Towards Worst-Case Bounds Analysis of the IEEE 802.15.4e

Harrison Kurunathan[§], Ricardo Severino[§], Anis Koubaa[§*], Eduardo Tovar[§]
[§]CISTER/INESC TEC and ISEP-IPP, Porto, Portugal
[*] Prince Sultan University, Saudi Arabia.
Email: (hkur, rarss, aska, emt)@isep.ipp.pt, akoubaa@psu.edu.sa

***Abstract*—The IEEE 802.15.4e amendment provides important functionalities to address timeliness and reliability in time-sensitive WSN applications, by extending the IEEE 802.15.4-2011 protocol. Nevertheless, in order to make the appropriate network design choices, it is mandatory to understand the behavior of such networks under worst-case conditions. This paper contributes in that direction by proposing a methodology based on Network Calculus that will, by modeling the fundamental performance limits of such networks, enable in the future a quick and efficient worst-case dimensioning of the networks' schedule and resources.**

I. INTRODUCTION

Wireless Sensor Networks have been enabling an ever-increasing span of applications and usages in domains such as industrial automation, environmental monitoring and personal health care. Naturally, each use case imposes a different balance of Quality of Service aspects that must be fulfilled in order to guarantee the correctness of the application. In general Cyber-Physical Systems (CPS) for instance, the provision of deterministic guarantees is of crucial importance. In addition, specially in the industrial domain, robustness and reliability are also of increasing importance, considering the harsh environment in which often these systems must be deployed.

To address several of these properties, the 802.15e Working Group proposed the IEEE 802.15.4e amendment, aiming at enhancing and extending the functionalities of the IEEE 802.15.4-2011 protocol. 802.15.4-2011 protocol. This is achieved for instance by proposing several MAC behaviors, which besides providing deterministic communications are also fitted with a multi-channel frequency hopping mechanisms, such as in the case of the Deterministic and Synchronous Multichannel Extension (DSME) and Time Slotted Channel Hopping (TSCH). However, to correctly address the demands in terms of latency and resources, it is mandatory to carryout a thorough network planning. To achieve this, modeling the fundamental performance limits of such networks is of paramount importance to understand their behavior under the worst-case conditions.

In this paper, we present a model for the DSME and TSCH MAC behaviors of IEEE 802.15.4e, based on Network Calculus formalism. The remaining of the paper is organized as follows: in the following section we overview the related work. In Section III we overview the IEEE 802.15.4e protocol and in particular the TSCH and DSME MAC behaviors. The network model for each of these is proposed next and the paper ends with some final remarks and a discussion of future work.

II. RELATED WORK

There are already a few works that analyze the DSME and TSCH performance. The authors in [1] have 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-latency, using an analytical model. The throughput of the DSME MAC protocol was found to be 12 times higher than that of the IEEE 802.15.4 slotted CSMA-CA in a multi-hop network. The DSME MAC behaviour was also analyzed in [2] under WLAN interference, showing that DSME-GTS was much more resilient to interference in comparison with IEEE 15.4 slotted CSMA-CA due to the included channel hopping mechanism.

Concerning TSCH, in [3], and [4], authors have developed analytical models for channel hopping mechanisms, and proposed efficient ideas to extend these, such as black listing and improved frequency hopping sequence algorithms. A comparative assessment [5] of DSME and TSCH MAC behaviors has also been developed using the OMNet++ simulation environment. QoS parameters such as delay, scalability and reliability were computed in this assessment. Interestingly DSME was found to outperform TSCH in terms of end-to-end latency in some scenarios.

The analytical works of the researchers are more dedicated to determine the throughput and end to end latency. In our researc, we propose to define the delay bounds of the MAC behaviors by using network calculus. As far as we know we are the first to use this methodology to determine the delay bounds of 802.15.4e

III. OVERVIEW OF THE IEEE 802.15.4E PROTOCOL

The IEEE standard 802.15.4e [6] proposes an enhanced version of IEEE 802.15.4-2011 [7], introducing a set of MAC behaviors which are tailored to suit the needs of industrial real time communications. Ideas which are prominent in the industrial communications 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 two MAC behaviors: DSME and TSCH. These aim fundamentally at guaranteeing determinism and enhancing the network's resilience to interference.

A. *DSME MAC Behavior*

A DSME enabled PAN coordinator uses a multi superframe structure. A multi superframe is composed of a cycle of multiple superframes similar to the IEEE 802.15.4 superframe format. Every superframe in a DSME multi superframe will have a Contention Access Period (CAP) and a Contention Free Period (CFP). Details like the number of superframes in a multi superframe and the timing synchronization are conveyed to the nodes through an enhanced beacon which is transmitted by the PAN Coordinator at the beginning of the multi superframe. The nodes contend for the channel in the CAP region and the CFP is composed multiple Guaranteed Time Slots (GTS). An available GTS slot can be occupied by any pair of nodes within the transmission range, these occupied slots are called DSME GTSs. Figure 1 shows the multi superframe and superframe structure of the DSME MAC behaviour. In the CFP region of the superframe structure in Figure 1, the columns indicate timeslots and the rows indicate the channels available for hopping.

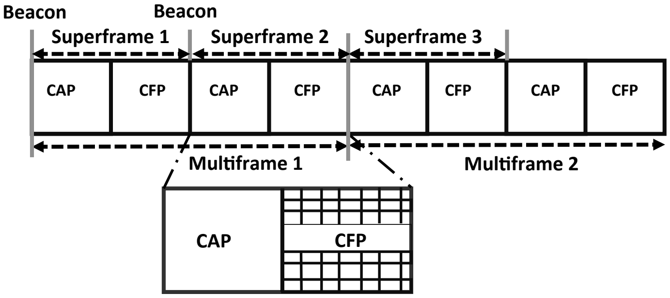

Fig. 1. Multi-frame structure of DSME

B. *TSCH MAC Behavior*

The concept of superframes has been amended into slotframes in TSCH. Every slotframe is comprised of multiple timeslots. TSCH uses either contention free or contention based communication during the slotframe period, depending on if it is using a guaranteed or a shared timeslot respectively, to transmit a frame and eventually an acknowledgement.

The slotframes are scheduled by the PAN Coordinator and are set to repeat periodically, advertised by enhanced beacons. Multi-channel support is one of the major characteristics of the TSCH MAC behaviour. There are 16 channels available for hopping in TSCH. Every channel is denoted by a channel offset that varies from 0-15. A timeslot absolute number (ASN), which increments globally, is used to compute the channel in any pairwise communication.

Figure 2 shows a three timeslot slotframe in which two devices communicate through 2 channels. In time slot 0 device A transmits its data to B through channel 1 and during time slot 1 B transmits to C through channel 2 and during time slot 2 the device remains in an idle state. The slot frame repeats periodically.

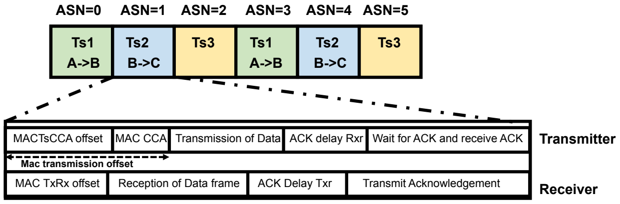

Fig. 2. Three time-slot frame in TSCH

IV. DELAY BOUND USING NETWORK CALCULUS

Among several analytical methods that have been used to determine the delay bound analysis of distributed networks, Network Calculus is well adapted to controlled traffic sources and provides upper bounds on delays for traffic flows [8]. For a cumulative arrival function $R(t)$ there exists an arrival curve $\alpha(t) = b + r.t$ where b, r, t are the burst rate, data rate and time interval respectively. A minimum service curve $\beta(t)$ is guaranteed to $R(t)$. 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 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 also adequate for periodic traffic which is commonly the case the of Wireless Sensor Networks. Figure 3 depicts the basic (b, r) model with the arrival and service curves, and the delay bound.

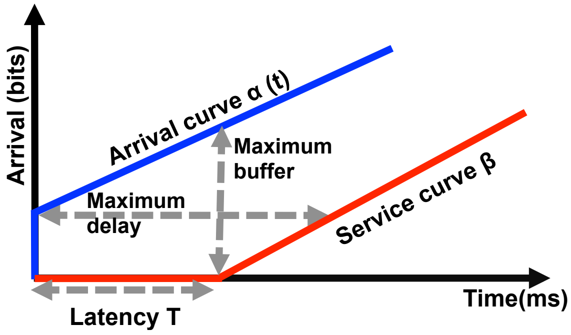

Fig. 3. Arrival curve, service curve, delay bound

A. *Service curve analysis of DSME*

Let us consider a single PAN coordinator and a set of nodes forming a DSME IEEE 802.15.4e network. The PAN coordinator sends an enhanced beacon for every multi superframe, and a beacon for each superframe. The beacon interval and superframe duration are computed as follows:

$$BI = aBaseSuperframeDuration \ \times 2^{BO} symbols \tag{2}$$

$$for \ 0 \leq BO \leq 14$$

$$SD = aBaseSuperframeDuration \ \times 2^{SO} symbols \quad (3)$$

$$for \ 0 \leq SO \leq BO \leq 14$$

In these equations $aBaseSuperframeDuration$ represents the minimum length of the superframe (i.e. SO = 0). The IEEE 802.15.4e standard has fixed this value to 960 symbols. Each symbol corresponds to 4 bits, resulting in a duration of 15.36 ms, considering an ideal data rate of 250 Kbps.

It is mandatory that the data transmission, intra-frame spacing and acknowledgements/Group acknowledgments (if requested) are completed within the end of a DSME GTS slot for successful transmission of a message. For the sake of simplicity, we consider one data frame transmission in each a DSME GTS per superframe. As the number of superframes in a multi superframe will remain the same, it is ideal to calculate the delay for a single superframe and multiply by the number of superframes in the multi superframe. Considering the time duration of a superframe is SD, the time duration of a multi superframe will be $Mx(SD)$, where M is the number of superframes. The value of a timeslot in a superframe, Ts is given by equation 5.

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

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 inside the guaranteed timeslots. T_{idle} is the time which is not used by the data, this mainly comprises of the time of inter frame spacing and acknowledgments. The latency is the difference of the bursts arrival and the time the data is served. Burst arrives at the beacon interval. The maximum latency T is given by equation 6, the maximum latency is the time a burst may wait for a service. This is the latency for service provided for the node that allocated one timeslot.

$$T = BI - T_s \quad (5)$$

The overall service provided by the network can be given by the product of the data rate and the time at which system receives the service. For the first superframe, the service curve calculated over time t, this is the minimum number of bits that has to be transmitted during a GTS, this value is given in equation 8.

$$\beta_1 = \begin{cases} C \ ((t - (BI - T_s)))^{+}, \forall \ 0 \ \leq t \ \leq BI - \ t_{idle} \\ 0, \qquad otherwise \end{cases} \quad (6)$$

$$where x^{+} = max(0, x)$$

This value of the service curve can be derived to N number of superframes, similarly to the equation derived for the service curve for n superframes of IEEE 802.15.4 in [9]. The service of the N_{th} superframe is given by:

$$\beta_N = \begin{cases} (N-1).C.t_{data} + C \, (t - (N.BI - T_N))^{+} \\ \forall 0 \leq t \leq (N-1)BI - t_{idle} \\ 0, \qquad otherwise \end{cases} \quad (7)$$

The DSME GTS service curves of DSME MAC behaviour is given as a Stair case model in Figure 4.

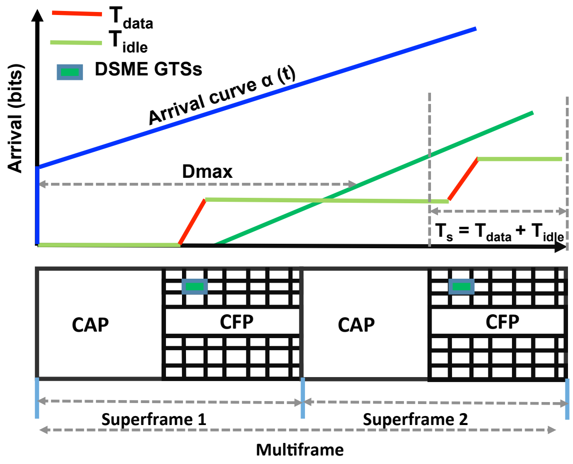

Fig. 4. Service curve of DSME MAC

B. Delay bound analysis of DSME

In a multi superframe the delay bound is calculated for every superframe separately. The sum of these delay bounds will be the overall delay bound of the multi superframe. Considering the burst size b is greater than $C.t_{data}$, the maximum delay bound of the first superframe will be the horizontal angular distance between the arrival curve and the first stair. We consider that a minimum service of (t) will be provided for cumulative data flow $R(t)$:

$$D_{max1} = \frac{b}{C} + (\ BI - \ T_s) \ \ if \ \ b \ \leq C.t_{data} \quad (8)$$

In general when $N.(C.T_{data}) < b \leq (N+1).C.T_{data})$, the delay of the system with N number of slotframes is given by:

$$D_{maxN} = \ \frac{b}{C} + (\ (N+1).BI - \ T_s) - N.t_{data} \quad (9)$$

$$if N(C.T_{data}) \ < b \leq (N+1).C.T_{data}$$

C. Service curve analysis of TSCH

Although TSCH supports peer-to-peer topologies, in this model we consider only a star topology in which the PAN coordinator sends an enhanced beacon to initiate the slotframe. The aim of this network model is to derive an expression for the delay bound of a data flow $R(t)$ bounded by a (b, r) curve, and that has allocated one timeslot in a slotframe either contention or non-contention-based. The default duration of every timeslot T_s is 10 ms [7], during which it has to accommodate Acknowledgment delays (on the receiver and transmitter end), and the receiver and transmitting frames during a transmission in non-shared timeslot. In shared timeslots, the duration for CCA and CCA CSMA-CA offset also has to be considered.

Every timeslot T_s (time duration of a single timeslot) is of equal duration and is composed of T_{data} and T_{idle}. T_{data} is the maximum duration used for data transmission inside the guaranteed timeslots. T_{idle} is the time which is not used by the data, this mainly comprises of the time of CCA offsets, Acknowledgement delays, MAC transmission and reception offsets and Acknowledgments. Let us consider the fixed duration for which the slotframes repeat in a periodic fashion as T_{cycle}. If a slot is insufficient for a complete message transmission, then the message has to wait for the next timeslot. The latency of the data transmitted in one timeslot of the slotframe is given by:

$$T = T_{cycle} - T_s \tag{10}$$

For the first slotframe, the service curve calculated over a time period t, this is the minimum number of bits that has to be transmitted during a timeslot, this value is given in equation 11.

$$\beta = \begin{cases} C \ \ (t - (T_{cycle} - T_s))^+ \ \forall \ 0 \ \le t \ \le T_{cycle} - \ t_{idle} \\ 0, \qquad otherwise \end{cases} \tag{11}$$

The service curve will remain constant over time and the entire service of the system can be computed by equation 12:

$$\beta_N = \begin{cases} (N-1).C.t_{data} + C\,(t - (N.t_{cycle} - T_N))^+ \\ \forall 0 \le t \le (N-1) \ \ .\, (t_{cycle} - t_{idle}) \\ 0, \qquad otherwise \end{cases} \tag{12}$$

The service curve of TSCH MAC behavior results in a stair case format as depicted in Figure 5.

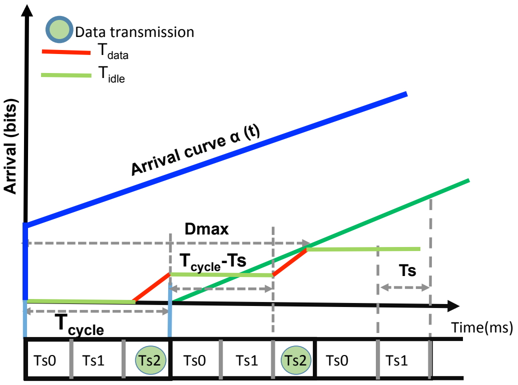

Fig. 5. Service curve of TSCH MAC

D. Delay bound analysis of TSCH

For the first slotframe, assuming $b \le C.T_{data}$ the maximum delay bound will be the horizontal angular distance between the arrival curve and the first stair. We consider that a minimum service of $\beta(t)$ will be provided for cumulative data flow $R(t)$ using equation 1, resulting as follows:

$$D_{max1} = \frac{b}{C} + (\ \ T_{cycle} - \ \ T_s) \tag{13}$$

The delay of the entire system consisting of N slotframes can be given as:

$$D_{max \ network} = \sum_0^N . \ D_{maxN} \tag{14}$$

V. DISCUSSION AND FUTURE WORK

Modeling the performance limits of a network is essential to guarantee the right latency and reliability requirements of a network. In this paper we have derived expressions for computing the worst case delays of DSME and TSCH MAC behaviors using Network Calculus. Though we have provided derivations based on star topology, the proposed results can be extended to all peer-to-peer communication networks. As a continuation of this work the end-to-end delay bounds will be derived for the rest of the MAC behaviors of IEEE 802.15.4e. We also aim at proposing new scheduling algorithms and a simulation model to compare with the analytical results.

ACKNOWLEDGMENT

This work was partially supported by National Funds through FCT/MEC (Portuguese Foundation for Science and Technology) and co-financed by ERDF (European Regional Development Fund) under the PT2020 Partnership, within project UID/CEC/04234/2013 (CISTER Research Centre); also by FCT/MEC and the EU ARTEMIS JU within project(s) ARTEMIS/0004/2013 - JU grant nr. 621353 (DEWI, www.dewi-project.eu) and ARTEMIS/0001/2012 - JU grant nr. 332987 (ARROWHEAD). This work is also support by the Research and Translation Center (RTC) at Prince Sultan University via Grant Number GP-CCIS-2013-11-10. This work is also supported by the Research and Translation Center (RTC) at Prince Sultan University via Grant Number GP-CCIS-2013-11-10.

REFERENCES

[1] W.-C. Jeong and J. Lee, "Performance evaluation of ieee 802.15. 4e dsme mac protocol for wireless sensor networks," in *Enabling Technologies for Smartphone and Internet of Things (ETSIoT), 2012 First IEEE Workshop on*. IEEE, 2012, pp. 7–12.

[2] J. Lee and W.-C. Jeong, "Performance analysis of ieee 802.15. 4e dsme mac protocol under wlan interference," in *ICT Convergence (ICTC), 2012 International Conference on*. IEEE, 2012, pp. 741–746.

[3] P. Du and G. Roussos, "Adaptive time slotted channel hopping for wireless sensor networks," in *Computer Science and Electronic Engineering Conference (CEEC), 2012 4th*. IEEE, 2012, pp. 29–34.

[4] C.-F. Shih, A. E. Xhafa, and J. Zhou, "Practical frequency hopping sequence design for interference avoidance in 802.15. 4e tsch networks," in *Communications (ICC), 2015 IEEE International Conference on*. IEEE, 2015, pp. 6494–6499.

[5] G. Alderisi, G. Patti, O. Mirabella, and L. L. Bello, "Simulative assessments of the ieee 802.15. 4e dsme and tsch in realistic process automation scenarios," in *Industrial Informatics (INDIN), 2015 IEEE 13th International Conference on*. IEEE, 2015, pp. 948–955.

[6] IEEE standard for information technology, WPANs Part 15.4 *IEEE Std 802.15.4-2006 (Revision of IEEE Std 802.15.4-2003)*, Sept 2006.

[7] IEEE standard for information technology, WPANs- Part 15.4 amendment 1: Mac sublayer," *IEEE Std 802.15.4e-2012 (Amendment to IEEE Std 802.15.4-2011)*, April 2012.

[8] J.-Y. Le Boudec and P. Thiran, *Network calculus: a theory of deterministic queuing systems for the internet*. Springer Science & Business Media, 2001, vol. 2050.

[9] A. Koubâa, M. Alves, and E. Tovar, "Energy and delay trade-off of the gts allocation mechanism in ieee 802.15. 4 for wireless sensor networks," *International Journal of Communication Systems*, vol. 20, no. 7, pp. 791–808, 2007.