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Abstract

Recent advancements in the IoT domain have been pushing for stronger demands of Quality-of-Service (QoS) and in particular for improved determinism for time-critical wireless communications under power constraints. The IEEE 802.15.4e standard protocol introduced several new MAC behaviors that provide enhanced time-critical and reliable communications. The Deterministic Synchronous Multichannel Extension (DSME) is one of its prominent MAC behaviors that combines contention-based and contention-free communication, guaranteeing bounded delays and improved reliability and scalability by leveraging multi-channel access and CAP reduction. However, DSME has a multi-superframe structure, which is statically defined at the beginning of the network. As the network evolves dynamically by changing its traffic characteristics, these static settings can affect the overall throughput and increase the network delay because of improper allocation of bandwidth. In this paper, we address this problem, and we present a dynamic multisuperframe tuning technique that dynamically adapts the multi-superframe structure based on the size of the network. This technique improves the QoS by providing 15-30% increase in throughput and 15-35% decrease in delay when compared to static DSME networks.

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DynaMO–Dynamic Multisuperframe Tuning for Adaptive IEEE 802.15.4e DSME Networks

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ABSTRACT Recent advancements in the IoT domain have been pushing for stronger demands of Quality-of-Service (QoS) and in particular for improved determinism for time-critical wireless communications under power constraints. The IEEE 802.15.4e standard protocol introduced several new MAC behaviors that provide enhanced time-critical and reliable communications. The Deterministic Synchronous Multichannel Extension (DSME) is one of its prominent MAC behaviors that combines contention-based and contention-free communication, guaranteeing bounded delays and improved reliability and scalability by leveraging multi-channel access and CAP reduction. However, DSME has a multi-superframe structure, which is statically defined at the beginning of the network. As the network evolves dynamically by changing its traffic characteristics, these static settings can affect the overall throughput and increase the network delay because of improper allocation of bandwidth. In this paper, we address this problem, and we present a dynamic multi-superframe tuning technique that dynamically adapts the multi-superframe structure based on the size of the network. This technique improves the QoS by providing 15-30% increase in throughput and 15-35% decrease in delay when compared to static DSME networks.

INDEX TERMS IEEE 802.15.4e, DSME, multi superframe tuning, QoS analysis.

I. INTRODUCTION

The recent boom in the IoT is strongly pushing technology into more time-critical domains, increasingly demanding for communication protocols that support predictable delivery of data. The IEEE 802.15.4 [2], [3], [9] is one among the legacy protocols that provided guaranteed bandwidth for time-critical data in low-rate networks with its Guaranteed Time Slot (GTS) mechanism. However, this protocol had limited scalability as only 7 Guaranteed timeslots was supported in its network infrastructure. The enhancement to this protocol, the IEEE 802.15.4e [7], [18] was able to rectify this problem.

The Deterministic Synchronous Multichannel Extension (DSME) is one of the prominent MAC behaviors of IEEE 802.15.4e that addresses this. DSME is supported by a network structure called the multi-superframe structure (Fig. 1). Every Multisuperframe consists of several consecutive stacks of superframes. Each superframe is divided into a Contention Access Period (CAP) that supports communication via CSMA/CA and Contention Free Period (CFP) for communications that works based on GTS. DSME also offers new techniques like CAP reduction with which the number of guaranteed resources can be significantly increased.

In DSME, many superframes can be stacked within a multi superframe period, which is defined by the *multi superframe Order* (MO), and as observed, these parameters have a significant impact in the QoS of these networks. Traditionally, DSME networks require careful planning of its several MAC parameters, such as MO, SO, BI and CAP Reduction usage, by an experienced network engineer, to achieve adequate QoS levels. However, if this is already an impediment for easy and straight-forward network deployment, in highly dynamic or unpredictable environments finding the right balance is borderline impossible. In scenarios where traffic or the number of nodes can change, which is increasingly becoming

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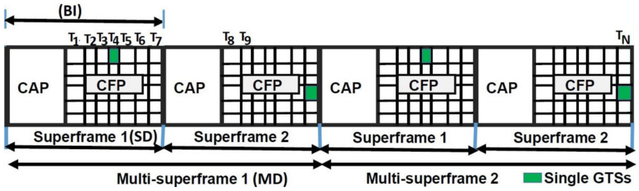

FIGURE 1. **Superframe structure with $BO = 3$, $MO = 3$, $SO = 2$.**

commonplace, static settings inevitably lead to some compromise in terms of delay or throughput that can only be addressed by devising mechanisms that can adapt on-the-fly to new conditions.

DSME has the ability to satisfy the QoS requirements of several applications using several presets specified in the standard. However, for a dynamically evolving network, these static configurations can dramatically affect the overall Quality of Service, and the network will also suffer from dire trade-offs. There have been several research works like [6] and [20] in which the performance of DSME was analyzed. However, in the literature, features like the CAP reduction and superframe structure were always kept static.

In this work, we contributed with creating an efficient multi-superframe tuning mechanism for DSME networks called DynaMO. It dynamically toggles the CAP reduction functionality and adapts the multi-superframe order to obtain improved Quality-of-Service in terms of delay and throughput as the network grows denser.

The main contributions in this paper are as follows:

- We provide a detailed overview of DSME networks and propose a dynamic multi superframe and CAP reduction tuning technique (DynaMO) that yields better QoS performance.
- We provide a modeling of the Guaranteed Timeslots under the proposed DynaMO technique and derive throughput and delay analysis under several scenarios. This model is then complemented with a detailed numerical analysis.
- We evaluate DynaMO using the simulation platform OpenDSME and validate our analytical model.

This tuning technique applies to DSME network coordinators that are aware of the number of resources that need to be allocated in its GTS period. This information can be achieved by integrating an RPL (Routing Protocol for Lossy Networks) layer over the DSME MAC layer. Using our multi-superframe tuning technique, we were able to make better QoS in terms of throughput (increase by 15-30%) and latency (decrease by 15-35%).

In what follows, we provide a brief literature survey in Section II followed by a background to the DSME MAC behavior in Section III. In Section IV, we present the system model and introduce our DynaMO algorithm. Then in Section V, we provide an in-depth mathematical model to determine the number of GTS resources available for data transmission, throughput and delay models. In Section VI, we provide a numerical analysis to validate our model. In Section VII, we complement our numerical analysis with in-depth simulation results and discussions. Finally, we discuss the future scope for this work.

II. RELATED WORKS

In our previous research [10], [30], we highlighted the impact of CAP reduction upon DSME networks using network calculus. In this work, we compare the worst case delay bounds and throughput for a DSME-enabled network with and without CAP reduction settings. When more nodes join the network, a traditional DSME network sometimes cannot accommodate all them. However, with the CAP reduction activated, the scalability increases significantly. This resulted in a considerable decrease in delay and also a 7% increase in the overall network throughput. However, in [10] we did not address the case of adaptively changing the multi-superframe to accommodate additional nodes.

Jeong et al. [11] proposes a mathematical model for comparing the contention-based IEEE 802.15.4 against a DSME network with CAP reduction, and they reported that the saturation throughput of DSME is 12 times higher when compared to the standard IEEE 802.15.4. In this case, the throughput also increases considerably because of the ability of the network to host several transmissions within a single multi-superframe time-period. From the two works mentioned above, we observed that a CAP reduction could yield improved performance in terms of scalability, however, it will have some limitations as the number of nodes increases given a certain length of a multi-superframe, which motivate the idea of adaptively changing it.

There was a simulation-based study to understand the traditional IEEE 802.15.4 and IEEE 802.15.4e DSME. In their work [20], the authors analyzed the energy consumption of both protocols and proposed a set of enhancements for Low-Power Instrumentation DSME applications. Their results show that, for end devices, their proposed improvements allowed an energy consumption reduction up to a factor of 9. Their results also show that a high throughput up to a factor of 7 is obtained when compared to the traditional IEEE 802.15.4e DSME. New enhancements like this help improving several QoS services.

In [21], the authors formulated a method such that the multi superframe Order (MO) has a value higher than the Beacon Order (BO). This helps in maintaining energy efficiency significantly as the multi-superframe duration will be reduced as it is higher than BO. However, the disadvantages of having a fixed MO was not explored in this work.

Some other performance enhancements to this standard have been proposed in the literature. For example, Sahoo *et al.* [12] proposed a new channel access and a beacon broadcast scheme for DSME dense networks. This channel access scheme helps in avoiding collisions in a mobile-dense wireless network. He also analytically showed that his proposal improves the reliability, throughput, and latency of the overall network.

The literature in varying the structure of MAC to improve QoS is not limited to DSME. Anwar and Xia [13] studied the variations in superframe of LLDN another essential MAC behavior of IEEE 802.15.4e and was able to provide an insight on the tuning of superframe to yield better network performance. Several parameters like sensors refresh rate, several devices accommodated in the network, data payload exchanged between the devices and even different levels of security was analyzed in this work.

Even in the traditional IEEE 802.15.4, researchers [16] have used algorithms to adjust Superframe Order (SO) of the coordinator by considering parameters of end devices such as queue size, queuing delay, energy consumption per bit and data rate. This has helped in improving the overall network lifetime. Dynamic superframe Adjustment Algorithm (DSAA) [17] alters the SO based on superframe occupation and collision rate. Superframe occupation time is dependent on the percentage of time the PAN coordinator is active, and the collision rate is calculated on the success of transmissions at the receiving end. A dynamic adjustment of SO in this work enabled a decrease in power consumption and improved channel utilization. In one of our earlier works [22], in contrast to the traditional explicit allocation of GTS in IEEE 802.15.4, we used implicit allocation as the number of GTSs is limited. We were able to produce betterment in QoS in terms of bandwidth utilization.

In [24], we have proposed an adaptive beacon scheduling technique that manages duty-cycles and ensures the fairest use of bandwidth resources in an IEEE 802.15.4 cluster-tree ZigBee based network. In this work, we take a similar approach in the improvement of IEEE 802.15.4e on top of RPL networks. A detailed survey by Farhad *et al.* [15] also provides a list of several works that were able to improve the quality in terms of energy consumption, improved network lifetime and throughput by dynamic variation in the SO of IEEE 802.15.4s beacon-enabled communication.

The primary added value of this work as compared to the state-of-the-art is that we propose an "adaptive multi-superframe tuning technique" that dynamically changes its parameters to accommodate more nodes and also to improve the QoS in terms of throughput and delay. To the best of our knowledge, this is the first proposal dealing with adaptive multi-superframe in DSME.

III. BACKGROUND ON DSME

A DSME network is capable of providing deterministic communications using its beacon-enabled multi superframe structure as shown in Figure 1. The concept of superframe is adopted from its predecessor standard, in which beacon-enabled mode, also supports non-deterministic communications via the CAP (Contention Access Period) using CSMA/CA and deterministic communications via the CFP (Contention Free Period) using guaranteed time slots. DSME follows the same method but incorporates the possibility of multiple channels. Unlike the classic IEEE 802.15.4, with its multi-channel extension, DSME supports complex topologies such as mesh, severely increasing its scalability.

The structure of the multi superframe can be defined by the values of Superframe Duration (SD), multi superframe Duration (MD) and the Beacon Interval (BI). The Multi superframe Duration is a new parameter introduced in DSME, and defines the length of all the individual superframes within the multi superframe and the beacon Interval is the time period between every beacon. These parameters are defined in the following equations:

$$MD = aBaseSuperframeDuration \times 2^{MO} symbols \quad for\ 0 \leq SO \leq MO \leq BO \leq 14 \quad (1)$$

$$BI = aBaseSuperframeDuration \times 2^{BO} symbols \quad for\ 0 \leq BO \leq 14 \quad (2)$$

$$SD = aBaseSuperframeDuration \times 2^{SO} symbols \quad for\ 0 \leq SO \leq BO \leq 14 \quad (3)$$

In the previous definitions, *MO* is the *MAC multi superframe Order* and it represents the beacon interval of a multi superframe. *BO* is the *MAC Beacon Order* and it defines the transmission interval of a beacon within a superframe. *aBaseSuperframeDuration* is the minimum duration of a superframe corresponding to the initial Order of the superframe (i.e, $SO = 0$). This duration is fixed to 960 symbols (a symbol represents 4 bits) corresponding to 15.36 ms, assuming a bit data rate of 250 Kbps in the 2.4 GHz frequency band. The total number of multi superframes in a beacon interval can be defined by $2^{(BO-MO)}$, and the number of superframes in a multi superframe can be given by $2^{(MO-SO)}$. The values of BO, MO and SO are statically defined by the PAN coordinator at the beginning of the network and are conveyed to the nodes through an Enhanced Beacon (EB) at the inception of its beacon period. This fact severely limits the robustness of the network and its performance as we will see in the following sections.

Let us consider a DSME network infrastructure where $BO = 3$, $MO = 3$ and $SO = 2$. In this case, two superframes are stacked within a single multi superframe which repeats periodically, as illustrated in Figure 1. The DSME GTSs in the available channels are shown as grids in the CFP region for the parameters as mentioned above. The horizontal axis of the grid represents the time, and the vertical axis of the grid represents the frequency. Across these various frequencies (channels) several GTSs can be allocated at the same time but on different frequencies (i.e., channels). DSME provides the facility to utilize 16 channels over 7 GTS.

In accordance with the standard [7] the CAP has a *minCAPlength* size of 440 symbols that are applied to all superframes of the multi superframe structure. Traditionally, in accordance to the standard, the GTS allocation is negotiated in the CAP region. In a time-critical system, there is a possibility for the schedule to be directly sent in the payload of the Enhanced Beacon (Figure 2). This schedule which will be issued periodically in the DSME PAN descriptor with any

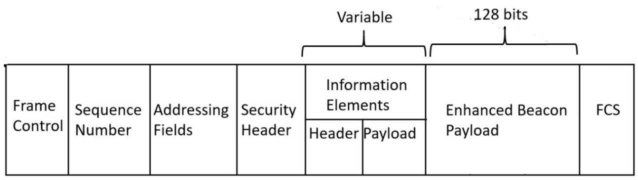

FIGURE 2. Structure of the Enhanced Beacon.

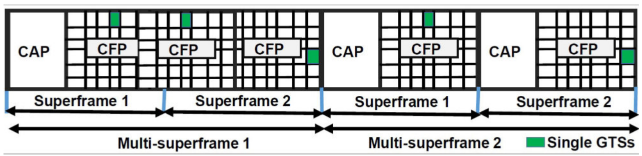

FIGURE 3. Multi superframes with and without CAP reduction.

change made to the schedule. In this way, a schedule can more flexible and can vary considering routing inputs, and also increase the network's reliability, based upon channel conditions.

In IEEE 802.15.4, when no GTS resources are available to allocate the queuing traffic, the nodes have to wait for a full superframe duration to get the next opportunity to transmit in a guaranteed time slot. Whereas in DSME, this can be averted by techniques like CAP reduction. The CAP reduction primitive is defined at the start of a multi superframe by the PAN-C, this will be carried out in the specific multi superframe determined by the PAN-C. By enabling CAP reduction, all the superframes in a multi superframe can be converted into CFPs, eventually increasing the available bandwidth in the CFP. Figure 3 visualizes the multi superframe 1 with CAP reduction and multi superframe 2 without CAP reduction, but following the same values for BO and MO given in Fig 1.

IV. SYSTEM MODEL

For our system architecture, we consider a DSME enabled 802.15.4e mesh network with nodes dynamically joining and leaving the network, as illustrated in Figure 4. The network consists of a central PAN coordinator (node a_1 in Figure 4), which can receive and transmit beacons and messages. Then we have the coordinators which can provide routing and also send Enhanced Beacons for association and timing synchronization. Unlike the coordinators, the Reduced Functional Devices (RFD) have the capability of only receiving information.

We envisioned a dynamic architecture with nodes entering and leaving the network. Most of the IoT applications bank on the dynamic nature of Wireless Sensor Networks. Our network is formulated with the help of RPL by which a point to many points (P2MP) or the vice versa can be achieved. Our algorithm will help to provide a multi superframe structure for the PAN coordinator of this network to help improve the scalability and also its QoS properties.

A. PROBLEM STATEMENT

In a dynamic mesh network, when new Fully Functional Devices (FFD) are added or removed, a statically defined MO

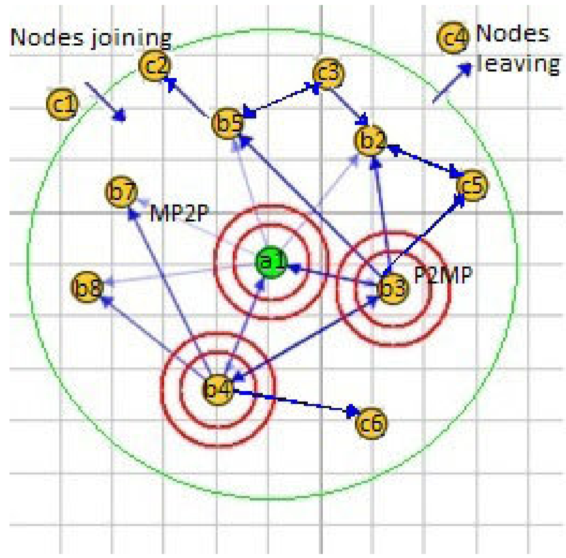

FIGURE 4. System model.

and CAP reduction primitive at the inception of the network can cause adverse results.

Problem 1: There can be a *"need for a more guaranteed bandwidth than what is available"*. The need for additional bandwidth can be sufficed if a bigger MO was defined at the beginning of the multi superframe based on the the required resources.

Problem 2: There can be *"excess of guaranteed time slots that what is exactly needed"*. Excess of bandwidth can also affect the throughput of the overall network due to a wastage resulting in to increased latency. This imbalance constitutes the fundamental cause of the decreased performance against TSCH [6]. TSCH overcomes the limitations as it does not have a fixed superframe like that of a DSME network. However, these issues can be avoided by a multi superframe tuning technique that can (1) employ/deploy CAP reduction based on the number of transmissions that need to be accommodated in the superframe, (2) provide a new multi superframe Order better suited to the number of pairwise transmissions scheduled for GTS service. Such information can be made available by implementing a routing layer over DSME that helps to provide the scheduling information to the link layers similar to the Orchestra schedules [1] used in 6TiScH [5].

B. NODE ASSOCIATION AND ROUTING

The coordinators (FFDs) advertise their superframe periodically sending Enhanced Beacons. A new node can join the network by associating to a coordinator node or directly to the PAN Coordinator itself, via an Association request, eventually leading to a network topology formation.

At the network level, the association process follows the RPL routing node joining process [4]. The PAN Coordinator will act as a DODAG (Destination oriented direct Acyclic Graph) root and will send DODAG messages. All the routers in the RPL overlay network keep sending their

TABLE 1. Notations for DynaMO.

Notations	Description
N	total number of nodes
a_i	node a_n where $i\ \epsilon(1, N)$
$N_{Channels}$	number of channels = 16
T_i	index of the timeslot in the multi superframe (see Figure 1)
N_{CFP}	total number of GTSs in the CFP of a multi superframe
$NCAP$	number of GTS added when CAP reduction is activated

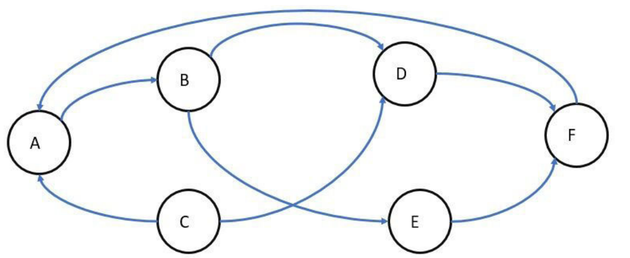

FIGURE 5. Example of a mesh network.

DIO (DAG Information Object) messages to announce the DODAG. A node will listen to DIO message only if it joined the WPAN via association process. When a node wants to join the DODAG it receives a DIO message from a neighbor router, it (*i.*) adds the DIO sender address to its parent list, (*ii.*) computes its rank according to the Objective Function (OF) specified in the OCP (Objective Code Point) field, which is an identifier that specifies what Objective Function that the DODAG uses. The OF can be reliability determining element like LQI (Link Quality Indicator), Packet Delivery Ratio (PDR) or even Power Consumption [23], (*iii.*) forwards the DIO message with the updated ranks. The client node chooses the preferred parent among the list of its parents (other associated FFDs) as the default node through which inbound traffic is forwarded.

C. DynaMO ALGORITHM

In this section, we introduce an efficient multi superframe tuning algorithm called DynaMO. The general idea of this algorithm is *adaptively increasing and decreasing the multi superframe structure based on the evolution of GTS allocation requirements over time*.

Algorithm 1 presents the DynaMO adaptive network configuration, and Table 1 shows the notation used for the description of the algorithm.

As the network grows/diminishes dynamically, the routing layer will update the topology and forward the respective schedules which contain the list of pair-wise GTSs transmissions. This is provided as an **input** (Algorithm line 1). Let us consider pairs of neighbor nodes (a_i, a_j) to transmit between each other. This transmission list will be provided as a bitmap to the link layers using the RPL backbone for every beacon interval. An example of a transmission bitmap for the network shown in Figure 5 is presented in Figure 6. Zero means that there is no transmission in a GTS between two nodes and one means there is a transmission in a GTS between the two nodes.

Algorithm 1: DynaMO

1: **Input** BO, SO, MO, CAP reduction Primitive
2: Pairwise transmissions from RPL: $((a_1, a_2), (a_1, a_3) \ldots .(a_2, a_1) \ldots .(a_i, a_N))$
3: $N_{channels}$ and N_{TS} $\in (1, 7 + (NCAP))$
4:
5: Initialization
6: **repeat**
7: **Schedule** R = Required number of resources to accommodate the network
8: **Resource test:** check $N_{CFP} = R$ in a multi superframe
9:
10: **Case 1: less resources**
11: **while** $N_{CFP} = R$ **do**
12: CAP Reduction = ON;
13: **if** resource test true **then**
14: **Print:** DynaMO is successful,
15: **else** MO = MO +1;
16: **end if**
17: **end while**
18:
19: **Case 2: abundant resources**
20: **while** $N_{CFP} = R$ **do**
21: CAP Reduction = OFF;
22: **if** Resource test true **then**
23: **Print:** DynaMO is successful,
24: **else** MO = MO -1;
25: **end if**
26: **end while**
Loop Repeat: Every multi superframe duration

	a	b	c	d	e	f
a	0	1	0	0	0	0
b	0	0	0	1	1	0
c	1	0	0	1	0	0
d	0	0	0	0	0	1
e	0	0	0	0	0	1
f	1	0	0	0	0	0

FIGURE 6. Transmissions bitmap.

The PAN Coordinator has access to all information needed to establish a multi-channel GTS allocation, including, the number of channels ($N_{Channels}$), the number of the GTSs time slots (N_{TS}) and the total available GTS resources ($N_{CFP} = N_{Channels} * N_{TS}$). The number of time slots can sometimes vary if the CAP reduction primitive is activated. In such a case, the number of time slots will be $7 + N_{CAP}$, where N_{CAP} is the number of time slots added via CAP reduction. The PAN-C initially randomly determines the values of BO, MO, and SO and the CAP reduction primitive.

In our algorithm, we first determine the number of resources that need to be allocated in the network.

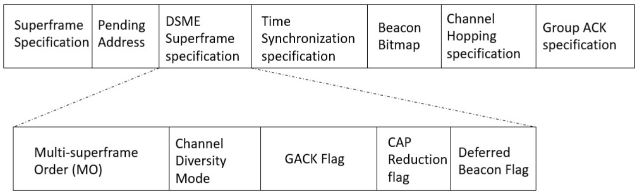

FIGURE 7. **DSME PAN descriptor structure.**

This number of resources required is obtained through a near-optimal scheduling algorithms like simulated annealing [25] or Symphony [26]. An optimal schedule must use the minimum number of time slots and channels so that minimal latency can be achieved. The nodes must also be placed in such a way that there are no overlapping transmissions amongst them. Using Symphony, a (near) optimal solution for the specific network in Figure 6 is given as below:

$$\begin{bmatrix} c \rightarrow d & c \rightarrow a & a \rightarrow b \\ b \rightarrow e & b \rightarrow d & d \rightarrow f \\ f \rightarrow a & e \rightarrow f & -- \end{bmatrix}$$

An optimal schedule gives us an idea of the total number of resources that need to be accommodated in the network. For the aforementioned example, we need 9 GTSs spanning across 3 channels and 3 time slots to accommodate the network. Let us call this amount of GTSs as R. Now we follow this by a resource check function (Resource test, Line 8, Algorithm 1). This function checks if the number of resources available in the network (N_{CFP}) are enough to accommodate the total number of GTS transmissions (R).

Based on this check, the PAN-C determines the value of the multi superframe Order (MO) and the CAP Reduction primitive. When the resource requirement is not satisfied (case 1 - algorithm line 11), DynaMO is initiated. When more resources are needed, the PAN-C initializes the CAP reduction and checks whether the schedule containing all the resources can be placed within the new multi superframe with more Guaranteed Timeslots. Even after switching ON the CAP reduction primitive, if the number of available resources is not enough, the PAN-C will increase the MO, eventually adding another superframe. This process continues until the schedule is placed adequately.

On the other hand (i.e., Case 2 - algorithm line 20), when abundant resources are available, the PAN-C decreases the MO dynamically and can also switch off CAP reduction. The change to the MO and CAP reduction primitive is sent through the DSME PAN descriptor IE (Figure 7) in the Enhanced Beacon at the start of every new multi superframe.

In the next section, we provide an analytical model for the GTS allocation in a DSME network and then we carry out throughput and delay analysis for a DynaMO-enabled DSME network.

V. MODELING OF THE GTSs UNDER DynaMO

For our analysis, we consider a DSME mesh network with N nodes under the network coverage of the PAN Coordinator. Being a time critical network, we provide guaranteed transmissions for all the nodes that are associated in the network. The RPL routing protocol [8] forms a network topology based on an Objective Function specifies the routing strategy [4], [14]. This schedule for an updated topology will be sent at every multi superframe duration. Every device is allocated with one or more GTSs based on the topology issued by the RPL. For our analytical analysis, as we only consider deterministic bounds, we assume that all the transmissions are successful.

IEEE 802.15.4e does not provide any limits on the number GTSs a device can allocate, however, the legacy IEEE 802.15.4 allows a maximum of only seven time slots. This gives us the freedom to consider that a device can occupy as many GTSs as needed. Let us consider the maximum number of GTS in a superframe to be N_{CFP1} and when considering 2 superframes with CAP reduction the maximum number of GTS in a superframe will be N_{CFP3}, as it includes 3 CFPs in a 2 superframe period. Hence in general, the maximum number of GTS available in a multi superframe can be given by $N_{CFP(n)}$, where n is the number of CFPs encompassed in the specific multi superframe.

In what follows we present the constraints on the number of timeslots that can be allocated based on the specifics of the DSME GTSs allocation mechanism of IEEE 802.15.4e.

A. NUMBER OF GTSs WITH CAP REDUCTION

In this subsection, we derive the value of $N_{CFP(n)}$, which is dependent on the values of the MO, BO and SO. D_{Max} represents the maximum delay a transmission has to undergo a successful GTS allocation in a multi superframe.

In accordance to the standard, there will be an Inter Frame Spacing (IFS) period between every successful transmission. Depending on their size if less than *aMaxSIFSFrameSize*, it is called Short Inter Frame Spacing (SIFS), else it is called Long Inter Frame Spacing (LIFS). Under LIFS, the size extends for a minimum period of *minLIFSPeriod* symbols. This IFS contributes to the delay along with other parameters such as L_{frame} the frame length, R_s the symbol rate and R_b the bit rate. In accordance to research work [28] done towards calculating delay in a superframe intervals, the maximum delay can be given as:

$$D_{max} = \begin{cases} D_{SIFS} = \dfrac{(L_{frame} \times R_s)}{R_b} + minSIFSPeriod, \\ D_{LIFS} = \dfrac{(L_{frame} \times R_s)}{R_b} + minLIFSPeriod \end{cases} \tag{4}$$

The duration of the multi superframe slot will depend on the multi superframe order (MO) issued by the PAN coordinator. Let T_{MS} be the duration of the multi superframe slot, N_{MD} be the total number of symbols forming the multi superframe, N_{MD_i} be the total number of symbols constituting the multi superframe since the value of $SO = 0$,

$$T_{MS} = \frac{N_{MD}}{T_{CAP} + T_{CFP}} = N_{MD_i} \times 2^{MO-4} \tag{5}$$

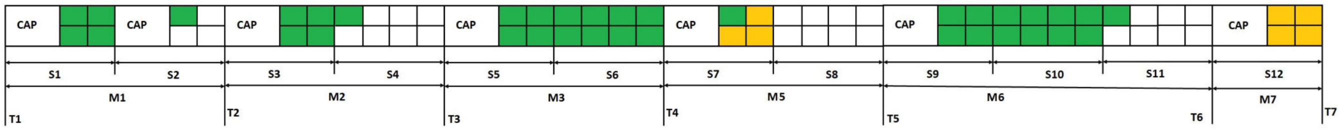

FIGURE 8. Scenarios taken for numerical analysis.

Equation 5 stands true for a scenario with CAP reduction for a single multi superframe period encompassing all the GTSs in the CFP time period. It also considers a CAP region of duration T_{CAP}.

A single GTS can span across several superframe slots, and so we should provide a constraint on it. GTS must be greater than the total forward delay D_{max}. Let us consider N_{min} to be the minimum number of superframe slots a single GTS can extend over.

$$N_{min} = \left\lceil \frac{D_{max}}{T_{MS}} \right\rceil \tag{6}$$

As we consider a critical data-oriented network, we neglect the delay that occurs in the CAP region of the traditional IEEE 802.15.4. Under CAP reduction the absolute number of GTSs is not specified, however, it can be expressed as $m \times N_{CFP}$, where m is the number of channels and N_{CFP} is the timeslots in CFP. From these, the maximum number of GTSs that can be allocated to devices can be given by:

$$N_{CFP(n)} = min\left(\left\lceil \frac{(T_{CAP}+T_{CFP})(1-\frac{T_{CAP}}{T_{MS}})}{N_{min}} \right\rceil, m \times N_{CFP}\right) \tag{7}$$

B. THROUGHPUT ANALYSIS UNDER CAP REDUCTION

Though in DSME there is no inactive slots, the time-frames spent for IFS and acknowledgment contribute to the delay as the overhead timing. Let us call this time as T_{idle} and it can be given by,

$$T_{idle} = T_{overhead} + T_{wasted} \tag{8}$$

T_{wasted} will include the time-frames that were lost due to failures and delay of transmission due to queuing in the CFP. T_{idle} has to be calculated separately for every superframe in a multi superframe, because in a dynamic CAP reduction scenario, we can have multi superframes with and without CAP reduction primitives utilized. In the throughput equation, the available resources of GTS $N_{CFP(n)}$ should be considered as they contribute to the bandwidth,

The throughput can be defined as the ratio of the data transmitted (T_{data}) to the total amount of bandwidth available for transmission. The maximum throughput for a multi superframe repeating every MD with n superframes and a data rate of C can be given by:

$$TH_{max} = \left(\frac{T_{data}}{MD \times N_{CFP(n)}}\right) \times m * C, \tag{9}$$

where, $T_{data} = n(T_{MS}) - T_{idle}$

VI. NUMERICAL ANALYSIS

For our numerical analysis, let us take the timeline of events as shown in Figure 8. The entire timeline is divided from T1 to T7 which comprises 7 multi superframes which are in turn composed of 12 individual superframes representing 6 different scenarios. For this numerical analysis, we assume that all the transmissions in the guaranteed timeslots to be successfully accommodated. The size of every timeslot taken for this analysis is evenly 1ms. For the sake of simplicity, we have only consider 2 channels in every CFP over 2 timeslots, overall providing 4 GTSs per individual superframe. An Enhanced Beacon (EB) will be sent at the start of every multi superframe. This EB will contain the primitive to activate CAP reduction and the schedule with channel and slot information.

The Scenarios Taken for the Numerical Analysis:

(i) From T1 to T2: CAP reduction is not employed in DSME multi superframe. In this scenario, the multi superframe is expected to support 5 GTS transmissions. But in this case, there are only 4 available slots in the superframe. Without CAP reduction, the nodes has to wait for an entire "duration of CAP" before it is able to transmit.

(ii) From T2 to T3: This is a multi superframe with CAP reduction employed in it. Unlike the previously discussed case, for 5 transmissions, the final transmission need not wait for a CAP duration to get accommodated.

(iii) From T3 to T4: This is a multi superframe with CAP reduction employed, but unlike the previous scenarios, the number of transmissions it has to accommodate is 13. Here the MO for this scenario is assigned static; as a result, the final transmission also has to wait for an entire CAP period before it gets transmitted.

(iv) From T4 to T5: This is a multi superframe with static CAP reduction employed akin to the previous scenario, but it should be noted that it only needs to accommodate 3 GTSs. As a result of this 8 GTSs remain unoccupied contributing to the wasted bandwidth. This wastage eventually affects the overall throughput of the network.

(v) From T5 to T6: This holds the same condition as scenario *iii*, but with DynaMO, PAN-C counts the number of transmissions to be accommodated by the CFP. As more resources are needed, it increases the MO by 1, leading to the addition of a superframe to the multi superframe. In this use case, the MO is 2, resulting 3 superframes within a multi superframe. Necessary bandwidth is hence dynamically available to accommodate the needed traffic.

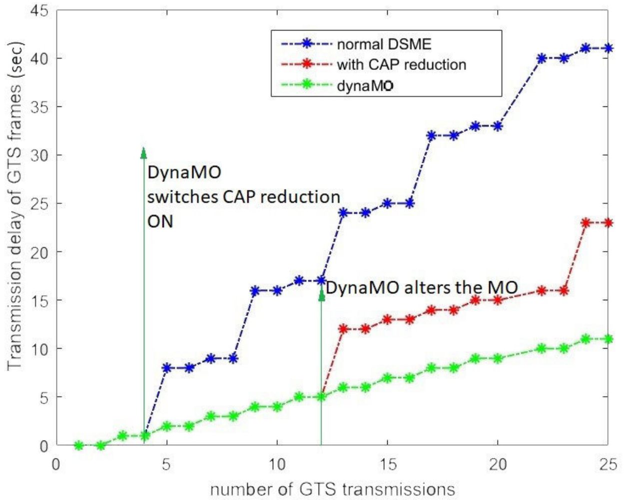

FIGURE 9. Comparison in terms of delay.

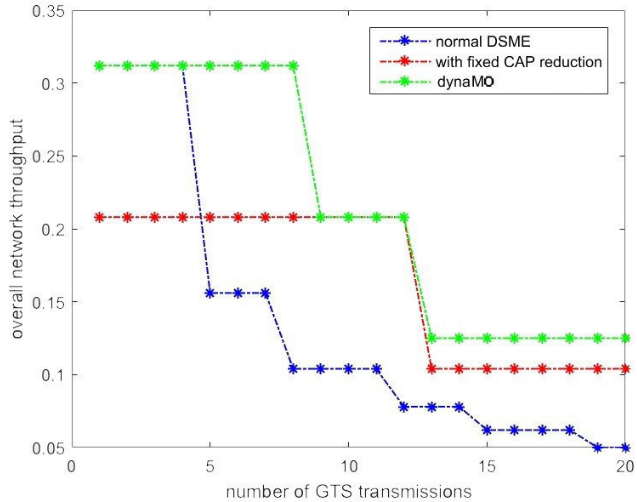

FIGURE 10. Comparison in terms of overall network throughput.

(vi) From T6 to T7: In this case the number of GTSs to be accommodated is 4. PAN-C using DynaMO deploys CAP reduction in this scenario eventually providing a single superframe to accommodate the 4 transmissions. This method will reduce the wastage of bandwidth by allocating only the required number of slots and thus increasing the throughput.

We calculated the delay of the network for all the use cases as mentioned above using Equation 4. We took a network that dynamically grows and demands more GTSs resources. For static CAP reduction scenarios, we take the value of MO to be 1. For this numerical analysis, we consider the idle time to be 0 and a constant bit rate of 1kbps.

From Figure 9, it can be noted that under traditional DSME, the transmission delay of the GTS frames starts to increase at a point where the multi superframe cannot allocate more GTSs. This results in a wait until the next multi superframe to accommodate the transmission. However, if CAP reduction is triggered, delay is much smaller when compared to the normal DSME, as more GTSs resources are available. However, as the MO is constant, delay inevitably starts to increase when enough resources are not available, imposing transmission deference to the next superframe. With DynaMO, the MO is increased when more resources are needed. Hence, it provides better results than networks with solely CAP reduction enabled (by 15%) and DSME networks with constant, non-dynamic settings (by 35%).

We also analyzed the throughput of the DSME network with several scenarios using Equation 10. For this analysis, we take a DSME network that has 2 channels and with a constant data rate of 250 kbps. We compared a normal DSME against a DSME with static CAP reduction that employs a fixed MO of 2 and a DynaMO enabled DSME network. We can witness an average 10% improvement in throughput was observed in a DynaMO enabled network.

From Figure 10, in case of DSME with fixed CAP reduction, it can be noticed that for a reduced number of nodes, there is an excess of resources. This affects the overall network throughput because of wasted bandwidth. As the number of GTSs transmissions increases, the throughput under normal DSME steadily decreases because traffic (as shown in scenario T3 -T4) has to wait en-queued for an entire superframe duration to be granted service. In the case of DynaMO, dynamic CAP reduction and the efficient tune of the MO results in better throughput. If the number of resources is abundant, the MO is reduced or the CAP reduction primitive is switched off in such a way that less bandwidth is wasted, thus resulting in better throughput.

VII. SIMULATION RESULTS

For evaluating DynaMO, we use the OpenDSME simulation platform [19]. OpenDSME is an OMNET++/C++ simulation-based environment that is dedicated to the simulation of the IEEE 802.15.4e DSME protocol. OpenDSME also provides the possibility of implementing a viable network layer on top of it. The DSME sublayer of OpenDSME employs a typical slot based reservation system for a schedule that is provided by the top layer.

In our model, we provide BO, MO, SO and the CAP reduction primitives as a direct input. Other network simulation parameters such as traffic rate, the burst size, the interference, and the mobility models are also be given directly. Furthermore, there is also a possibility to input the schedule based on a static schedule. We have also incorporated delay and throughput parameters [29] in the network definition files to obtain the appropriate output for the network simulated.

For our simulation set up, we consider several nodes that are arranged in a static concentric mobility pattern around the PAN coordinator [27]. The static concentric mobility pattern is one of the several mobility patterns in OpenDSME, and it places several nodes in a set of concentric circles around the PAN Coordinator. A static concentric pattern can be used

TABLE 2. Simulation parameters.

Parameters	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Packet Length	75B	75B	75B	75B	75, 100B	75, 100B
Packet Traffic Interval	50ms	50ms	50ms	50, 30, 15ms	50, 30, 15ms	50, 30, 15ms
Destination	sink	sink	sink	sink	sink	sink
MAC Queue Length	30	30	30	30	30	30
MAC Frame Retries	7	7	7	7	7	7
BO	6	6	6, 10	6	10	6, 10
SO	3	3	3, 5	3	5	3, 5
MO	4	4,5,6	4, 6	DynaMO	6, DynaMO	4, 6, DynaMO
Number of Nodes	5 to 50	5 to 50	5 to 50	5 to 50	5 to 50	5 to 50
Traffic Rate	50 Kbps	50 Kbps	50 Kbps	15, 25, 75k Kps	15, 25, 50, 75 Kbps	25, 50, 75, 100 Kbps
CAP Reduction	ON/OFF	ON	ON	DynaMO	OFF	ON/OFF/DynaMO

to represent several DSME based use cases like intra-car communication and smart area monitoring.

We conduct our experiments using contention-based and non-contention communication over IEEE 802.15.4e. A traffic of 100 packets of 75B length was generated from the node to the sink. In our first three scenarios, we understand the impact of the change in throughput and delay with respect to the change in MO and CAP reduction primitive in a DSME network without DynaMO, and then in the next three scenarios, we demonstrate the impact of DynaMO on a DSME network.

We demonstrate the performance of the DSME in terms of throughput with and without CAP reduction in Scenario 1. In Scenario 2, we vary the MO and analyse the throughput to have a general understanding of its behavior without DynaMO. In Scenario 3, we compare throughput and delay obtained through several presets (refer to Table 3) in accordance to the standard. In Scenario 4, we study the impact of DynaMO on throughput and bandwidth in a DSME network. In scenarios 5 and 6, we study the performance of DymaMO with against high throughput and delay-sensitive settings in terms of delay for different traffic configurations. In Table 2, we provide the parameters that we have used for all the scenarios we put under extensive simulations.

1) SCENARIO 1: IMPACT OF CAP REDUCTION ON DSME

The objective of Scenario 1 is to illustrate the base throughput of IEEE 802.15.4e DSME with and without CAP reduction. We calculate the throughput of IEEE 802.15.4e under the parameters of BO=6, SO=3, MO=4. As mentioned in Section III, these parameters result in 2 superframes per every multi superframe and 4 multi superframes for a beacon interval. The throughput is calculated for a varying number of nodes ranging from 5 to 50. We also present the results of CSMA/CA throughput under the same conditions as a baseline for comparison.

As expected, the throughput under guaranteed bandwidth is constantly higher than that of CSMA/CA ($\geq 50\%$). This is because CSMA/CA is contention-based which will, in turn, affect the bandwidth of the network and eventually affect the throughput. Up to 10 nodes, there is no relevant difference in throughput for scenarios with and without CAP Reduction. However, as the number of nodes increase, the number of

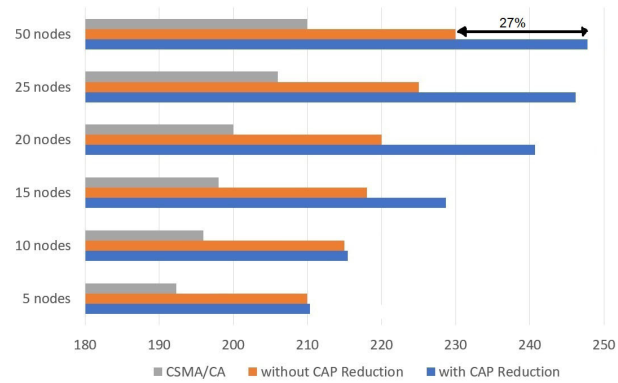

FIGURE 11. Througput under different configurations.

transmissions to be scheduled also increases. In such a case, traffic must wait till the next superframe to be granted service, thus reducing the throughput. In contrast, by using CAP reduction, the number of resources available increases. It is thus resulting in better service and increased throughput, reaching around 20-30 % for the provided scenario.

2) SCENARIO 2: IMPACT OF MO VARIATION ON DSME

The objective of Experiment 2 is to investigate the impact in terms of throughput with respect to the multi superframe Order setting without using DynaMO.

When increasing the MO, the number of superframes carried inside a multi superframe increases. This helps in increasing the number of available resources to accommodate the transmissions. We calculate the throughput for MO ranging from 4-6. For this MO, the number of superframes inside a multi superframes are 2, 4 and 8 respectively. The experiment is conducted for varying number of nodes from 5-50, and the CAP reduction is set permanently "ON" for this scenario. The Beacon Order (BO) and the Superframe order (SO) are kept constant at 6 and 3.

From Figure 12, it can be understood that when the number of nodes is small, the throughput of the network remains approximately the same, independently of the MO setting. However, as the number of nodes increases, more resources are needed to accommodate the transmissions. At higher MO settings, more superframes are packed within the multi superframe duration, resulting in improved throughput.

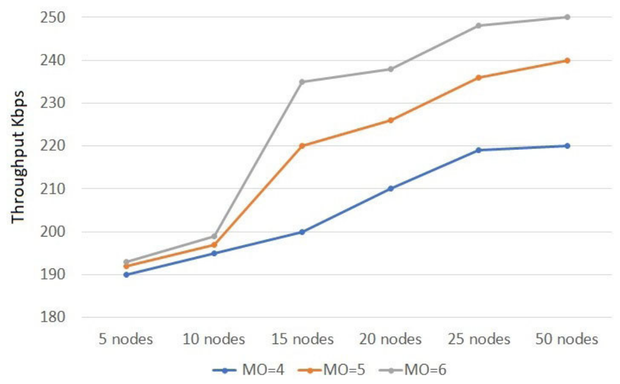

FIGURE 12. Throughput for MO=4,5,6.

DynaMO triggers the appropriate change in MO to maintain a high throughput. Also, as shown in Scenario 1, CAP reduction also plays an integral part in determining the throughput. However, one cannot blindly increase MO or trigger CAP reduction as this has an impact on delay. Also, there is a trade-off between employing CAP reduction and changing the MO. For a reduced number of nodes, it is preferable to use CAP reduction if sufficient. As we will see next, DynaMO adapts these parameters to obtain a better throughput and delay for the overall network, independently of the scenarios and MO settings initially setup.

3) SCENARIO 3: IMPACT OF STANDARD PRESETS ON THROUGHPUT

The IEEE 802.1.4e standard provides several parameters to support various application scenarios, as given in Table 1. The objective of this experiment is to learn how the throughput and delay are affected with respect to these settings.

In our experiment, we take the high throughput specification provided in the standard (BO = 10, SO = 5, MO = 6). Under these parameters it can be calculated that the number of superframes in a multi superframe interval is 2 and the number of multi superframes within a beacon duration is 16, providing 1792 GTSs. The delay sensitive parameters will only provide 2 superframes within a multi superframe interval, and 32 multi superframes in a beacon duration. The throughput will not be very high in this scenario, but traffic will be serviced with minimal latency. As the QoS requirements of the network can change at runtime, an algorithm like DynaMO can trigger the appropriate changes in the MO and CAP-reduction parameters, so that the throughput, latency and even the reliability of the network can be maintained without any dire compromise or trade-off.

Figure 13, presents the delay and throughput analysis carried out for high throughput setting of DSME with a capability of accommodating 50 nodes in the network. These are compared against a normal DSME with CAP reduction that can accommodate only 15 nodes within the beacon interval. We understand that the delay under high throughput settings is higher for a reduced set of nodes than in the case of CAP reduction. Under high throughput settings, nodes have to wait the entire beacon period for the next transmission, due to the static nature of its lengthy schedule. This results in wastage of bandwidth, thus affecting the overall throughput. Whereas, if we just rely on CAP reduction, only a small amount of bandwidth is wasted in the allocation process and the delay is thus minimal. Now as the number of nodes is increased, there is a need for additional resources, the throughput steadily drops in the case of CAP reduction, and the delay starts to increase.

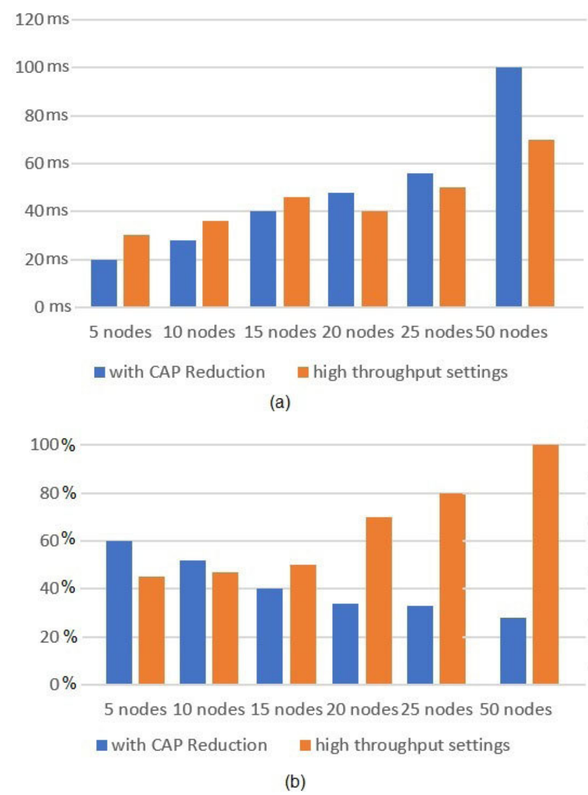

FIGURE 13. Delay (a) and throughput (b) analysis with high throughput settings.

The opposite occurs in a high throughput setting as adequate resources are available to service the transmissions. Maximum throughput is achieved because of sending data within small intervals. From this experiment, we conclude that relying on static high throughput settings, corresponding to the allocation of larger MOs in a DSME network, to achieve higher throughput, is not always the best option in terms of performance, due to the increased delay. Better behaviour can be guaranteed if one relies upon a dynamic tuning mechanism, capable of dynamically varying MO to provide optimal throughput and delay. This is the objective of DynaMO.

4) SCENARIO 4: IMPACT OF DynaMO ON THROUGHPUT

The objective of this experiment is to investigate the impact of DynaMO with respect to overall network throughput and spare bandwidth.

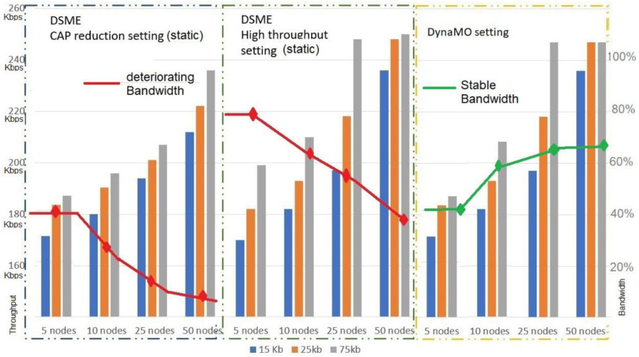

FIGURE 14. Throughput and BW analysis for various traffic rates.

DynaMO dynamically varies the MO and CAP reduction primitives to provide better throughput. Figure 14 provides a throughput analysis of DynaMO with respect to different traffic rates. In addition to the throughput, we also represent the spare bandwidth for each case. A comparison was conducted for varying number of nodes and different traffic rates (15, 25, 75 kbps), under static settings (i.e., DSME with CAP reduction, and high throughput setting) against a DSME with DynaMO. When we compare to the DSME settings with CAP reduction, a high throughput setting is able to achieve almost 20 - 30% higher throughput for higher traffic rates (75Kb - 25, 50 nodes), since throughput under static CAP reduction setting deteriorates when no more GTS resources are available (it cannot scale up). This is visible in the steep decrease in available bandwidth (BW) in the first case as the number of nodes increases (red line - CAP Reduction setting).

We initialize the DynaMO scenario with a static CAP reduction DSME setting (5 nodes). As seen, when the number of nodes increases, the static CAP reduction, and high throughput settings lose the ability to guarantee the necessary throughput. Contrary, in the DynaMO case, as the network evolves with the addition of more nodes, DynaMO turns on CAP reduction and also increases the MO as follows: When the number of nodes increases past 5, DynaMO switches on CAP reduction. As the number of nodes rises above 10, DynaMO increases the MO, providing more superframes to accommodate data, thus increasing the throughput effectively. We obtain almost 15-20 % increase in throughput under DynaMO against a static CAP reduction enabled network.

We also notice that unlike the static CAP reduction setting, the spare bandwidth does not deteriorate steeply but gives us more bandwidth (green line in Fig 14) for utilization as the number of nodes increase. Though high throughput settings can provide on-par throughput results, they have a decline in terms of spare bandwidth. This also has an effect on the delay which we will later investigate in scenario 6.

5) SCENARIO 5: IMPACT OF DynaMO ON DELAY AGAINST CAP REDUCTION SETTINGS

The objective of this experiment is to investigate the impact of DynaMO with respect to network delay. In this experiment,

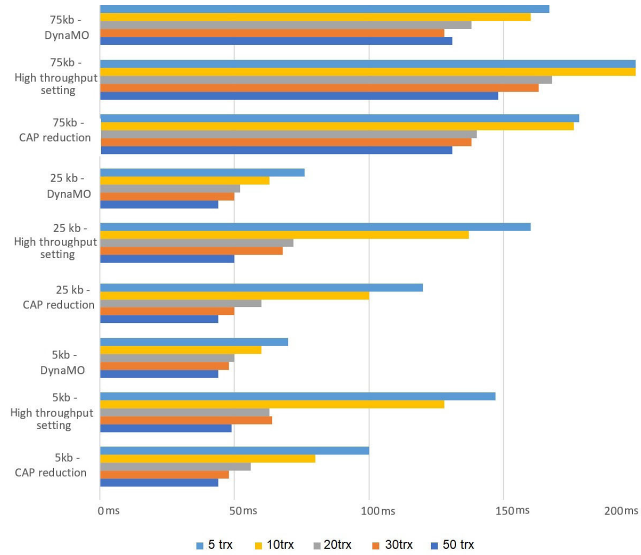

FIGURE 15. Delay analysis for DynaMO against static settings.

TABLE 3. Application scenarios for BO,MO,SO variation.

Application type	BO	SO	MO	CAP reduction
Delay sensitive	6	0	1	Enabled
Reliability sensitive	8	3		Disabled
Energy Critical	14	1	14	Enabled
High throughput	10	5	6	Disabled
Large scale	10	1	8	Enabled

we compare a static CAP reduction settings against DynaMO for several traffic rates.

For this experiment, we calculate the values of the overall delay of the network with respect to the number of GTSs transmissions, over 50 nodes under different traffic rates ranging from 5-75 Kbps for CAP reduction and without CAP reduction scenarios in Fig 15. This result complements our theoretical analysis shown in Figure 13, clearly showing DynaMO in action.

We use the high throughput parameter settings for this experiment (mentioned in Table 3) against a static CAP reduction setting. With a limited number of GTSs transmissions, the delay performance does not have a significant decrease with the scenarios without CAP reduction (5,10,15 transmissions). Delay performance is in-fact sometimes better without CAP reduction when the number of nodes is less than 10, due to less wasted bandwidth. However, as the number of transmissions increases, with CAP reduction, delay is minimized. This is due to the fact that nodes need not wait till another superframe duration to accommodate the transmissions that did not occur during the first superframe interval. DynaMO switches the CAP reduction parameters according to the resource requirements and hence doesn't compromise on the delay for those scenarios in which CAP reduction is still not needed, offering a clear advantage over static settings.

For a clear understanding, the example of DynaMO is demonstrated along with the 75kbps case in Figure 16. At T0,

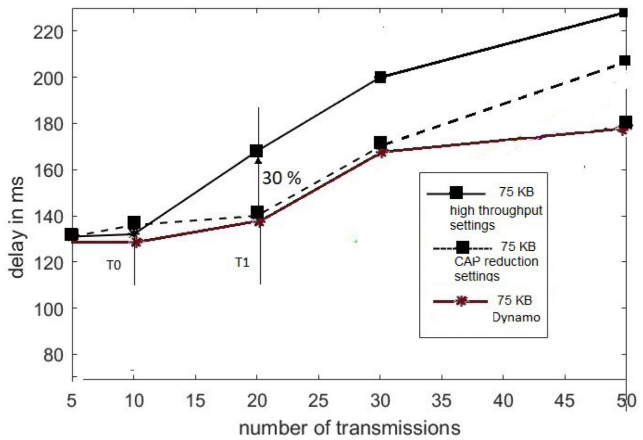

FIGURE 16. Delay analysis for 75 Kbps traffic rate.

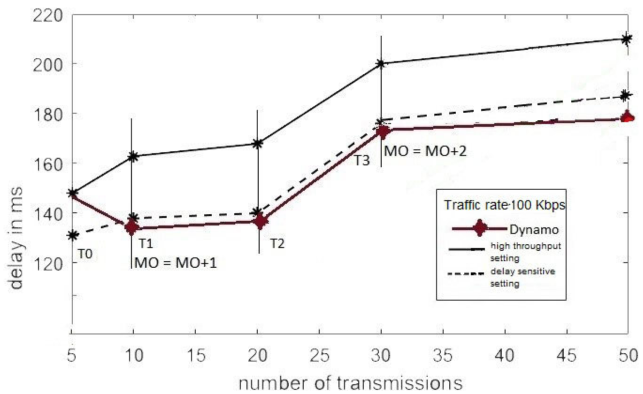

FIGURE 17. Delay analysis against delay-sensitive settings.

the CAP reduction is OFF providing minimal delay (similar to the scenario without CAP reduction), whereas at T1, due to the scarcity of the resources, the CAP reduction is turned ON dynamically and we can witness a reduction in delay by almost 30%. Above 30 scheduled transmissions, an increase in MO under DynaMO further maintains a lower delay in comparison to static settings including the CAP reduction enabled setting, again in the order of 30%.

6) SCENARIO 6: IMPACT OF DynaMO ON DELAY AGAINST DELAY SENSITIVE AND HIGH THROUGHPUT PRESETS

The objective of this final experiment is to investigate the impact of DynaMO with respect to network delay against the delay sensitive settings provided in Table 3.

In this experiment, we compare the static high throughput settings and the static delay sensitive settings (dotted lines) with DynaMO. In Figure 17, we demonstrate this comparison over 100Kbps. The other traffic rates also have similar behavior. OpenDSME does not allow the value of SO to be set to '0' by default. So we took another delay sensitive setting of BO, SO and MO to be 6,3,4 such that the number of superframes within a multi superframe will be 2 and every beacon interval will have 4 multi superframes.

The delay is always higher in the high throughput setting, and this gap increases with traffic rate. The higher MO in the high throughput settings causes a wastage of bandwidth which results in additional delay, contrary to the time-sensitive settings in which the superframes are tightly packed. We observe almost 20-25% reduction of delay under delay sensitive settings when the number of transmissions is maximized. However, as previously shown in Experiment 4, relying on static settings which provide shorter MO is often not an adequate solution, as it can compromise throughput if the network needs to accommodate an increase in traffic.

In Figure 17, at T0, we start DynaMO with a high throughput setting, consisting of one superframe in a multi superframe. However, as the timeframe moves on to T1 and the number of transmissions increases, DynaMO automatically adapts its MO based on the number of resources. In this case, by increasing MO, DynaMO packs more superframes within the beacon interval, providing more GTS bandwidth and eventually obtaining lesser delay. We can observe a significant reduction in delay, even below the delay-sensitive setting scenario. Notice, that the delay-sensitive setting does not outperform DynaMO in terms of delay when the number of transmissions are less. Although this could somewhat appear counter-intuitive, as the number of transmissions increases, the short MO is not able to accommodate the transmissions causing deference of transmissions to the subsequent superframes. These increases delay, and its effect is particularly visible above 35 scheduled transmissions.

VIII. CONCLUSION AND FUTURE WORK

Traditionally, IEEE 802.15.4 enabled networks require a careful planning of its several MAC parameters, such as MO, SO, BI and CAP Reduction usage to achieve adequate QoS levels. However, if this is already an impediment for easy and straight-forward network deployment, in highly dynamic or unpredictable environments finding the right balance is an arduous task. In a complete dynamic evolving network, static settings can inevitably lead to some compromise in terms of delay or throughput. These compromises can only be addressed by devising mechanisms that can adapt dynamically to new conditions.

In this paper, we proposed an efficient multi superframe tuning mechanism for DSME networks called DynaMO that dynamically toggles the CAP reduction functionality and adapts the Multi-superframe Order to obtain improved Quality of Service (QoS) in terms of throughput and delay. We provided a detailed mathematical model of the network and complemented it with a performance analysis.

We also used OpenDSME, a simulation platform for DSME to evaluate the advantages of DynaMO over several DSME network configurations, focusing on throughput and delay over a lossy wireless network. DynaMO dynamically adapts the network parameters at run-time and helps to obtain a better QoS, coping with on-demand changes to traffic and scheduled transmissions. With DynaMO, we were able to achieve an average increased throughput by 15-30% and a 15-35% reduction in delay against a DSME network with static settings.

We believe that the IEEE 802.15.4 and in particular the DSME MAC behaviour is a prominent candidate to become a de-facto standard for IoT implementations, although some mechanisms such as DynaMO can and should be devised to improve its efficiency. Although we believe this analysis is quite conclusive in regards to the impact of this mechanism, we intend to develop an open-source implementation of this protocol for Commercially Off The Shelf WSN platforms (COTS), to validate the results over real WSN hardware.

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