

Service Modeling and Delay Analysis of Packet Delivery over a Wireless Link

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Abstract—A lot of Internet of Things (IoT) applications are time-sensitive, requiring reliable low latency communication (RLLC) or delay guarantee from the underlying wireless network. Fundamentally, this demands service modeling and delay guarantee analysis of data packet delivery over a wireless link. However, few such results are available for IEEE 802.15.4 links, though IEEE 802.15.4 has been the basis for a number of IoT related specifications such as Zigbee and 6LoWPAN. To bridge the gap, an integrated approach is introduced in this paper, which combines empirical models obtained from measurement with analytical models. Extensive experimental investigation under a wide range of settings has been conducted. The effectiveness of the proposed ideas is validated with the experiment results.

Index Terms—Reliable Low Latency Communication (RLLC), IEEE 802.15.4 Wireless Link, Service Modeling, Delay Guarantee

I. INTRODUCTION

IEEE 802.15.4 is the basis for a number of specifications such as Zigbee and 6LoWPAN, which have been adopted in a broad range of Internet of Things (IoT) applications. Many of these applications are delay-sensitive, requiring *reliable low latency communication (RLLC)* [1] [2]. This demands investigation on the capability of an IEEE 802.15.4 link in delivering RLLC, for which, it is crucial to establish service models and conduct delay guarantee analysis of the link. In the literature, a lot of results can be found for modeling and analyzing the performance of wireless links. The majority focuses on throughput-related metrics such as Shannon capacity [3] where delay is not taken into account. For delay and loss analysis, queueing models have been adopted where the service process may be characterized by the throughput process (see e.g. [4]) or from some Markov characterization of the channel process (see e.g. [5]). In these investigations, to simplify the analysis, no error or loss is considered in the service process, queues are often assumed to have infinite buffer space, and the loss rate is approximated only by the exceeding probability of the backlog higher than a threshold (e.g. see [6] for a recent example).

However, for RLLC study of an IEEE 802.15.4 link [7], those results cannot be readily applied. This is because on an 802.15.4 link, packet loss also happens on the link, which is not considered in those analytical investigations. An RLLC requirement can be represented using a tuple (a, d) , where a represents the reliability requirement, i.e. the probability that packets are successfully received, and d the delay requirement, i.e. packets are received within this delay. If a packet is not successfully received, it is lost and its delay is infinite. Denote

D as the delay of a packet. The RLLC requirement can be expressed as delay violation probability:

$$P\{D > d\} \leq 1 - a.$$

Since the violation has two possible causes, i.e. loss and excessive delay in queue, $P\{D > d\}$ can be written as

$$P\{D > d\} = P\{\mathcal{L}\} + P\{D > d|\bar{\mathcal{L}}\}(1 - P\{\mathcal{L}\}) \quad (1)$$

where \mathcal{L} represents loss and $\bar{\mathcal{L}}$ otherwise, and $P\{D > d|\bar{\mathcal{L}}\}$ is due to excessive delay in queue. However, in studies like [4], [5] and [6], $P\{\mathcal{L}\}$ due to non-buffer-overflow is ignored.

For performance investigation of IEEE 802.15.4 links, the literature investigation has mainly been based on measurement. Specifically, several empirical measurement-based studies have been conducted for packet delay and loss, e.g. [8], [9] and [10]. Their focus is on reporting observations from their measurement study and proposing node-coordination mechanisms, such as access and routing, to improve their interested performance. In [11], [12], a set of extensive experimental studies were conducted based on which several empirical models were proposed. However, their focus is on throughput [11] and packet loss $P\{\mathcal{L}\}$ [12]. Surprisingly after the introduction of 802.15.4 for almost two decades, the literature has *little touch on constructing models for the service of 802.15.4 links and analyzing their RLLC / delay guarantee performance*.

To bridge the gap, an integrated approach is introduced in this paper. The approach combines empirical models obtained from measurement, including for $P\{\mathcal{L}\}$, with analytical models from both queueing theory [13] and stochastic network calculus (SNC) [14]. Specifically, to enable delay performance analysis with loss, we propose a non-loss queueing model that factors in the loss by integrating with measurement-based empirical models. To validate the non-loss queueing model, mean delays, estimated using a classical queueing theory result, are compared with measurement results. Finally, for delay guarantee analysis, we propose an SNC-based approach to estimate the delay distribution $P\{D > d|\bar{\mathcal{L}}\}$. The delay distribution model is also validated with measurement data, further indicating the effectiveness of the proposed approach.

The rest is structured as follows. Sec. II introduces the focused link and the experiment setup and Sec. III reports empirical models. Sec. IV introduces the non-loss queueing model, validated using mean delay. Sec. V introduces the SNC based approach to delay distribution analysis, where validation is also provided. Finally, conclusion is given in Sec. VI.

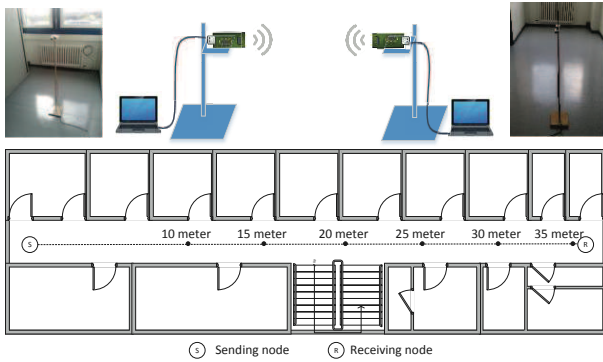


Fig. 1: Experiment setup

II. THE 802.15.4 LINK AND EXPERIMENT SETUP

A. The 802.15.4 link

We consider an IEEE 802.15.4 link. To obtain an in-depth understanding of its service and delay performance, we conducted an extensive set of experiments in an indoor office building environment. We employed a sender-receiver pair of TelosB motes, each equipped with a TI CC2420 radio using the IEEE 802.15.4 stack implementation in TinyOS [16]. As shown in Fig. 1, the experiments were conducted in a long hallway. In each experiment, the sender sends packets to the receiver under a particular stack parameter configuration. For each stack parameter configuration, 7 key parameters residing at different layers are considered. Specifically, at the physical layer (PHY) are the *distance* between nodes and the *transmission power* level. At the medium access control (MAC) layer are the *maximum number of transmissions*, the *retry delay time* for a new retransmission, and the *maximum queue size* of the queue on top of the MAC layer used to buffer packets when they are waiting for (re-)transmission. At the application layer are the *packet inter-arrival time* and the *packet payload size*.

B. The data delivery scheme

The IEEE 802.15.4-standard defines both the PHY and MAC layers. The MAC layer has two channel access methods: beacon enabled and non-beacon enabled modes. In this paper, a non-beacon-enabled unslotted CSMA/CA mechanism is considered. The unslotted CSMA/CA procedure including backoff procedure and packet retransmission proceeds based on acknowledgments. Each time a generated data packet waits for a random backoff time to check whether the channel is busy or not before transmission. If the channel is idle during the backoff period, the device transmits its data packet. When the channel is busy, the random backoff procedure is repeated. When retransmissions are enabled, the destination node must send an acknowledgement (ACK) after receiving a data frame, otherwise data frame will be re-transmitted up to the defined maximum times, and then dropped.

The packet delivery scheme implemented in TinyOS 2.1 is as illustrated in Fig. 2. At the PHY layer, TinyOS allows the user to configure the radio transmission power to eight different levels. On top of the MAC layer, a buffer with maximum

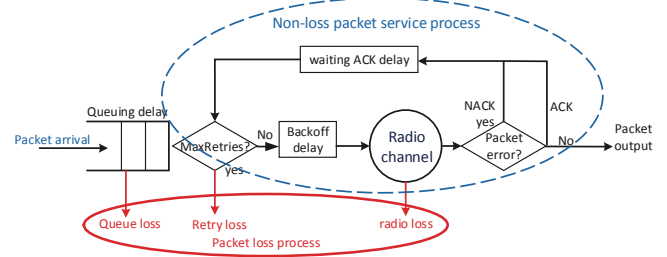


Fig. 2: Packet transmission system

length is implemented to queue the application packets. Once the buffer is full, newly arriving packets are dropped. The packets in the queue are served based on the FIFO (First In First Out) policy. Each time the sender node wishes to transmit data frames, it shall wait for a random backoff period. If the channel is found to be idle, following the random backoff period, the device shall transmit its data. After the frame is sent, a copy of each transmitted packet is temporarily kept in a waiting buffer until the ACK of that packet is received. After a maximum acknowledgement waiting duration, if no ACK is received, it triggers a retransmission until that the maximum number of retransmissions is reached and the packet is discarded. Between each retry there is a delay decided by the specified retry delay time. Once an ACK is received, the packet is removed from the waiting buffer and a new packet is transmitted.

In total, close to 50000 *parameter configurations* were experimented and detailed transmission information of more than 250 million packets was collected, which provides statistical information for modeling the data delivery performance. A related dataset has been made publicly available [17].

III. MEASUREMENT-BASED EMPIRICAL MODELS

In this section, based on measurement results, statistical empirical models for packet error rate, service time and loss rate are presented. The measurement dataset for periodic packet arrival traffic pattern is used as the basis. The obtained empirical models will be applied in later delay analysis. All these statistical results are reported with 95% confidence level.

A. Packet error rate (PER)

PER is the ratio of the number of unacknowledged data packets to the total number of transferred packets. By curve fitting over the measured average PER data as shown in Fig. 3, PER P_e can be modeled as an exponential function of Signal-to-Noise Ratio (SNR) and data packet payload size l as:

$$P_e = c_1 \cdot l \cdot \exp(-c_2 \cdot \text{SNR}), \quad (2)$$

with $c_1 = 0.0128$ and $c_2 = 0.15$ for our tested environment.

B. Packet service time

The packet service time, denoted as T , is defined as the time interval between when a packet reaches the head-of-queue ready for transmission at the sender and when it is received at the receiver. It depends on (1) t_{SPI} – the one-time hardware

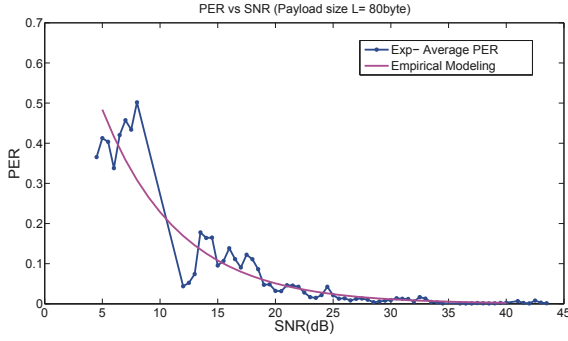


Fig. 3: Packet error rate

SPI bus loading time of a data frame; (2) t_{frame} – the time to transmit a frame consisting of packet payload and overhead; (3) t_{MAC} – MAC layer delay consisting of two parts: t_{TR} and t_{BO} , where t_{TR} is the turn around time (set to $0.224ms$ in our experiments) and t_{BO} is the average value of initial backoff period (set to $5.28ms$); (4) t_{ACK} – the ACK frame transmission time if ACK frame is received, and based on prior tests $t_{ACK} \approx 1.96ms$; (5) $t_{waitACK}$ – the maximum software ACK waiting period (set to be $8.192ms$); (6) n_{tries} – the number of transmissions to deliver each packet; (7) D_{retry} – the delay between two consecutive retransmissions.

There are two cases in per-packet service time, denoted as T_{ACK} and T_{nonACK} respectively, depending on whether a packet is successfully transmitted (i.e., ACK received):

- If $1 \leq n_{tries} \leq N$ (with ACK),

$$T_{ACK} = t_{SPI} + t_{succ} + (n_{tries} - 1) \cdot t_{retry} \quad (3)$$

- If $n_{tries} = N$ (with no ACK),

$$T_{nonACK} = t_{SPI} + t_{fail} + (N - 1) \cdot t_{retry} \quad (4)$$

where N denotes the maximum number of transmission tries set in the system, $t_{succ} = t_{MAC} + t_{frame} + t_{ACK}$, $t_{fail} = t_{MAC} + t_{frame} + t_{waitACK}$, and $t_{retry} = D_{retry} + T_{fail}$.

Due to the random nature of wireless transmission, the actual number of retransmissions of a packet n_{tries} is a random value. Hence the packet service time T is also random. From the measurement results, we found that the mean and variance of packet service time, denoted as $E(T)$ and $Var(T)$ respectively, are sensitive to the maximum number of transmissions N , payload size l , the delay between two consecutive retransmissions D_{retry} and SNR. Through curve fitting, empirical models for them are

$$E(T) = \frac{0.06}{N} D_{retry} \cdot l \cdot \exp(-0.12SNR) + 15 \quad (5)$$

$$Var(T) = 30N \cdot D_{retry} \cdot \exp(-0.15SNR) \quad (6)$$

Example fitting results under different parameter configurations are shown in Fig. 4.

C. Packet loss rate (PLR)

Packet loss over a wireless link is mainly caused by poor link quality and limited buffer size. The former may result in

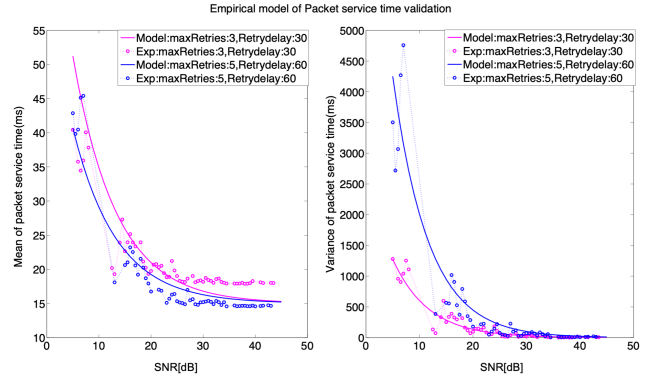


Fig. 4: Packet service time: mean and variance

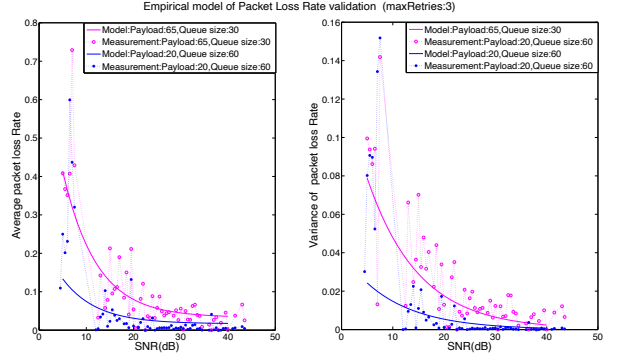


Fig. 5: Packet loss rate

the drop of a packet after the maximum transmission attempts $N_{maxTries}$ have been tried. The latter will cause a packet being dropped when its arrival sees a full buffer. Note that PLR, i.e. $P\{\mathcal{L}\}$ in (1), differs from PER. The difference is that while PER considers all transmissions including retransmissions, PLR only counts it one time for each packet no matter whether it may have been retransmitted multiple times.

For PLR, we also consider its variance, denoted as $Var(PLR)$. It is found that both are functions of payload size l , SNR, and buffer size b , under each configured maximum number of transmission tries (maxTries) N . By curve fitting as exemplified and shown in Fig. 5, for $N = 3$, the PLR and its variance can be approximately modeled as:

$$P\{\mathcal{L}\} = \frac{l}{100} \exp(-0.14SNR) + \frac{1}{b} \quad (7)$$

$$Var(PLR) = \frac{l}{500} \exp(-0.1SNR) \quad (8)$$

IV. QUEUEING MODEL FOR DELAY ANALYSIS

In comparison to estimating packet loss rate $P\{\mathcal{L}\}$, which can be easily made by counting the numbers of packets sent and received, *estimating delay particularly its distribution tail, e.g. $P\{D > d|\mathcal{L}\}$, is difficult*. This is not only because measuring delay requires time-synchronisation among nodes in the system and accurate time information from both the

sender and the receiver, but also because estimating the delay distribution tail requires much higher number of packets to be involved. To address this difficulty, our approach is to construct a queueing model on which delay analysis can be performed, including finding the delay tail distribution.

A. The non-loss queueing model

The basic idea is to treat the system as a blackbox from the receiver view, where all received packets have been successfully delivered without the lost packets. As such, we model the transmission process of successfully received packets over the link as a $G/G/1/\infty$ non-loss queueing system shown in Fig. 6. Specifically, as illustrated in Fig. 6, the (successfully received) packets arriving to the equivalent system are served in the FIFO manner with an infinite size buffer for possible queueing. Let $A(t)$ and $L(t)$ respectively represent the original packet arrival process and the loss process. Then, the packet arrival process after considering lost packets becomes $A(t) - L(t) \equiv A^*(t)$. In addition, we let $R(t)$ represent the service time process of successfully received packets.

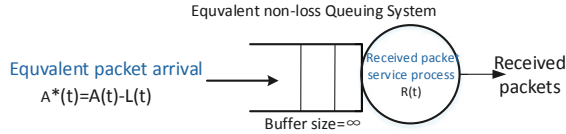


Fig. 6: Equivalent non-loss queueing model

Given the packet loss rate and its variance, the mean and variance of the equivalent packet arrival rate, respectively denoted as λ and $Var(A^*)$, can be found as:

$$\lambda = \frac{1}{\tau} \cdot (1 - P\{\mathcal{L}\}) \quad (9)$$

$$Var(A^*) = \left(\frac{1}{\tau}\right)^2 \cdot Var(PLR) \quad (10)$$

where τ denotes the packet inter-arrival time of the original packet arrival process.

B. Model validation using mean delay

For a $G/G/1/\infty$ system that is not overloaded and hence has finite waiting time, let λ denote the mean arrival rate and $\sigma_{A^*}^2$ its variance, and $E[T]$ the mean service time and σ_T^2 its variance. The following approximation for mean waiting time in queue, denoted as $E[W]$, is from the classical queueing theory, e.g. see [13]:

$$E[W] \approx \frac{\lambda(\sigma_{A^*}^2 + \sigma_T^2)}{2(1 - \rho)} \quad (11)$$

where $\rho = \lambda \cdot E(T)$ is the traffic intensity of the system. With (11), the mean (system) delay, denoted as $E[D]$, is simply:

$$E[D] = E[W] + E(T). \quad (12)$$

For the equivalent $G/G/1/\infty$ system, λ is the equivalent average packet arrival rate that can be found from (9) and $\sigma_{A^*}^2$ its variance from (10), and $E(T)$ and σ_T^2 can be found from

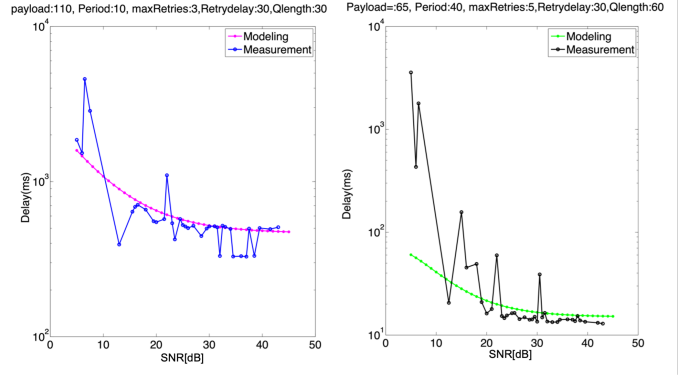


Fig. 7: Model validation: mean delay

(5) and (6) respectively. With these, the mean delay can be analytically estimated from (12).

Fig. 7 compares mean delay results obtained through experiment and through the analytical model above under different parameter settings. It can be observed that a good agreement between the two results can be found in most cases. This confirms the effectiveness of the proposed equivalent $G/G/1/\infty$ and its validity for mean delay analysis. For the delay from measurement results has larger variation in small SNR region, we remark that this is due to lack of delay samples in this SNR region under our experiment environment.

V. INVESTIGATION ON DELAY DISTRIBUTION

For time-sensitive applications, average delay is often not enough. Instead, RLLC or probabilistic delay guarantee, specified by a non-asymptotic guarantee on the tail delay distribution, is more important. However, for such delay distributions, particularly $P\{D > d|\bar{\mathcal{L}}\}$ for RLLC in 802.15.4 networks, there are few applicable (non-asymptotic) results from the classical queueing theory [13]. In the following, a new queueing theory, i.e. stochastic network calculus [14], is exploited.

A. Stochastic network calculus background

Stochastic network calculus is a queueing theory for (non-asymptotic) stochastic performance guarantee analysis of communication networks [14]. It is built upon two fundamental concepts, which are stochastic arrival curve (SAC) for traffic modeling and stochastic service curve (SSC) for server modeling [14]. There are several definition variations of SAC and SSC. In this paper, the following are adopted from [14].

Definition 1. (Stochastic Arrival Curve) A traffic flow is said to have a stochastic arrival curve α with bounding function f , if its arrival process $A(t)$ satisfies, for all $t \geq 0$ and $x \geq 0$,

$$\Pr\left\{\sup_{0 \leq s \leq t} [A(s, t) - \alpha(t - s)] > x\right\} \leq f(x). \quad (13)$$

where $A(s, t)$ denotes the cumulative amount of traffic of the flow from time s to time t , and $A(t) = A(0, t)$.

Definition 2. (Stochastic Service Curve) A system is said to have a stochastic service curve β with bounding function g , if for all $t \geq 0$ and all $x \geq 0$ there holds:

$$\Pr\{A \otimes \beta(t) - O(t) > x\} \leq g(x), \quad (14)$$

where $A \otimes \beta(t) \equiv \inf_{0 \leq s \leq t} \{A(s) + \beta(t-s)\}$, $O(t)$ denotes the cumulative output traffic amount up to time t .

Theorem 1. (Stochastic delay bound) For a stable $G/G/1/\infty$ system, if the input has a stochastic arrival curve and the system provides a stochastic service curve to the input, as defined above respectively, and the arrival process is independent of the service process, then the delay D satisfies:

$$P\{D > h(\alpha + x, \beta)\} \leq 1 - \bar{f} * \bar{g}(x) \quad (15)$$

where $\bar{f}(x) = 1 - [f(x)]_1$, $\bar{g}(x) = 1 - [g(x)]_1$ with $[\cdot]_1$ denotes $\max(\min(\cdot, 1), 0)$, $h(\alpha + x, \beta)$ represents the maximum horizontal distance between curves $\alpha + x$ and β , and $*$ is the Stieltjes convolution operation $\bar{f} * \bar{g}(x) = \int_0^x \bar{g}(x-y) d\bar{f}(y)$.

In the literature, SACs of various types of traffic process have been derived [14], [15]. Examples are: For a periodic arrival process with period length τ and packet length l , $\alpha(t) = \frac{l}{\tau} \cdot t + l$ and $f(x) = 0$; If the arrivals follow a Poisson process with rate λ , $\alpha(t) = \frac{\lambda t}{\theta} (e^{\theta t} - 1)$ and $f(x) = e^{-\theta x}$ for any $\theta > 0$.

Assuming i.i.d. packet service times, the SSC has the following expressions [15]:

$$\beta(t) = R \cdot t \quad (16)$$

$$g(x) = e^{-\theta \frac{x}{R}} \quad (17)$$

with $R = \frac{l \cdot \theta}{\ln(M_T(\theta))}$ for $\theta > 0$, where l denotes the packet length and $M_T(\theta)$ the moment generating function (MGF) of packet service time T , i.e., $M_T(\theta) = E[e^{\theta T}]$ for any $\theta > 0$.

With these SAC and SSC results, the corresponding stochastic delay bounds for different types of arrival process are readily obtained from Theorem 1.

B. Service modeling of the wireless link

To apply SNC results to delay distribution analysis of the wireless link, the discussion above indicates that we need to find a stochastic service curve for the link. To this aim, equations (16) and (17) are the bridge, where a variable that needs to be decided is R , a rate parameter.

In order to obtain R , we have to first find the MGF of packet service time. Since the distribution of packet service time is unknown and difficult to obtain directly, we consider the following approach by making use of the empirical model for packet error rate obtained from measurement.

As introduced in Sec.III, the per-packet service time is determined by the random variable n_{tries} , i.e., the number of transmissions per packet. The probability that a packet is not transmitted successfully is determined by PER P_e , which is also the packet retransmission probability. For each transmission attempt, the successful probability is $1 - P_e$. As a result, n_{tries} has a truncated geometric distribution, from

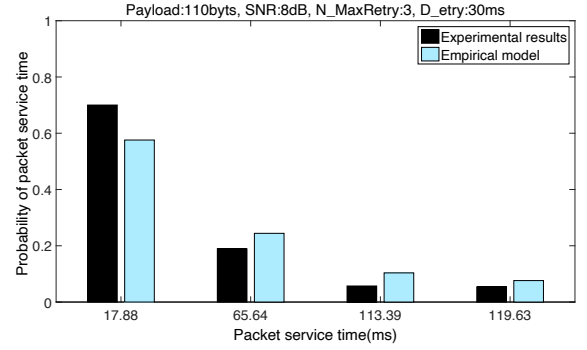


Fig. 8: Validation of packet service time distribution model

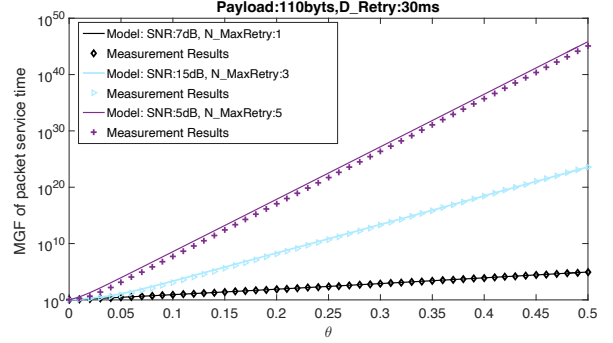


Fig. 9: Validation of empirical model of packet service time MGF

which the distribution of per-packet service time T can also be found. Specifically, we have

$$P\{T = T_{ACK}(n_{tries})\} = (1 - P_e)P_e^{n_{tries}-1}$$

for $1 \leq n_{tries} \leq N$, and otherwise,

$$P\{T = T_{nonACK}\} = 1 - \sum_{n=1}^N (1 - P_e)P_e^{n-1}$$

where P_e is approximated by (2), and T_{ACK} and T_{nonACK} are given in (3) and (4) respectively. Further, according to the definition of moment generation function, an approximation of packet service time MGF $M_T(\theta)$ is given by:

$$\begin{aligned} M_T(\theta) &\equiv E(e^{\theta T}) \\ &= \sum_{n=1}^N e^{\theta T_{ACK}(n)} P\{T = T_{ACK}(n)\} \\ &\quad + e^{\theta T_{nonACK}} P\{T = T_{nonACK}\} \end{aligned} \quad (18)$$

where $\theta > 0$ is in a small neighborhood of zero.

Applying (18) to (16) and (17), a stochastic service curve of the link is obtained, based on which delay distribution analysis can be further conducted with Theorem 1.

Validation: To verify the distribution and MGF empirical approximation model of packet service time, we analyzed the statistics of measured packet service time under different parameter settings. We also compared results from the model (18) with those from statistical analysis of the per-packet

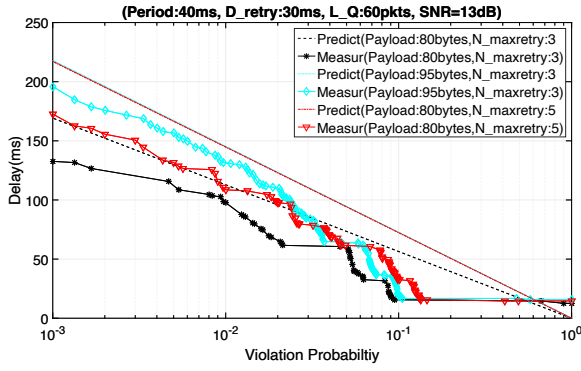


Fig. 10: Validation under different parameter configurations

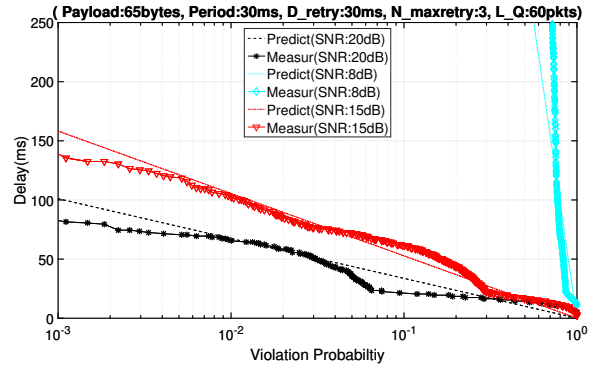


Fig. 11: Validation under different SNRs

service time measured in different parameter configurations. As illustrated in Fig. 8, the truncated geometric distribution matches the measurement data well, meaning that the distribution of packet service time can be approximately modeled by PER and truncated geometric distribution. Further, by using statistic analysis of the measured per-packet service time, the MGF of packet service time can be computed. Fig. 9 shows the comparison between computed MGF of measured packet service time and the proposed model under different parameter settings. As Fig. 9 illustrates, the approximated MGF is in good agreement with the measured result.

C. Delay distribution

In Section IV-B, we have introduced the non-loss queueing model for delay analysis and used mean delay to validate. Further in this section, the above discussion has shown how the delay distribution $P\{D > d|\mathcal{L}\}$ can be estimated based on SNC with the non-loss queueing model. Fig. 10 and Fig. 11 present results for period arrival traffic under different parameter configurations and different SNRs, which are obtained from both the SNC-based analysis and the experiments.

As can be observed, the estimated distributions based on the analysis agree well with the measurement results for all cases. A cause of the slight difference in the matching is the MGF approximation model of packet service time, which has been used in deriving SSC and delay distribution bound. The validation has also been conducted under other traffic patterns and the results can be found in [18].

Finally, with the empirical model for $P\{\mathcal{L}\}$ and the SNC-based analysis for $P\{D > d|\mathcal{L}\}$, the capability of the wireless link in delivering RLLC can be readily assessed.

VI. CONCLUSION

We investigated the performance of packet delivery over an IEEE 802.15.4 link. By exploiting measurement results, both the classical queueing theory and the stochastic network calculus (SNC) theory have been utilized for service modeling and delay analysis of the performance. Specifically, a non-loss queueing model is first constructed. Then, a classical queueing theory result is utilized to estimate the mean delay performance. Finally, for probabilistic delay guarantee, SNC is

applied to estimate the delay distribution, for which, a method to model the service time is introduced. The comparisons, showing a good match between analytical results and measurement results, give cross-validation of the proposed non-loss queueing model, the classical queueing theory based mean delay analysis and the SNC based delay distribution analysis. This indicates the effectiveness of the proposed approach of integrating empirical models with analytical models for assessing the capability of a wireless link in providing reliable low latency communication (RLLC).

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