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Worst-Case Bound Analysis for the Time-Critical MAC behaviors of IEEE 802.15.4e

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Abstract

With an advancement towards the paradigm ofInternet of Things (IoT), in which every device will be interconnected and communicating with each other, the field of wirelesssensor networks has helped to resolve an ever-growing demandin meeting deadlines and reducing power consumption. Amongseveral standards that provide support for IoT, the recentlypublished IEEE 802.15.4e protocol is specifically designed to meetthe QoS requirements of industrial applications. IEEE 802.15.4eprovides five Medium-Access Control (MAC) behaviors, includingthree that target time-critical applications: Deterministic andSynchronous Multichannel Extension (DSME); Time SlottedChannel Hopping (TSCH) and Low Latency Deterministic Network (LLDN). However, the standard and the literature do notprovide any worst-case bound analysis of these behaviors, thusit is not possible to effectively predict their timing performancein an application and accurately devise a network in accordanceto such constraints. This paper fills this gap by contributingnetwork models for the three time-critical MAC behaviors usingNetwork Calculus. These models allow deriving the worst-caseperformance of the MAC behaviors in terms of delay andbuffering requirements. We then complement these results bycarrying out a thorough performance analysis of these MACbehaviors by observing the impact of different parameters.

Worst-Case Bound Analysis for the Time-Critical MAC behaviors of IEEE 802.15.4e

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Abstract—**With an advancement towards the paradigm of Internet of Things (IoT), in which every device will be interconnected and communicating with each other, the field of wireless sensor networks has helped to resolve an ever-growing demand in meeting deadlines and reducing power consumption. Among several standards that provide support for IoT, the recently published IEEE 802.15.4e protocol is specifically designed to meet the QoS requirements of industrial applications. IEEE 802.15.4e provides five Medium-Access Control (MAC) behaviors, including three that target time-critical applications: Deterministic and Synchronous Multichannel Extension (DSME); Time Slotted Channel Hopping (TSCH) and Low Latency Deterministic Network (LLDN). However, the standard and the literature do not provide any worst-case bound analysis of these behaviors, thus it is not possible to effectively predict their timing performance in an application and accurately devise a network in accordance to such constraints. This paper fills this gap by contributing network models for the three time-critical MAC behaviors using Network Calculus. These models allow deriving the worst-case performance of the MAC behaviors in terms of delay and buffering requirements. We then complement these results by carrying out a thorough performance analysis of these MAC behaviors by observing the impact of different parameters.**

Keywords: *IEEE 802.15.4e; Network Calculus; Quality of Service*

I. INTRODUCTION

Wireless Sensor Networks have been enabling an ever-increasing span of applications in domains such as industrial automation, environmental monitoring and personal health care. Naturally, each of these domains impose a different balance in the quality of service of an application. For example, in the industrial domain, applications are often deployed in harsh environments under which they have to ensure higher robustness and reliability in addition to increased lifetime and rigorous timeliness.

To address several of these properties, the IEEE 802.15 Working Group for Wireless Personal Area Networks (WPAN) proposed the IEEE 802.15.4e amendment [1], aiming at enhancing and extending the functionalities of the IEEE 802.15.4-2011 protocol [2]. This is achieved by proposing several MAC behaviors, which besides providing deterministic communications are also fitted with a multi-channel frequency hopping mechanism. For example, Deterministic and Synchronous Multichannel Extension (DSME) and Time Slotted Channel Hopping (TSCH) are fitted with guaranteed timeslots and multi-channel frequency hopping mechanism. There are also other MAC behaviors like the Low Latency Deterministic network (LLDN), which uses Time Division Multiplexing Access (TDMA) to provide timing guarantees. Nevertheless, thorough network planning is needed to correctly address the demands of the network in terms of delay and resources. To achieve this, modeling the fundamental performance limits of these networks is of paramount importance to understand their behavior under the worst-case conditions, and effectively allocate the necessary resources.

In this paper, we:

- present an extended analytical model to calculate the worst case bounds of the DSME, TSCH and LLDN MAC behaviors of the IEEE 802.15.4e, based on Network Calculus formalism, thus extending our previous work in [3]. Our previous work only partially addressed DSME and TSCH, and no thorough analysis had been carried out.
- devise methods to calculate the throughput and the overall delay of the time critical MAC behaviors of IEEE 802.15.4e.
- carry out a complete performance analysis of all the time critical MAC behaviors of IEEE 802.15.4e in terms of throughput and delay.

The remaining of the paper is organized as follows: In the next section we present an overview of the related work. In Section III, we provide an overview of the IEEE 802.15.4e protocol and in particular the DSME, TSCH and LLDN MAC behaviors. The delay bound model devised using network calculus for the aforementioned MAC behaviors is proposed in Section IV and the paper ends with a performance evaluation of these MAC behaviors and some final remarks.

II. RELATED WORK

Emerging applications in IoT and CPS, have been increasingly imposing stringent time constraints. Due to its pervasiveness, wireless sensor networks became interesting infrastructures to support such systems [4], particularly with standards such as IEEE 802.15.4 [2]. Though this standard provided new opportunities of communications in the field of Low-Rate Wireless Personal Area Networks (LR-WPAN), it lacked features to suit the stringent timeliness, scalability and reliability constraints of realtime networks. Several protocols [5], [6] have been developed for Wireless Ad-Hoc networks aiming at improving the Quality of Service (QoS). These protocols provide additional enhancements like multi-channel access and adaptive channel hopping to ensure the timeliness and reliability of the network, but these do not address any particular standard. Relying on standardized technologies is important, specially with the IoT paradigm where all the devices are expected to communicate and even actuate.

There are already a few works that analyze the time critical MAC behaviors of the IEEE 802.15.4e. The authors in [7] have analytically compared the DSME MAC behaviour of IEEE 802.15.4e to the traditional IEEE 802.15.4 in terms of throughput and end-to-end delay. The throughput of the DSME was 12 times higher than IEEE 802.15.4 slotted CSMA/CA in a multi-hop network. The DSME MAC behaviour was also analytically analyzed in [8] under interference of Wireless Local Area Network (WLAN). Due to its multi-channel access mechanism, DSME-GTS was more resilient to interference in comparison with IEEE 802. 15.4 slotted CSMA-CA.

Concerning TSCH, in [9], authors have developed analytical models for channel hopping mechanisms, and proposed efficient ideas like blacklisting algorithms. A comparative assessment [10] of the DSME and the TSCH MAC behaviors has been developed using the OMNet++ simulation environment. Interestingly DSME was found to outperform TSCH in terms of end-to-end delay when the number of nodes increases because of its enhanced features. Watteyne et al explored the capabilities of TSCH. They present a hardware model [11] to estimate the delay, power consumption and throughput of a network. This model supports SmartMesh IP, a commercial solution for highly reliable and ultra low-power wireless sensing.

The authors in [12] claim that the efficiency and scalability of the LLDN can be enhanced using improved multichannel communication. OMNet++ was used to simulate this model. There is a performance evaluation with respect to variations in the superframes in which the authors of [13] provide an insight about the relationship of superframe size, base timeslot size and data payload. A mobility-aware (MA-LLDN) scheme has been implemented for LLDN in [14], in which the authors claim that their approach minimizes both latency and energy consumption when compared to the standard LLDN enabled network.

The current state of the art focuses mostly on improving the QoS aspects of the networks, but it lacks in characterizing the service provided by MAC behaviors and providing the respective delay bounds. Modeling the worst case bounds will help in understanding the aspects that impact the performance of the network.

In our previous work [3], we presented analytical models for DSME and TSCH MAC behavior and we derived equations for the traffic flows and service offered by these MAC behaviors. It lacked the model for LLDN, for an extensive comparison in terms of QoS between all the MAC behaviors and a thorough performance analysis.

In this paper, we define the worst case bounds for DSME, TSCH and LLDN using Network Calculus. Network Calculus is a mathematical tool used to provide deep insights into flow problems faced in networking. It is an approach independent from the traffic representation and more adapted to the computation of network delays [15]. To the best of our knowledge, we are the first to use Network Calculus methodology to effectively determine the delay bounds of the time critical MAC behaviors of IEEE 802.15.4e. In addition, we also provide an extensive performance analysis for all the time critical MAC behaviors in terms of overall delay and throughput.

III. IEEE 802.15.4 E - AN OVERVIEW

The IEEE 802.15.4 standard [2] specifies the Physical and Data Link Layers of the communication stack. Its MAC (Medium Access Control) supports the beacon-enabled or non beacon-enabled modes that may be selected by a central controller of the WSN, called Personal Area Network *(PAN)* coordinator. Beacon-enabled mode enables the provision of guaranteed bandwidth through the Guaranteed Time Slot (GTS) mechanism. In this mode, beacon frames are periodically sent by each PAN coordinator to synchronize nodes that are associated to it and to form a structure called the superframe. The superframe specified in IEEE 802.15.4 is divided into 16 equally-sized time slots, within which data transmission is allowed. Each active portion can be further divided into a Contention Access Period (CAP) that uses slotted CSMA/CA for best-effort data delivery, and an optional Contention Free Period (CFP) supporting the time-bounded data delivery. The CFP supports up to 7 GTSs and each GTS may contain one or more time slots. Each GTS can be used to transfer data either in transmit direction, i.e. from child to parent node (upstream flow), or from parent to child node (downstream flow). Despite having a very powerful architecture, because of the limited number of timeslots and absence of multichannel access, IEEE 802.15.4 was not able to cope up with the scalability and QoS requirements of realtime IoT applications.

The IEEE 802.15.4e standard [1] proposes an enhanced version of IEEE 802.15.4-2011 by introducing a set of MAC behaviors which are tailored provide additional QoS support. Mechanisms which are prominent in the industrial communication field such as frequency hopping, dedicated and shared timeslots and multichannel communication have been implemented in this amendment. In this section, we provide an insight into three MAC behaviors: DSME, TSCH and LLDN. These MAC behaviors are enhanced with unique properties and they aim at guaranteeing determinism and improving QoS properties like timeliness, reliability and scalability of the network.

A. DSME MAC Behavior

A DSME enabled PAN coordinator relies on a multi superframe structure, which is composed of a cycle of superframes that are similar to the IEEE 802.15.4 superframe format. Details such as the number of superframes in a multi superframe and the time synchronization are conveyed to the nodes through an Enhanced Beacon (EB) which is transmitted by the PAN Coordinator at the beginning of every multi superframe. The nodes contend for the channel in the CAP region using standard CSMA/CA. The CFP is composed of multiple communication slots across different channels, which can be occupied by any pair of nodes within the transmission range. These slots are called *DSME GTSs*. Figure 1 shows the multi superframe and superframe structure of the DSME MAC behaviour. In Figure 1, the columns in the CFP region of the superframe structure indicate *timeslots* and the rows indicate the *channels* available for hopping.

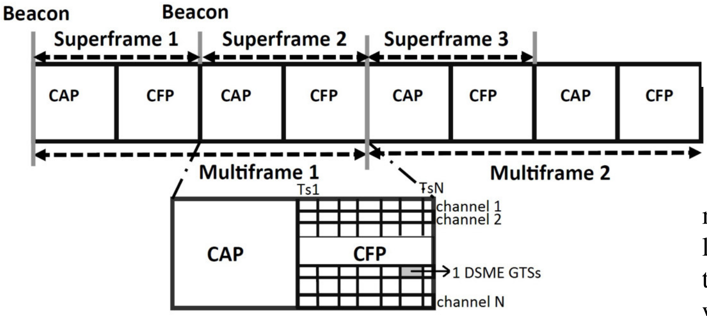

Fig. 1. DSME Throughput analysis - CAP reduction

B. TSCH MAC Behavior

In a TSCH network, the concept of superframes used in beacon enabled communication protocols has been shifted into periodically repeating *slotframes*. Every slotframe is composed of multiple timeslots which are pre-defined periods of communication. TSCH uses either contention free or contention based communication, depending on if it is using a reserved or a shared timeslot to transmit a frame, and eventually an acknowledgement. Multi-channel support is one of the major characteristics of the TSCH MAC behaviour. There are 16 channels available for hopping in TSCH. *Absolute Slot Number* (ASN) for every timeslot increases globally and is used to find the number of elapsed slots since the beginning of the network. Figure 2 shows a slotframe with three timeslots in which two devices are transmitting through 2 different channels. In timeslot 1 (Ts1), device A transmits its data to B through channel 1 and during timeslot 2 (Ts2) B transmits to C through channel 2 and during timeslot 3 (Ts3) the device remains in an idle state. The slot frame repeats periodically.

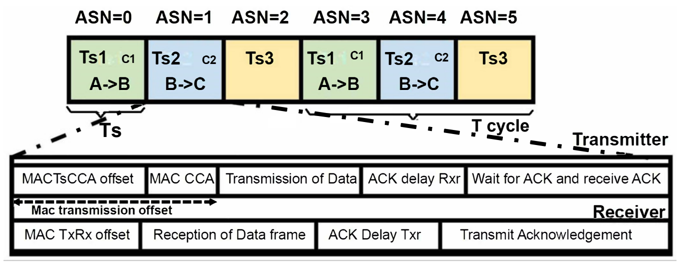

Fig. 2. Three timeslot-slotframe of TSCH

C. LLDN MAC Behavior

LLDN exclusively uses a beacon enabled star topology with a minimal superframe structure called the *LL frame* (Figure 3) for transferring data. The beacon issued by the PAN coordinator at the start of the superframe provides the schedule for the entire network (time synchronization data).

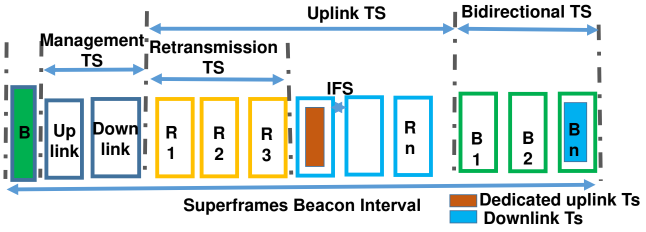

Fig. 3. Low-Latency Frame

Following the beacon, an LL frame is composed of two management timeslots (one uplink and one downlink), uplink timeslots and bidirectional timeslots. The management timeslots are used during the setup phases of the network, in which the discovery and configuration of a new device is done. Following the management timeslots, the uplink timeslots can be used for unidirectional transmissions (from node to the PAN coordinator). PAN Coordinator can assign a timeslot for a specific nodes transmission. Bidirectional timeslots are used to send the data from the PAN Coordinator to the nodes and vice-versa. The direction of the bidirectional timeslots is set during the setup phase. We focus on the transmitting stage of the setup phase in Section 4.5 for our analysis, for a fair comparison with the other MAC behaviors, considering it is only in the *Online state* the data transmission takes place.

IV. DELAY BOUND USING NETWORK CALCULUS

Network Calculus is a theoretic formulation which is well adapted to controlled traffic sources and provides upper bounds on delays for traffic flows [16]. For a cumulative arrival function $R(t)$ there exists an arrival curve $\alpha(t) = b + rt$ where b, r, t are the burst size, data rate and time interval respectively. A minimum service curve $\beta(t)$ is guaranteed to $R(t)$. As shown in Figure 4, the maximum delay of the network is given by the horizontal distance between the arrival and the service curves. The delay is computed in accordance to the maximum latency of the service (T) and the data rate (r) as shown in Equation 1:

$$D_{max} = \frac{b}{r} + T \tag{1}$$

The leaky bucket (b, r) model is used to derive the network models of DSME and TSCH. It is simple and it can represent the higher bound of any kind of traffic. The variance between the (b, r) curve and the realistic model is adequate for periodic traffic which is commonly the case of Wireless Sensor Networks.

A. Service curve analysis of DSME

Let us consider a single PAN coordinator and a set of nodes forming a DSME enabled IEEE 802.15.4e network. The PAN coordinator sends an Enhanced Beacon to every multi superframe, and a beacon to each superframe. The superframe

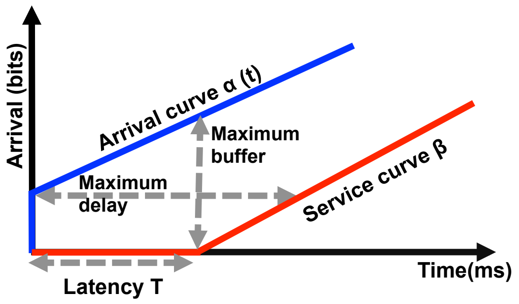

Fig. 4. Arrival curve, service curve, delay bound

duration of DSME enabled network when $SO = 0$ (i.e) *aBaseSuperframeDuration* will be 15.36 ms, considering an ideal data rate C of 250 kbps. [3]

It is mandatory that the data transmission, Short and Long Inter-Frame Spacing (SIFS (.048 ms)), (LIFS (.16 ms)) and acknowledgements/Group acknowledgments (if requested) are accommodated within the end of a DSME GTS for successful transmission of a message. For the sake of simplicity, we consider one data frame transmission in each a DSME GTS per superframe.

The size of a timeslot in a superframe, T_s, is given by,

$$T_s = \frac{SD}{16} = aBaseSuperframeDuration \ \times 2^{SO-4} \tag{2}$$

SD is the duration of a single superframe. Every timeslot T_s in a superframe is made up of T_{data} and T_{idle}. T_{data} is the maximum duration used for data transmission in a guaranteed timeslot. T_{idle} is the time period that accommodates the acknowledgments and inter-frame spacing in the network. Beacon Interval (BI) marks the duration between every beacon issued in-between superframes. As shown in Equation 3 latency T, the time for which a burst waits for its service is the difference between the bursts arrival at the beacon interval and the time at which the data is served.

$$T = BI - T_s \tag{3}$$

The overall service provided by the network can be given by the product of the data rate and the time at which the system receives the service. The service given for the guaranteed timeslots i.e the number of bits that has to be sent during a GTS during a time t is given by Equation 4,

$$\beta_1 = \begin{cases} C\ ((t-(BI-T_s)))^+, \forall 0\ \leq t \leq BI - T_{idle} \\ 0, otherwise \end{cases} \tag{4}$$

$$wherex^+ = max(0,x)$$

This value of the service curve can be derived to N number of superframes, similar to the equation derived for the service curve for n superframes of IEEE 802.15.4 in Reference [17]. The overall duration of all the timeslots considered in the superframes is given by T_N. The service of the N_{th} superframe is given by:

$$\beta_N = \begin{cases} (N-1)CT_{data} + C\left(t-(N(BI)-T_N)\right)^+ \\ \forall 0 \leq t \leq (N-1)BI - T_{idle} \\ 0, \qquad otherwise \end{cases} \tag{5}$$

The DSME GTS service curves of DSME MAC behaviour is given as a staircase model in Figure 5.

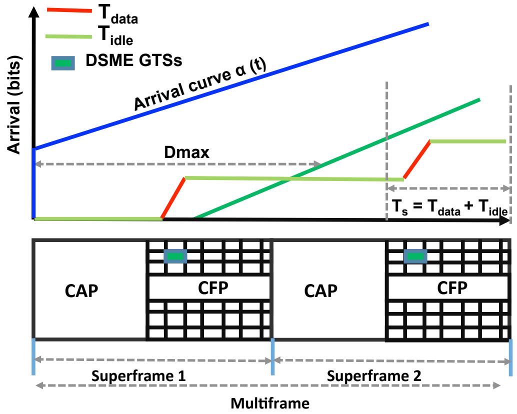

Fig. 5. Service curve of DSME MAC

B. Delay bound and Throughput analysis of DSME

The summation of every individual delay bounds for every superframe within a multi superframe will give its overall delay bound. For burst size b greater than CT_{data}, the maximum delay bound of the first superframe D_{max1} with m channels will be the horizontal angular distance between the arrival curve and the first stair as shown in Figure 5. In accordance to Equation 1 for a minimum service of $\beta(t)$ that will be provided for cumulative data flow $R(t)$, the delay will be:

$$D_{max1} = \frac{b}{C} + (\ BI - \ T_s)\ \ if\ \ b\ \leq CT_{data} \tag{6}$$

When $N(CT_{data}) < b \leq (N+1)CT_{data})$, the delay of the system with N number of super-frames and m channels is given by:

$$D_{maxN} = \frac{b}{m \times C} + (\ (N+1)BI - \ T_s) - Nt_{data} \tag{7}$$

$$if N(CT_{data})\ < b \leq (N+1)CT_{data}$$

We employ the method used in [18] for the throughput calculation of all the time critical MAC behaviors. DSME has the parameters of Inter-Frame Spacing (IFS) similar to that of legacy IEEE 802.15.4. The throughput of a DSME enabled GTS will be the same as that of IEEE 802.15.4 under same parameters such as arrival rate and data rate, if multichannel access is not taken into consideration. Whereas from a network perspective, considering the entire CFP, channel capacity will have an increasing impact on the overall network throughput. The following Equation 8 is derived based on the throughput derivation in [18] and it represents the overall network throughput, which is defined as the maximum amount of traffic that can be transmitted simultaneously over the network. The throughput formulated for m channels and n superframes is given by:

$$Th_{max} = n \times \min \begin{cases} (b + rT_S)/BI, \\ \max \begin{cases} ((T_s - (N_{LIFS} - 1) \cdot LIFS \\ -\triangle(IFS)\ C \cdot m/BI, (8) \\ \\ Ts - N_{SIFS} \cdot SIFS))\ C \cdot m/BI \end{cases} \end{cases} \tag{8}$$

C. Service curve analysis of TSCH

The aim of the TSCH network model is to derive an expression for the delay bound of an arrival rate $R(t)$ bounded by a (b, r) curve for a single timeslot in a non-contention based slotframe. In accordance to the standard, the duration of every timeslot (T_s) is strictly 10 ms [1]. During a transmission in non-shared dedicated timeslot, an unit timeslot has to accommodate acknowledgment delays (of both the receiver and the transmitter) and the receiving and transmitting frames.

Every timeslot is comprised of equal periods and is composed of T_{data} and T_{idle}. T_{data} is the time duration for a data transmission in the timeslot. T_{idle} comprises the acknowledgment delays, MAC offsets and acknowledgments. Let us consider T_{cycle} to be the duration for which the slotframes repeat periodically. The latency (T) for data transmission in one timeslot in a slotframe is given by Equation 9 and the service obtained by the first slot frame at a time t is given by Equation 10:

$$T = T_{cycle} - T_s \tag{9}$$

$$\beta = \begin{cases} C(t - (T_{cycle} - T_s))^{+} \forall 0 \leq t \leq T_{cycle} - T_{idle} \\ 0, \quad otherwise \end{cases} \tag{10}$$

Considering a TSCH enabled network with N number of slotframes, the overall service of the system till the Nth timeslot can be computed as follows:

$$\beta_N = \begin{cases} (N-1)CT_{data} + C\left(t - (NT_{cycle} - T_N)\right)^{+} \\ \forall 0 \leq t \leq (N-1) \quad (T_{cycle} - T_{idle}) \\ 0, \quad otherwise \end{cases} \tag{11}$$

The service curve of the TSCH MAC behavior results in a staircase shape as depicted in Figure 6.

D. Delay bound and throughput analysis of TSCH

For the first slotframe, assuming that $b \leq CT_{data}$, the maximum delay bound D_{max1} will be the horizontal angular distance between the arrival curve and the first stair. We consider that a minimum service of $\beta(t)$ is provided for cumulative data flow of $R(t)$, the corresponding delay will be:

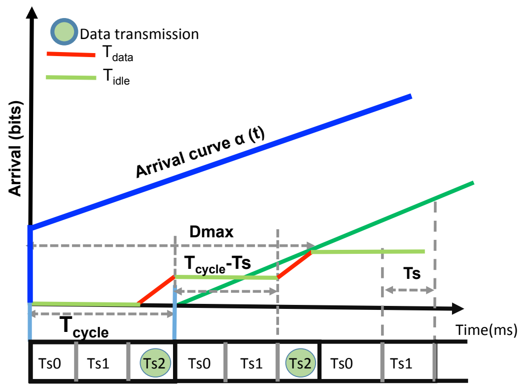

Fig. 6. Service curve of TSCH MAC

$$D_{max1} = \frac{b}{C} + (T_{cycle} - T_s) \tag{12}$$

When $N(CT_{data}) < b \leq (N+1)CT_{data})$, the delay of the system with N number of slotframes is given by:

$$D_{maxN} = \frac{b}{C} + (\ (N+1)T_{cycle} - T_s) - Nt_{data} \tag{13}$$

The overall throughput of TSCH networks is a function of the duty cycle. $T_{dutyCycle}$ is the ratio of the current T_{Cycle}, which is the active period of the network to the total number of T_{Cycles} present in the network. The throughput taking a single timeslot in to account can be given by:

$$Throughput = \ (T_{data}/T_{dutyCycle}) \times C \tag{14}$$

Considering the multichannel aspects of TSCH and assuming m is the number of channels, the value of the network throughput Th_{Max}, which is the maximum traffic transmitted simultaneously over the network is given by:

$$Th_{max} = ((b + r \cdot T_S)/T_{dutycycle})m \times C \tag{15}$$

E. Service curve analysis of LLDN

LLDN network setup is composed of three different states: Discovery, Configuration and Online. In the *Discovery state*, the device that wants to join the networks scans the available channels for a LLDN PAN coordinator which is broadcasting beacons indicating discovery state. The scanning device sends its current configuration to the PAN coordinator during this state, which is in-turn acknowledged. In the *Configuration state* the PAN Coordinator sends the new configuration details for the receiving device. The configuration message contains the length of the management slots and the directions of the bidirectional frames. Each device will receive a number of shared/dedicated timeslots in accordance to its respective IDs. LLDN facilitates retransmission using uplink timeslots in case of collisions. For the service curve analysis, we only consider the *Online state* as data transmission and retransmission occurs solely in this state. We design the Network Calculus model assuming a data transmission from a dedicated node to a PAN coordinator (uplink timeslot) and the transmission from PAN coordinator to the node using a bidirectional timeslot (configured to downlink). It is mandatory that the data transmission, inter-frame spacing and acknowledgments/Group acknowledgments (if requested) complete within the end of the allocated timeslot for a successful data transmission.

Let us consider a dedicated slot allocated for single node as T_{Uplink} and $T_{downlink}$ as the timeslot allocated for the transmission of data from the PAN coordinator. Both are composed of T_{data} and T_{idle}. T_{data} is the maximum duration used for data transmission inside the dedicated timeslot and T_{idle} comprises the time occupied by inter-frame spacing (IFS) and group acknowledgments. The latency of an LLDN enabled network is the difference between the bursts arrival (start of the beacon interval) and the time at which the data is served either as an *uplink* or a *downlink*. The maximum latency, T either in the *uplink* or the *downlink* is the time a burst may wait for a service. It is given by Equation 16:

$$T = BI - [T_{uplink/downlink}] \tag{16}$$

The total service provided by the network is given as the product of the data rate and the time at which the system receives the service. The service curve (Figure 7) calculated over time t, is the minimum number of bits that has to be transmitted during an uplink of a dedicated node.

$$\beta_{uplink} = \begin{cases} C\left(t - (BI - T_{uplink})\right)^{+} \\ \forall 0 \leq t \leq (N-1)BI - T_{idle} \\ 0, \qquad otherwise \end{cases} \tag{17}$$

Similarly the service curve for the downlink slots can be derived as,

$$\beta_{downlink} = \begin{cases} C\left(t - (BI - T_{downlink})\right)^{+} \\ \forall 0 \leq t \leq (N-1)BI - T_{idle} \\ 0, \qquad otherwise \end{cases} \tag{18}$$

LLDN works using the mechanism of Time Division Multiplexing Access (TDMA). The superframes repeat in cyclic intervals. If N is the total number of cycles for which the superframe repeats, the service of the system can be given by:

$$\beta_N = N \times \beta_{[uplink/downlink]} \tag{19}$$

F. Delay bound and throughput analysis of LLDN

To calculate the delay bound, we consider the transmission of data in one timeslot (T_s) in a single LL frame. T_s can either be an uplink timeslot or a downlink timeslot. The maximum delay bound will be the horizontal linear distance between the arrival curve and the first stair. The value of the delay can be given as follows:

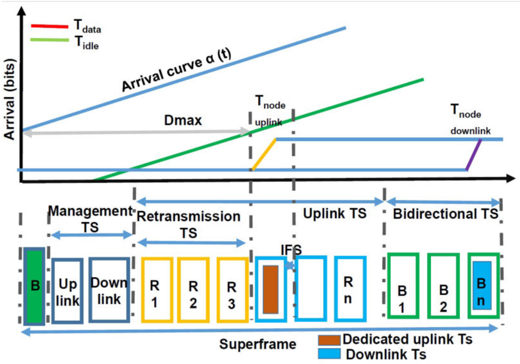

Fig. 7. Service curve of LLDN MAC

$$D_{max1} = \frac{b}{C} + (\ \ BI - \ \ T_s) \tag{20}$$

The maximum delay of a network having N superframes can be given by:

$$D_{max\ network} = \sum_{1}^{N} D_{maxN} \tag{21}$$

The throughput of a single LLDN node depends on the T_{data} which is composed of either T_{uplink} or $T_{downlink}$ or both depending upon the configuration of the network. The throughput equation can be given by:

$$Th_{max} = \ (T_{uplink/downlink}/BI) \times C \tag{22}$$

Considering T_S can either be an *uplink* or a *downlink*, the maximum traffic transmitted simultaneously over the network (i.e) the network throughput is given by Equation 23,

$$Th_{max} = \min \begin{cases} (b + rT_S)/BI, \\ \max \begin{cases} ((T_s - (N_{LIFS} - 1) \cdot LIFS \\ -\triangle(IFS)C/BI, \\ Ts - N_{SIFS} \cdot SIFS))C/BI \end{cases} \end{cases} \tag{23}$$

V. PERFORMANCE EVALUATION

We have implemented a MATLAB tool which has been submitted for inclusion in the Open-ZB framework [19]. It implements the Network Calculus models of DSME, TSCH and LLDN networks. Being LLDN, a star-topology exclusive network, we consider star topology for all the MAC behaviors to even the field in terms of performance analysis, then we summarize the main lessons.

A. DSME Performance Evaluation

In the multi superframe format of DSME, several superframes can be stacked one after the other within a specific beacon interval. If we compare a transmission in a DSME GTSS with an IEEE 802.15.4 GTS, under the equal conditions like superframe duration, traffic and burst size, the throughput will remain the same. However, the maximum throughput of a DSME network can be increased using effective techniques such as CAP reduction. Using CAP reduction technique, the CAP region of a superframe can be completely eliminated and be replaced with a CFP region. The entire multi superframe will be composed of a single CAP region and larger CFP region. CAP reduction can be enabled by the PAN coordinator by issuing an information element through an Enhanced Beacon at the beginning of the multi superframe. For the analysis we take a multi superframe that accommodates three superframes. Using Equation 8, we computed results with and without CAP reduction, for different arrival rates ranging from 5-100 kbps. This was carried out for a sequence of superframe orders.

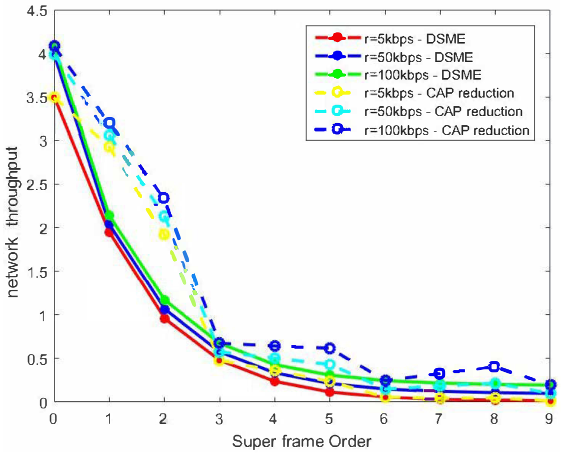

Fig. 8. DSME Throughput analysis - CAP reduction

From Figure 8, it can be inferred that an average 7% increased network throughput is obtained under CAP reduction, as the available guaranteed timeslot bandwidth increases. CAP reduction also increases the overall scalability of the system by inclusion of additional DSME GTSs.

Because Multichannel capability is such a prominent enhancement from IEEE 802.15.4, we compared the service delay for a burst to receive its service in legacy IEEE 802.15.4 and a multichannel enabled DSME network. In the case of DSME, we considered the usage of multiple (2, 3, 4, 6) channels providing an equal bandwidth of 20 Kbits/sec for transmission. Figure 9 shows the delay calculation of the DSME with respect to IEEE 802.15.4. It is clearly evident that DSME outperforms IEEE 802.15.4 because of multichannel capability. For instance, when using five channels, we observe that the delay gets reduced almost by more than 50% in comparison to IEEE 802.15.4.

B. TSCH Performance Evaluation

Regarding TSCH, we learned and analyzed the impact of the average arrival rate on the maximum throughput using Equation 15. We considered 5 channels providing equal data rates of 250kbps. Figure 10 is plotted for a constant burst size of 2 kbits and different arrival rates. It is clear that the throughput decreases by 13 to 20% with the increase of the duty cycle. In addition, higher arrival rates allow achieving higher throughputs. Due to DSMEs multi superframe structure and multichannel capabilities, TSCH gives a lesser throughput if compared with DSME.

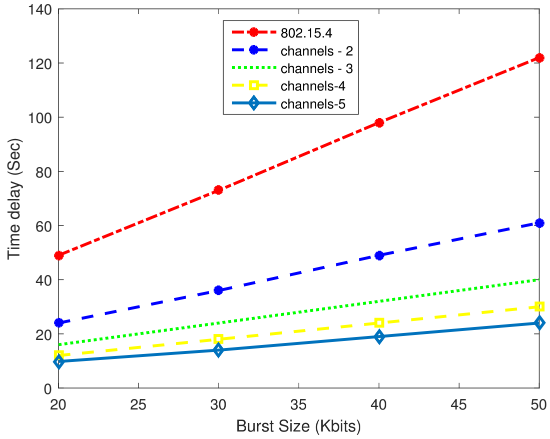

Fig. 9. DSME Delay Analysis - Function of burst size

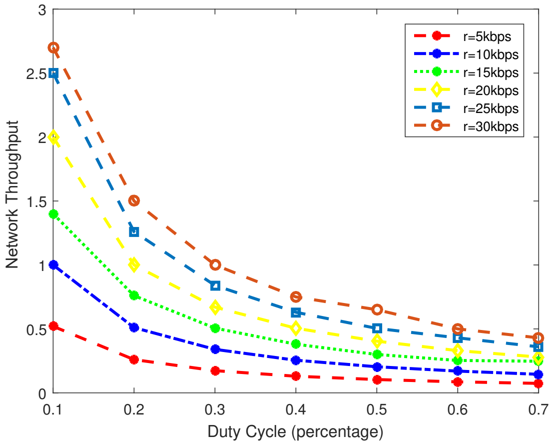

Fig. 10. TSCH - Throughput to $T_{dutycycle}$

Figure 11 shows the time delay as a function of T_{cycle}. We observe that the delay increases linearly with T_{cycle}. The delay increases by 7% with the increase of 10 nodes in the network. As shown in Equation 13, the delay in TSCH is predominantly dependent on the value of T_{cycle}. According to the standard IEEE 802.15.4e, the value of T_s is fixed at a default value of 10 ms, this results in zero delay till the value of T_{cycle} of 10 ms is reached. This makes TSCH a very suitable MAC behavior for application that operate under small T_{cycles}.

C. LLDN Performance Evaluation

For the throughput analysis of LLDN, we consider BO=SO. We increased the values of the superframe order of the LL frame to learn the impact on its respective throughput. From Equation 22, we infer that throughput remains a function of the data rate and it diminishes with the increase of the Beacon Interval (BI). Figure 12 was plotted for a data rate

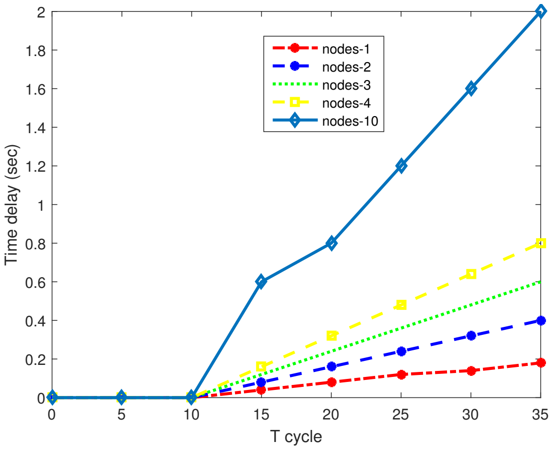

Fig. 11. TSCH - Delay over T_{cycle}

varying from 60kbps to 250kbps at a constant burst size of 5kbs. We observe that, there is almost 50% decrease in throughput with the increase superframe order because of wasted bandwidth.

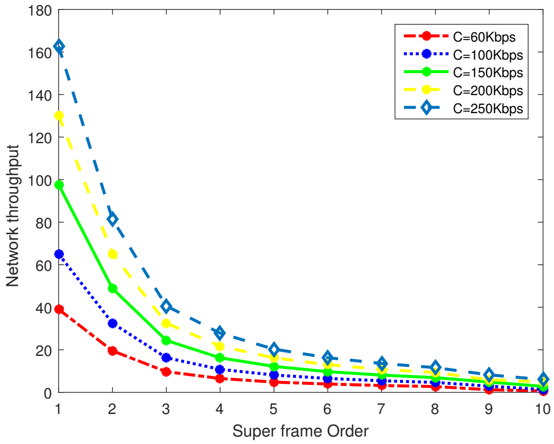

Fig. 12. Throughput of LLDN

We also tried to understand the effect of delay over the number of timeslots. Delay decreases as the amount of timeslots available to accommodate the data increases. As shown in Equation 20 and 22, the increase in delay is more dependent on the value of T_{uplink} or $T_{downlink}$. Figure 13 gives the impact of the number of timeslots over the delay of the system. The number of nodes was varied from 1-15 to be accommodated by timeslots of equal length. It can be noticed that delay increases by 80% when the number of nodes are increased from 1 to 10.

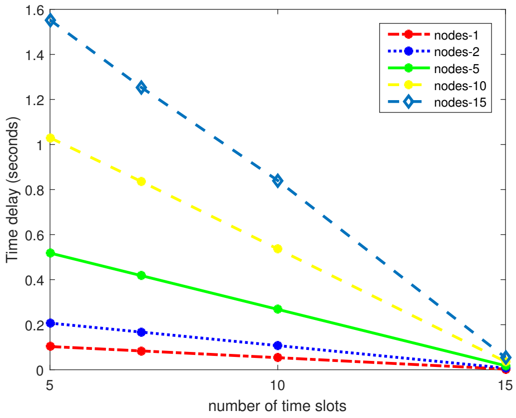

Fig. 13. LLDN - Delay over T_s

VI. DISCUSSION AND FUTURE WORK

In this paper we have derived expressions for computing the worst case bounds of the DSME, TSCH and LLDN MAC behaviors to guarantee the right latency and reliability for a IEEE 802.15.4e network. We also provided a performance analysis in terms of throughput and delay to understand the impact of several parameters in the IEEE 802.15.4e performance. We were able to infer that, because of multichannel access, a DSME network is able to outperform IEEE 802.15.4 in terms of end-to-end delay and throughput. We explored the different capabilities of DSME such as CAP reduction to analyze its features and advantages. We also analyzed the impact of the arrival rates on the throughput of the LLDN and TSCH MAC behaviors. We were able to infer that these MAC behaviors are suited to support different application scenarios due to their flexibility. For example, DSME will be a suitable MAC behavior to implement large scale applications such as structural health monitoring where more nodes have to be connected to a network. LLDN will be suitable for low latency and dense applications in which the network has to be robust and at the same time provide low latencies. On the other hand, TSCH would be efficient for applications that demand low end-end delays.

We believe that this work will enable us to design more efficient ways of scheduling transmissions in these protocols and carrying out efficient network planning, by computing in advance the worst case service and needed resources.

As a future work, we aim at implementing a simulation model for these networks which will enable us to compare results with the analytical model. We also intend to develop an open-source implementation of this protocol for Commercially Off The Shelf WSN platforms (COTS) (e.g. TelosB devices), to validate the results over real WSN hardware.

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