the rate is increased to 4 packets per second (Figure 6). Minimal scheduling and Orchestra show a stable delay for different arrival rates as long as the stability condition holds ($\rho_A < \rho_S$). For a Poisson traffic arrival pattern, Figure 7 shows that the delay increases with the arrival rate at a faster rate (when compared to periodic arrival).

VI. Related Work

This section reviews previous works on modeling and performance analysis of TSCH networks. The schedule primarily determines the performance of the network and there have been plenty of surveys in the literature regarding different types of schedulers [12], [13]. Here, we browse some tools that have been applied to model TSCH networks.

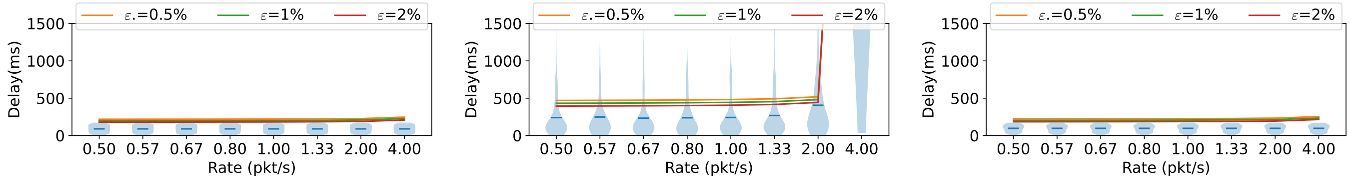
Elst et.al. [14] have studied the impact of schedulers (specifically autonomous schedulers such as Orchestra). This work has formulated an analytical model based on the probability of hash collisions. Their model neglects the collision between different traffic classes (EB, BC, UC). On the other hand, network calculus provides a more flexible framework to model the network under many different parameters.

Van Leemput et.al. [15] proposed an analytical model for 6TiSCH based on a real-time telemetry approach thus relying heavily on the availability of real-time reports from the in-network nodes. Additionally, this model focuses on the impact of protocols accompanying TSCH, such as RPL and CoAP, rather than the underlying schedule.

Unlike classical queue theory models [16] that focus on the average performance of the network, network calculus models study (deterministic and stochastic) bounds on the performance of the system. *Deterministic Network Calculus* (DNC) is another modeling tool that allows worst-case performance analysis and dimensioning. DNC has been used to model the allocation of the *Guaranteed Time Slots* (GTS) in IEEE 802.15.4 [17]. Kurunathan et. al. [18] addressed three different modes of IEEE 802.15.4e (TSCH and two other modes) in a single-hop setting. *Sensor Network Calculus* [19] is another DNC model that studied duty-cycling radio that can be used for various topologies. Evidently, DNC fails to capture the stochastic nature of wireless networks, resulting in pessimistic bounds. Importantly, accepting a certain risk of deadline violation allows to compute tighter bounds and more realistic network modeling and dimensioning.

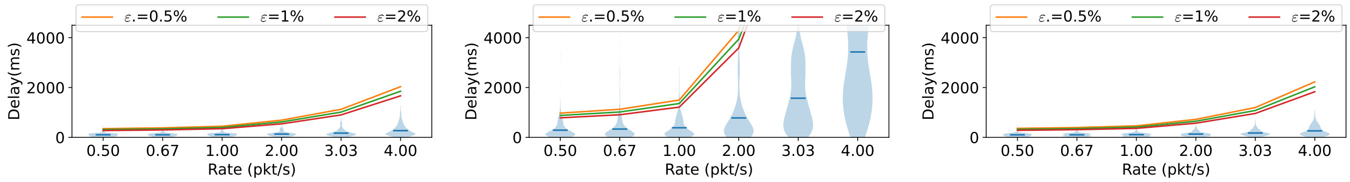
Stochastic bounds were derived for IEEE 802.15.4 networks using the (min, x) calculus, later extended to optimize transmission power [20]. The (min, x)-network calculus proposed a variation of SNC that is more convenient for multihop networks [21]. While we opted to use MGF-based network calculus, (min, x)-network calculus is a parallel choice. For IoT networks, Cui et. al. [9] used the MGF-based SNC and proved bounds for three fading channels commonly used to model IoT networks: Rayleigh, Rician, and Nakagami-m. They also devised bounds on schedulers such as blind multiplexing, generalized processor sharing, and rate latency service.

All previous models neglect important aspects of TSCH, such as the underlying scheduling and contention between control and data packets. To our best knowledge, our proposed SNC model is the first work that models different TSCH-



(a) (b) (c)

Fig. 6. Delay relative to arrival rate under periodic arrival for various schedulers: (a) collision-free, (b) Minimal, and (c) Orchestra.



(a) (b) (c)

Fig. 7. Delay relative to arrival rate under Poisson arrival for various schedulers: (a) collision-free, (b) Minimal, and (c) Orchestra.

specific schedulers under a comprehensive set of parameters.

VII. Conclusion

We propose a Stochastic Network Calculus model for 3 TSCH schedulers. Analytical and simulation results show that considering a small deadline violation probability, tighter performance bounds are achieved. Our model is flexible and considers different parameters. We show the results of the model for some of those parameters including the underlying scheduler, traffic arrival models, and link characteristics.

We plan to extend the SNC model to multi-hop topology, optimizing parameters such as transmission power [22], and to integrate it in a centralized scheduler that adapts to changing network dynamics, for example, due to nodes' mobility.

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