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A Performance-to-Cost Analysis of IEEE 802.15.4 MAC With 802.15.4e MAC Modes

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ABSTRACT The IEEE 802.15.4 standard is one of the widely adopted networking specification for Internet of Things (IoT). It defines several physical layer (PHY) options and medium access control (MAC) sub-layer protocols for interconnection of constrained wireless devices. These devices are usually battery-powered and need to support requirements like low-power consumption and low-data rates. The standard has been revised twice to incorporate new PHY layers and improvements learned from implementations. Research in this direction has been primarily centered around improving the energy consumption of devices. Recently, to meet specific Quality-of-Service (QoS) requirements of different industrial applications, the IEEE 802.15.4e amendment was released that focuses on improving reliability, robustness and latency. In this paper, we carry out a performance-to-cost analysis of Deterministic and Synchronous Multi-channel Extension (DSME) and Time-slotted Channel Hopping (TSCH) MAC modes of IEEE 802.15.4e with 802.15.4 MAC protocol to analyze the trade-off of choosing a particular MAC mode over others. The parameters considered for performance are throughput and latency, and the cost is quantified in terms of energy. A Markov model has been developed for TSCH MAC mode to compare its energy costs with 802.15.4 MAC. Finally, we present the applicability of different MAC modes to different application scenarios.

INDEX TERMS IEEE 802.15.4, IEEE 802.15.4e, low-power wireless personal area networks, energy conservation, IoT.

I. INTRODUCTION

Internet of Things (IoT) has applications in diverse areas like smart industries, smart homes, smart cities, smart grid, smart health, intelligent transportation, smart agriculture etc. [1]–[9] to name a few. Industry 4.0 [10], [11] in fact refers to machines capable of sensing, communicating and optionally taking decisions. The IEEE 802.15.4-2011 [12] is one of the enabling standard that has been widely adopted for networking of low-power, low-rate, battery-powered devices, which are commonly referred to as things in IoT applications. The standard is intended for applications with limited power and non-stringent throughput requirements. Therefore, the protocols that have been developed mainly aim to minimize power consumption. Several research works have been carried out to further enhance the energy efficiency of the IEEE 802.15.4-2011 MAC [13]–[17]. Power-conserving schemes like synchronization [18]–[21], duty-cycling [22]–[25], cluster-head rotation [26]–[29], etc., have been proposed. But, moving towards Industry 4.0, accommodating growing QoS requirements like latency, throughput, energy, reliability and robustness has been a major concern. Realising this, the IEEE Standards Association recently came up with IEEE 802.15.4e [30], an amendment to the existing 802.15.4 standard. The revised standard [31] is designed for real-time applications with latency constraints that need to provide better reliability and robustness.

The IEEE 802.15.4e defines new MAC behaviors that guarantee latency and enable robust communication through multi-channel frequency hopping. The standard considers the QoS demands from various industrial applications [32]. It defines five new MAC modes, namely, Blink Radio Frequency Identification (RFID), Asynchronous Multi-channel Adaptation (AMCA), Low-Latency Deterministic Networks (LLDN), DSME, and TSCH. Blink RFID targets applications intended for object/personnel identification, tracking,

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and location. AMCA is a multi-channel approach used in non-beacon enabled (NBE) mode for large deployments. DSME MAC mode supports multi-channel operation in the contention-free period (CFP) [12] to guarantee low and deterministic latency using Guaranteed Time Slot (GTS) [12]. TSCH MAC mode has received considerable attention with the establishment of IETF 6TiSCH Working Group. The TSCH mode supports channel-hopping and multi-channel communication links (dedicated and shared) over a single time-slot. The TSCH CSMA/CA is distinct from the 802.15.4 CSMA/CA and requires a complex operation for scheduling of links over different channels. Note that the DSME and TSCH modes support multi-hop topologies, whereas modes like LLDN that support stringent timing requirements, operate in only star topology.

Currently, the IEEE 802.15.4e standard is still in the early days of adoption and research is actively being carried out to analyze its performance and address the gaps in implementation. Several works have been carried out highlighting some of the limitations [33] and open issues that need to be investigated, especially in protocol implementations. Security schemes and availability of supporting hardware is one of the primary requirements for commercial viability [33]. ZigBee [34], 6LoWPAN [35], and WirelessHART [36] have commercially implemented the IEEE 802.15.4-2011 as their underlying standard. In addition, petroleum industries and refineries [37]–[39], agricultural implementations [40], [41], smart city applications [42], and smart grids [43] have continued with their implementation of IEEE 802.15.4 for its simplicity and low complexity. Few survey [33], [44], [45] and recent works on LLDN [46], [47], TSCH [48]–[51], and DSME [51]–[53] MAC modes of operation have addressed several existing limitations.

In this paper, we present the trade-off of choosing a particular MAC protocol over others in terms of energy, latency, and associated overhead. A Markov model for the TSCH CSMA/CA is presented and compared with a similar model for 802.15.4 MAC. To summarize, the contributions of this paper are as follows.

- First, an analysis and comparison of the DSME and TSCH MAC modes with the IEEE 802.15.4 MAC is presented. Also, we discuss major research challenges associated with the respective MAC behaviors.
- Second, we propose a Markov model to estimate the transmission time and energy consumption for transmission of frames using the multi-channel approach of TSCH CSMA/CA.
- Third, we perform the simulation and numerical analysis on the performance of 802.15.4, TSCH, and DSME MAC modes. Based on these results, we outline the discussion on the choice of MAC for different applications that have varying QoS requirements.

The rest of the paper is organized as follows. Related study is presented in Section II. Section III provides an overview of the IEEE 802.15.4 MAC and IEEE 802.15.4 MAC enhancements. Section III-C and Section III-D describe the DSME and TSCH modes of MAC operation and their respective challenges in implementation. The proposed Markov model for TSCH CSMA/CA and its comparison with 802.15.4-2011 MAC (to be referred as 802.15.4 MAC) is presented in Section V. The experimental results are described in Section VI. Section VII presents a summary of the supported QoS features of different MAC modes along with their suitable application areas. Finally, conclusions are drawn in Section VIII.

II. RELATED STUDY

The revised IEEE 802.15.4-2015 [31] standard includes DSME and TSCH MAC modes along with the 802.15.4 slotted CSMA/CA MAC. Support for different application specific QoS has encouraged research on the newly developed MAC modes. Several works on TSCH [54]–[61] and DSME [51], [52], [62]–[65] have been carried out recently that focus on several aspects of their MAC behavior and performance. The works in [54]–[57] propose scheduling mechanisms for TSCH networks. For example, Orchestra [54] achieves a high throughput with minimal overhead, whereas the adaptive static scheduling in [55] focuses on low and deterministic delay for the static networks. In addition, Wave [56] targets minimal delay by scheduling the slots based on data traffic flows. It automatically adapts to the available radio interfaces and channels of the sink. The Stripe [57] is a distributed scheduling mechanism that reconfigure random pre-allocated slots and later schedules additional slots based on traffic. Further, authors in [59], [66] propose an adaptive channel selection mechanism for data transmission based on estimated link quality. Networks prone to interference can hop over other channels and improve reliability by adopting channel hopping measures as described in [58], [67]. Finally, synchronization among devices in multi-hop networks is studied in [60]. These works aim to improve the overall performance of TSCH networks by supporting one or more QoS features.

Similar to Orchestra [54], Symphony [63] proposes a new multichannel multi-time slot scheduling algorithm that integrates IPv6 Routing Protocol for Low Power and Lossy Networks (RPL) over DSME. The authors in [64] presents an effective multisuperframe tuning technique that utilizes CAP reduction in an effective way to improve flexibility and scalability while guaranteeing deterministic and low delay. Reference [65] proposes a learning based beacon scheduling mechanism for IEEE 802.15.4 as well as DSME networks. The authors in [62] proposes a DSME-based distributed scheduling mechanism for mobility support. It adaptively assigns communication slots by analyzing the channel traffic at each node to improve the network reliability and timeliness. A channel access mechanism is proposed in [52] for constrained devices to reduce the packet drop rate, energy consumption and collisions.

Previous works in this direction primarily focused on evaluating and improving the performance of the TSCH and DSME MAC modes. Works like [51], [68] have compared the DSME and TSCH MAC mode based on the QoS features. However, in this paper, we aim to present the trade-off of choosing a particular MAC protocol over the others. We analyse the cost (in terms of power consumption) to achieve the desired QoS features like throughput and latency. In the subsequent sections, we discuss the IEEE 802.15.4 MAC followed by DSME and TSCH MAC modes of operation.

III. OVERVIEW OF 802.15.4, DSME AND TSCH MAC

To support low-power and low-rate wireless communications among resource-constrained devices, IEEE 802.15.4 standard was designed. Over the last decade, it has become the most widely adopted standard for IP based IoT networks. Although new MAC behaviors have been defined, 802.15.4 MAC is still a relevant part of the current specification of the standard. Next, we present a brief overview of the 802.15.4 MAC, followed by an introduction to the new MAC modes.

A. IEEE 802.15.4 MAC

Devices operating the IEEE 802.15.4 standard can either be Fully Functional Devices (FFD) or Reduced Functional Devices (RFD). FFDs are capable of initiating a Personal Area Network (PAN) and serve as a PAN coordinator (PANC). They allow other FFDs and RFDs to associate with it to extend the network. On the other hand, RFDs are resource-constrained and can only associate to an FFD to transmit data. It acts as an end device in the network topology. Synchronization between these devices is achieved with the help of a superframe structure [12] (shown in Fig. 1). The time interval between two consecutive beacons is the Beacon Interval ($\mathtt{BI}$), and it consists of an active period and an optional inactive period (sleep period). Data transmissions take place in the active period (divided into 16 equal slots), whereas the device enters sleep state during the inactive period. The length of the active period is known as Superframe Duration ($\mathtt{SD}$). Transmissions in the active period can either be contention-based using slotted CSMA/CA or contention-free using Guaranteed Time Slot (GTS) mechanism. A maximum of seven GTS slots can be allotted to the associated devices in a single BI. This combination of GTS slots are optional and is known as Contention-Free Period (CFP). GTS allows exclusive usage of the channel to an associated device to decrease latency in transmission. Beacon transmission indicates the beginning of the Contention Access Period (CAP), and all the associated devices participate in transmitting any pending data using the CSMA/CA procedure [12]. Two parameters `macBeaconOrder` ($\mathtt{BO}$) and `macSuperframeOrder` ($\mathtt{SO}$) together defines the structure of superframe. Devices sleep in the inactive period until the beginning of the next superframe structure, forming a superframe cycle. $\mathtt{BI}$ and $\mathtt{SD}$ can be determined using the following expressions,

$$\mathtt{BI} = \text{aBaseSuperframeDuration}.2^{\mathtt{BO}} \quad (1)$$

$$\mathtt{SD} = \text{aBaseSuperframeDuration}.2^{\mathtt{SO}}, \quad (2)$$

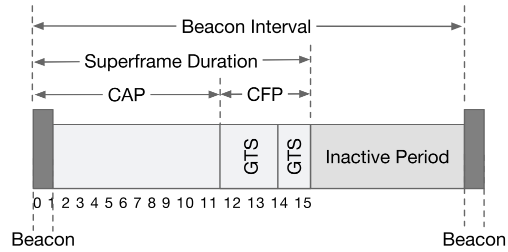

FIGURE 1. **Superframe structure [12].**

where aBaseSuperframeDuration is defined as the number of symbols constituting a superframe when the $\mathtt{SO}$ is set to zero. With $0 \leq \mathtt{SO} \leq \mathtt{BO} \leq 14$ and $\mathtt{BO} = 15$ implies a non-beacon mode.

However, the 802.15.4 MAC suffers from several limitations [13], [69] like unbounded latency and low reliability. This makes the standard unsuitable for applications having strict QoS requirements. Available GTS are either not sufficient or may not be continuously allocated in multi-hop networks. The transmissions over a single shared channel result in increased latency and frame loss due to contention and collisions, respectively. Moreover, these are also potentially vulnerable to interference with other wireless technologies working in the same 2.4 GHz ISM band such as WLAN-systems of IEEE 802.11, Bluetooth, and microwave ovens. Therefore, 802.15.4 MAC is suitable for applications with flexible requirements of latency and throughput. In view of this, new MAC modes are presented in the IEEE 802.15.4e standard that supports different QoS requirements of various applications. These MAC modes are expected to provide data transmissions with low and deterministic latency, high reliability with dedicated communication, and multi-channel access.

B. MAC ENHANCEMENTS IN IEEE 802.15.4e

The enhanced version of the standard includes new network structures and functionalities along with the slotted CSMA/CA MAC to accommodate application-specific requirements in low-rate wireless personal area networks (LR-WPAN). IEEE 802.15.4e defines five different MAC behaviors, viz., Blink RFID, AMCA, LLDN, DSME, and TSCH. Both RFID and AMCA are the two non-real-time MAC behaviors. The former targets applications intended for object/personnel identification, tracking, and location. On the other hand, AMCA is a multi-channel approach used in NBE mode for large deployments. The other three MAC modes provide deterministic latency guarantees for time-critical applications. However, in LLDN mode, all the devices in the network are required to be directly associated with the PANC, thereby, forming a star topology-based network. Therefore, among all the new MAC behaviors, DSME and TSCH operate in beacon-enabled mode (BEM) as well as support peer-to-peer connectivity to form medium to large-sized networks. Also, these two MAC modes have been

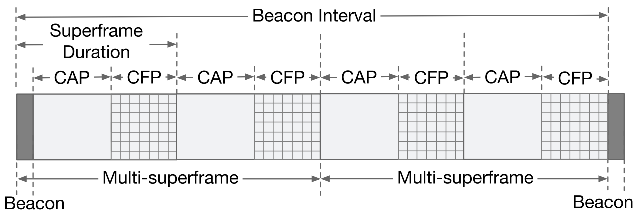

FIGURE 2. DSME multi-superframe structure [31].

incorporated in the revised IEEE 802.15.4-2015 standard. In what follows, we present an analysis of the two MAC behaviors, namely DSME and TSCH.

C. DETERMINISTIC AND SYNCHRONOUS MULTI-CHANNEL EXTENSION

DSME targets the time-critical applications like health monitoring system that requires high reliability along with low and deterministic latency. It is suitable for several industrial applications such as factory automation, process automation, smart metering, etc., and commercial applications like home automation and smart building. These applications demand high scalability and robustness, which are part of the design goals of DSME. It defines a multi-superframe structure, that is a combination of one or more 802.15.4 superframes, as defined by the PANC. The cycle of one or more superframes repeating periodically is called multi-superframe structure. A single channel is used in the CAP as well as to transmit an enhanced beacon (EB) [31]. The EB communicates to the associated devices about the number of superframes present in the multi-superframe. DSME defines a new parameter called multi-superframe order ($\mathtt{MO}$) which is related to superframe order ($\mathtt{SO}$) [12], [31] and beacon order ($\mathtt{BO}$) [12], [31] as follows.

$$0 \leq \mathtt{SO} \leq \mathtt{MO} \leq \mathtt{BO} \leq 14 \tag{3}$$

$$\mathtt{MD} = \text{aBaseSuperframeDuration}.\, 2^{\mathtt{MO}}, \tag{4}$$

where $\mathtt{MD}$ is the multi-superframe duration, that signifies the length of all the individual superframes in the multi-superframe. A DSME multi-superframe structure is shown in Fig. 2.

Contrary to 802.15.4 MAC, the DSME superframes accommodate a higher number of GTS slots using multi-channel communication in the CFP period. In a multi-superframe structure, a coordinator can reduce the size of the CAP by disabling all but the first superframe CAP, a technique called CAP reduction. This further increases the number of available GTS in a single superframe. The multi-channel approach in DSME mode is equipped with channel adaptation and channel hopping techniques. Note that the link quality indicator is used to switch between channels at different timeslots. On the other hand, channel hopping uses a pre-defined set of channels (decided by upper layers) called hopping sequence, which is followed by all the devices in the network.

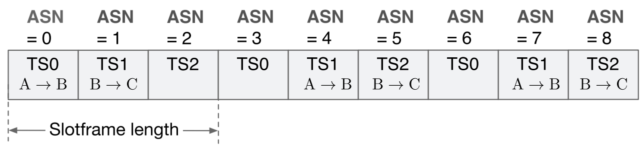

FIGURE 3. Example of three timeslot slotframe in TSCH [31].

D. TIME-SLOTTED CHANNEL HOPPING

The TSCH networks are suitable for applications prone to interference from other wireless networks. Moreover, the TSCH MAC behaviour provides high reliability and time-critical assurance for oil/refinery industries that primarily concern human and environmental safety. Other applications include equipment and process monitoring like food and chemical products, pharmaceutical products, water treatment, etc. In this mode, devices synchronize within a periodic slotframe (collection of timeslots). Each timeslot is pair-wise communication between two devices. A communication schedule is formed by setting the number of timeslots in a slotframe that determines how frequently each timeslot repeats. Fig. 3 illustrates an example of a slotframe consisting of three timeslots wherein three devices A, B, and C are communicating.

The network maintains a global count of the number timeslots that have elapsed since the beginning of the network operations. This count is the Absolute Slot Number (ASN). The communication links at any timeslot can either be shared (CSMA/CA) or dedicated (contention free). Different communication schedules can be established by defining several concurrent slotframes of different sizes. This is useful when the network is operated at different duty-cycles. The multi-channel communication in TSCH depends on the channel hopping mechanism. A link between devices is defined as a pairwise assignment of directed communication. The physical channel or frequency in a link is determined as follows:

$$f = F[(\text{ASN}) + \text{Channel Offset}]\% N_{\text{channels}}, \tag{5}$$

where F is the channel Hopping Sequence list and N_{channels} is the number of channels used in the current network operation. Communication reliability is increased through channel hopping that mitigates the effects of interference. Also, time-slotted access with dedicated links reduces collisions. This results to reduction in retransmission of frames. The most popular feature of TSCH mode is the TSCH CSMA/CA algorithm and the retransmission algorithm. Devices perform a Clear Channel Assessment (CCA) prior to transmission. If the channel is found to be idle, data is transmitted in the link; else, the device waits for the forthcoming transmission link to the destination device. The presence of dedicated communication links in the multi-channel timeslots facilitates the transmission of time-critical data as well as improves the network robustness.

IV. MAC COMPARISON AND CHALLENGES: DSME, TSCH, AND 802.15.4

A. DSME AND 802.15.4 MAC

Guaranteed Time Slots has been previously used (optionally) in 802.15.4 MAC for transmitting in a contention-free approach. However, DSME has mandatory CFP constituting of several GTS. It addresses the limitation on GTS slots (seven in 802.15.4 MAC) through the multi-channel approach. The total available DSME-GTS depends upon the number of channels used, as a single slot can be used for multiple communications in different frequencies. Thus, it allows applications operating DSME MAC to schedule transmissions with low latency and high reliability. The CAP reduction mechanism further increases the number of GTS slots by allotting the CAP slots (single channel) to multi-channel GTS slots. If N_{channels} channels are used in current network operation, then the maximum possible GTS allocation in a single superframe is given by

$$\text{GTS}_{\text{max}} = (7 \times N_{\text{channels}}) + \text{CAP}_{\text{slots}}, \tag{6}$$

where $\text{CAP}_{\text{slots}}$ is the total number of slots in the CAP. Although all communications can take place through DSME-GTS slots, significant overhead is incurred in the GTS management.

Generally, associated devices transmit pending data to the parent device within a single BI (through slotted CSMA/CA), whereas GTS transmissions require at least two superframes. This is because GTS transmissions are preceded by GTS allocation requests (in the current CAP) and response control frames that are exchanged between the parent and the associated device. If GTS slots are successfully allotted, a device transmits in the subsequent BI. Hence, DSME-GTS may not decrease latency compared to transmissions during CAP (as in 802.15.4 MAC) when contention in the channel is low. However, high contention generates frequent backoffs (in slotted CSMA/CA) among the transmitting devices that results to increase in transmission delay. This issue is addressed by the multi-channel feature of DSME MAC, allowing concurrent communication through different channels. Thus, in such network scenarios, DSME MAC considerably reduces the transmission latency compared to 802.15.4 MAC.

The IEEE 802.15.4 standard is designed for networking of wireless devices constrained in terms of power, computation, and memory. The 802.15.4 MAC allows devices to enter sleep state after the active period. Duty-cycling schemes [23], [24], [70] optimize devices' sleep period to prolong their battery life. However, in DSME, coordinators remain active for the multi-channel GTS in the CFP, resulting in higher energy dissipation.

Illustrative Example: Let us consider a network topology, as shown in Fig. 4 with coordinators c1, c2, c3, c4, c5 and c6. Let BO = 5 and SO = 2 for all the coordinators in the network. We assume low channel contention when devices are contending for transmitting a fewer number of frames in a given period of time. Initially, let each device sense and generate one frame per BI. To increase the contention, we increase the number of frames generated by each device to eight frames per BI. We compare the total time required (in terms of BI) for transmitting a set of frames between 802.15.4 MAC and DSME MAC. The associated end-devices generate and transmit data frames to coordinator c1 through their respective parent coordinator. We assume preference in transmission using GTS over slotted CSMA/CA by the devices. This is done for ease of comparison between 802.15.4 MAC and DSME mode, where GTS is the primary mechanism of transmission. The sequential steps of the 802.15.4 transmission (CAP and GTS) mechanism at each coordinator is presented below.

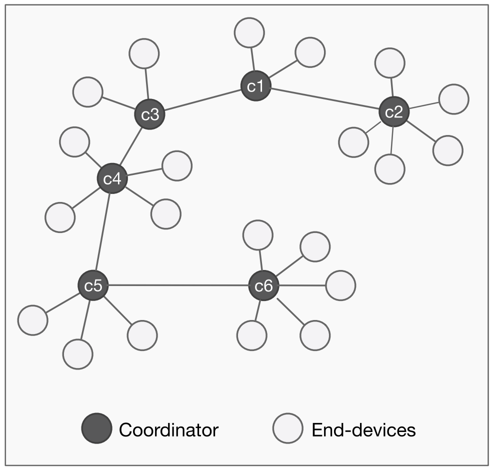

FIGURE 4. An IEEE 802.15.4 network topology.

1) **Step 1** (At c6). Total frames expected by coordinator c6 is five (one from each end-device). In the first (current) BI, end-devices request for GTS allocations. The GTS allocation requested frames are transmitted in the subsequent SD (next BI) after successful a allocation response by c6. Therefore, the time for receiving the last frame by c6 is within two BIs.
2) **Step 2** (At c5). The total frames expected is eight (including five frames from c6). Similar to Step 1, all frames are transmitted (in CAP and GTSs) within two BIs.
3) **Step 3** (At c4). c4 receives frames from c5 and its associated end-devices. Thus, total frames expected is twelve (eight from c5 and four from the end-devices). Here, seven frames can be transmitted through GTS request (in 1st BI); the rest five frames can contend in the CAP period for transmission.
4) **Step 4** (At c3). Similar to Step 2, c3 receives fourteen frames in total that can be transmitted within two BIs.
5) **Step 5** (At c1). Finally, c1 receives frames from c3 (fourteen frames), c2 (five frames) and two frames from the associated end-devices within three BIs. Here, if the SD is not sufficiently long for transmissions of all the frames, remaining frames may be transmitted in the subsequent SD.

Therefore, the aggregate time for receiving the last frame by c1 is the sum of all the steps mentioned above, i.e., $2 + 2 + 2 + 2 + 3 = 11$ BIs. Again, let the number of available channels in the DSME MAC mode be three. Therefore, available GTS for each superframe is $7 \times 3 = 21$ GTS. For the same number of transmissions, the time required using the GTS mechanism will be two BIs per coordinator. That is, in aggregate, ten BIs are required. Note that we have not considered CAP reduction, which can reduce the total transmission time. Therefore, we observe that in low channel contention, performance in terms of transmission time is similar.

1) CHALLENGES WITH DSME MAC

Although DSME provides a higher number of GTS compared to 802.15.4 MAC, it poses several challenges.

- Firstly, a sophisticated slot scheduling mechanism is necessary for allocating time and frequency slots to multiple communicating devices.
- Secondly, for multi-hop communication, the scheduling scheme needs to maintain the specific GTS allocations across hops to adhere to various QoS requirements. The difficulty arises as coordinators do not have the same number of associated devices, and traffic flows vary throughout the network. Thus, the scheduling mechanism needs to be traffic aware and decentralized for scalable network operations.
- Thirdly, slot management [71] in DSME is not adequately addressed in the standard. This results in issues like inconsistent slot allocation bitmap, failure of GTS deallocation in volatile topology and collisions of slot management handshakes in CAP.
- Finally, the absence of sleep periods in the multi-superframe structures is the primary energy-draining issue in DSME. CAP reduction minimally addresses this issue by allowing associated devices to sleep during DSME-GTS when they are not in either transmission or receiving state. However, coordinators, including the PANC, has to remain active for longer duration resulting in a reduction in network lifetime. Hence, further investigations are required to combine energy efficiency and low-latency in the DSME mode of transmissions.

B. TSCH AND 802.15.4 MAC

Unlike the 802.15.4 superframe structure, the concept of CAP and CFP no longer exists in TSCH. Each timeslot can either be a dedicated or shared communication link. A dedicated link resembles to a GTS, and shared links operating the TSCH CSMA/CA mechanism are allocated to more than one pair of devices. Transmissions in the shared links may be prone to collisions. Recurring collisions are reduced through the TSCH retransmission mechanism, as shown in Fig. 5. The TSCH CSMA/CA and 802.15.4 CSMA/CA primarily differ in the backoff strategy followed, and the number of CCA performed. A device with data to transmit waits for the next shared link, instead of a random backoff wait as in 802.15.4 MAC. It performs a single CCA before transmission, whereas, in 802.15.4, a device performs two CCA (channel free) before transmitting the frame.

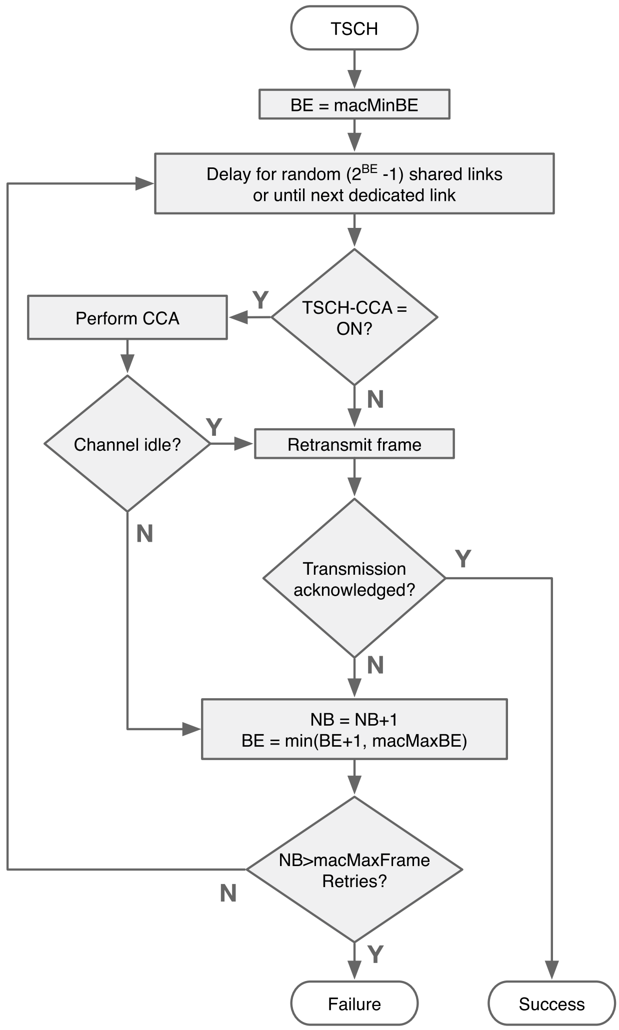

FIGURE 5. TSCH CSMA-CA [31] retransmission backoff mechanism.

Further, in 802.15.4 CSMA/CA, the retransmission mechanism is a repetition of the entire transmission procedure, beginning from a random backoff wait, followed by two CCA and finally transmission. However, the TSCH retransmission for shared links is distinct from the TSCH CSMA/CA transmission mechanism. The retransmission exponential backoff is expressed in terms of the number of shared links that must be skipped before attempting transmission. The backoff window increases for each failed transmission in a shared link. A successful transmission resets the backoff window to a predefined minimum value.

The superframe structure in 802.15.4 MAC ensures that devices enter periodical sleep periods. However, in TSCH mode, devices involved in transmission remain active in their allotted timeslots. They may or may not enter a low-power mode in between slots. Even if they do, the transceiver has to be frequently switched between listening and sleep mode.

TABLE 1. Comparison of the IEEE 802.15.4, DSME, TSCH MAC modes.

MAC mode	GTS	Multichannel	Operational channel suitability	Superframe	Sleep period	CSMA/CA	Input for schedule
IEEE 802.15.4	7 (optional in CFP)	No	Low to medium contention	Yes	Yes	Slotted CSMA/CA in CAP	BO, SO parameters
DSME	GTS_{max}	Yes (only in the CFP)	Medium to high contention	Yes	No	Slotted CSMA/CA in CAP	BO, SO parameters and flow deadlines.
TSCH	Number of dedicated links	Yes	Medium to high contention	No	No	Slotted CSMA/CA only in shared links	Traffic flow information including flow deadlines

This is because only one pair of devices can communicate at each timeslot, and multiple communication requires several timeslots, which may not be continuous. Also, a channel switching overhead for different communications (between different or same pair of devices) is incurred.

The transmission schedule for devices operating in an IEEE 802.15.4 network is based on allocating non-overlapping slots. Distributed schedules allocate slots within the 2-hop neighborhood. It is based upon the BO and SO parameters of the devices. However, in the TSCH mode of operation, computation of a schedule is highly complex [72]. The TSCH scheduling task is an NP-hard problem [73]. The schedule has to comply with various QoS demands like low latency and high reliability. For this, the schedule needs to consider the following. a) Traffic flows between the devices and the associated deadlines for each of these flows. For instance, to achieve a given latency deadline, the last fragment transmitted must be received by the sink before the deadline. b) Ensure optimal slot allocation for each flow and consider link qualities along the flow path. For this, the schedule may consider parameters like the number of radio interfaces per node and the number of available channels. c) Additionally, the schedule has to respect several constraints like half-duplex constraints, interference constraints, QoS constraints, buffer length constraints, and hardware constraints. Table 1 summarizes the comparison between the three MAC modes.

1) CHALLENGES WITH TSCH MAC

The TSCH is empowered with time-slotted access along with channel hopping and multi-channel capabilities. Several challenges arise with the implementation of these functionalities, which are yet to be addressed in the IEEE 802.15.4e standard.

- The first and foremost challenge is devising a scheduling mechanism that schedules the TSCH time slots for data frames to be sent on for both dedicated and shared links. The standard does not specify any policy to build and maintain the communication schedule over multi-hop paths. The scheduling mechanism will also control the resources allocated to each link in the network topology. Moreover, the output schedule has to be compact, i.e., new flows may be allocated without changing the entire schedule. To guarantee low-latency and high reliability, the schedule must allocate sufficient dedicated and shared links. Retransmission opportunities should be available to all devices. Also, the schedule should be adaptable to variations in traffic flow with minimum changes. In the process of building such an optimal schedule, a trade-off must be made with the energy consumption of the devices. In centralized approaches, all the devices in the network transmit their expected traffic flows along with the set of constraints to the central node, leading to a very high transmission overhead. In the distributed approach, each node may exchange traffic flow information with its neighbors for constructing a consistent schedule. Further, the schedule must follow a channel hopping sequence, defined by the higher layer in allocating channel offsets for different communication links. Finally, the schedule must decide an optimal number of shared and dedicated slots to maintain the traffic flow deadlines of all the devices in the network.
- Secondly, timeslots introduced in-place of the superframe duration of IEEE 802.15.4 do not have continuous sleep periods. They may or may not enter sleep state when there are no specified communication links. Alternately, the radio frequently switches between active and sleep states in TSCH mode as well as need to switch between channels for different communications. Also, the multi-channel approach in TSCH entirely depends on the channel hopping mechanism. All the devices in the network must be synchronized to the shared hop sequence in use. Thus, a network-wide slot synchronization among the devices is required. Therefore, devices periodically transmit control (sync) frames that consume significant energy over a period of time. The network consists of few time-source neighbors that periodically transmit data or acknowledgment frames to all the neighboring coordinator devices for synchronization.
- Finally, the standard does not specify the criteria behind the selection of a link as shared or dedicated in TSCH CSMA/CA. The retransmission procedure in TSCH CSMA/CA introduces a longer delay through random backoff (in terms of links) compared to the 802.15.4 CSMA/CA retransmission procedure. This is

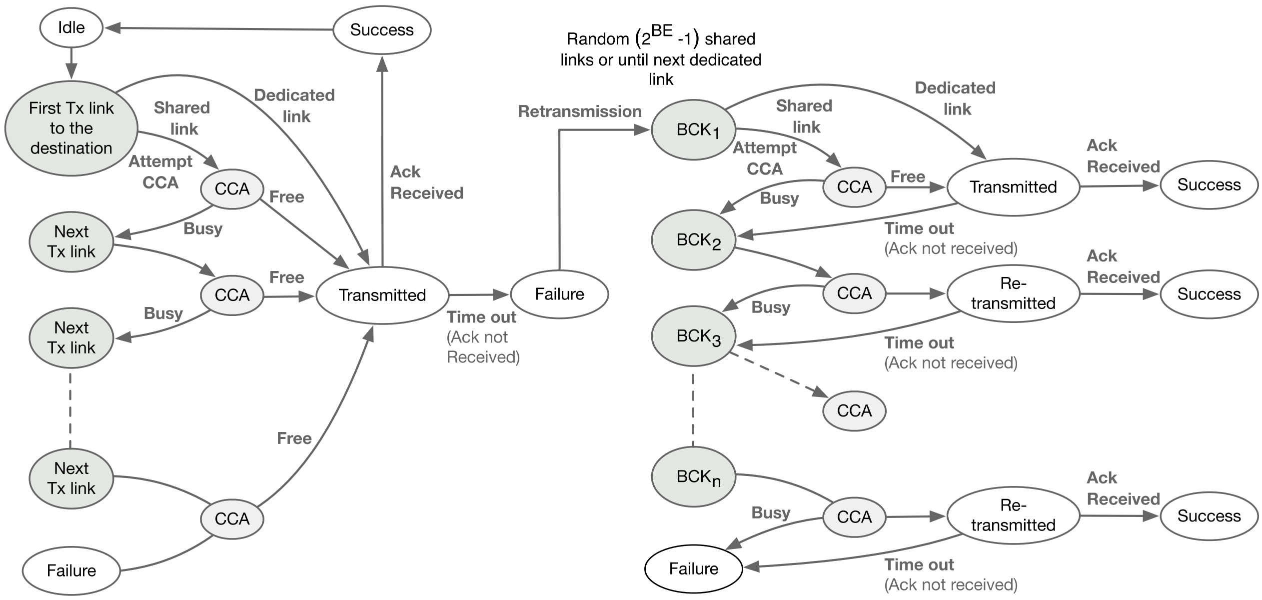

FIGURE 6. **Markov model for TSCH CSMA/CA and retransmission backoff mechanism.**

discussed and analyzed through a proposed Markov model in the next section.

V. PROPOSED MARKOV MODEL FOR TSCH CSMA/CA

We consider an IEEE 802.15.4e network topology with n devices. We assume the existence of a TSCH transmission schedule for the pairwise communication. The schedule defines each allotted timeslot as either shared or dedicated. In dedicated links, devices directly initiate transmission of frames, whereas, in shared links, devices initially perform a single CCA. Transmission failure in shared links is detected by non-receipt of an acknowledgement. In order to reduce the probability of recurring collisions, the retransmission backoff algorithm is followed, as shown in Fig. 5. CCA is independent of the backoff stages as well as the number of retransmissions previously attempted.

The Markov model for TSCH CSMA/CA and retransmission is shown in Fig. 6. Each state in the model can be represented with a 4-valued tuple (i, j, CCA, rnd) (i, j, CCA, rnd), where $i = 0, \ldots, 7$ signifies the `macMaxFrameRetries` parameter, $j = 0, \ldots, 5$ signifies the `macMaxCSMABackoffs` and rnd ranges from 0 to $2^{BE} - 1$ that signifies the random number of shared links that must be skipped before attempting transmission. CCA needs to be performed prior to frame transmission. It decreases after each successful CCA and frame is transmitted when this value reaches 0.

The transmission time of a frame in a shared link can be expressed as

$$Tx_n = \sum_{i=1}^{n} T_{\text{next-link}_n} + nT_{CCA} + T_{ta} + T_l + ACK_{\text{wait}} + ACK_{\text{rec}}, \quad (7)$$

where $T_{\text{next-link}_n}$ is the nth constant time waiting for the next transmission link to destination before attempting CCA. T_{CCA} is the time required in CCA, T_{ta} is the turn around time, T_l is the time for transmitting a frame of length l, ACK_{wait} is the time spent in waiting for acknowledgement from the coordinator, and ACK_{rec} is time required in receiving the ACK. For transmissions in dedicated links, the transmission time is given by

$$Tx = T_{\text{next-link}} + T_{ta} + T_l + ACK_{\text{wait}} + ACK_{\text{rec}} \quad (8)$$

The energy consumption in shared transmission links is

$$\mathrm{E}_{tx_n} = E_x\,(T_{CCA}) + E_{ta}T_{ta} + E_{tx}T_l + E_x\,(ACK_{\text{wait}} + ACK_{\text{rec}}) + (n-1)E_x\,(T_{CCA}) \quad (9)$$

and for dedicated communication link is expressed as

$$\mathrm{E}_{tx} = E_xT_{ta} + E_xT_l + E_x\,(ACK_{\text{wait}} + ACK_{\text{rec}}) \quad (10)$$

where E_x is energy consumed after completing a specific operation.

In case of a retransmission in the shared link, identified by i in the Markov model (`macMaxFrameRetries` parameter in TSCH backoff algorithm), the transmission time and energy consumed will be as follows

$$\mathrm{RTx}_n = Tx_n + \sum_{i=1}^{n} T_{n\text{BCK}_{\text{next-link}}} + nT_{CCA} + T_{ta} + T_l + ACK_{\text{wait}} + ACK_{\text{rec}} \quad (11)$$

$$\mathrm{E}_{Rtx_n} = \mathrm{E}_{tx_n} + E_x\,(T_{CCA}) + E_{ta}T_{ta} + E_{tx}T_l + E_x\,(ACK_{\text{wait}} + ACK_{\text{rec}}) + (n-1)E_x\,(T_{CCA}), \quad (12)$$

where $T_{n\text{BCK}_{\text{next-link}}}$ is the random number of shared links that must be skipped before attempting transmission again.

TABLE 2. Configuration of the coordinators.

Coordinator	SO	BO	Association order
c1	2	4	0
c2	2	3	1
c3	1	3	2
c4	1	4	3
c5	1	4	4
c6	1	3	5

A Markov model for IEEE 802.15.4 CSMA/CA was presented in [23]. The transmission time and energy consumed for IEEE 802.15.4 CSMA/CA frame transmission was computed as [23]

$$T_{n_{max}} = \sum_{i=1}^{n} T_{BCK_n} + nT_{CCA_1} + T_{CCA_2} + T_{ta} + T_l + ACK_{\text{wait}} + ACK_{\text{rec}} + (n-1)T_{CCA_2} \quad (13)$$

$$E_{n_{max}} = E_x\left(T_{CCA_1} + T_{CCA_2}\right) + E_x T_{ta} + E_x T_l + E_x\left(ACK_{\text{wait}} + ACK_{\text{rec}}\right) + (n-1)E_x\left(T_{CCA_1} + T_{CCA_2}\right), \quad (14)$$

where T_{BCK_n} is the time spent in nth backoff state and T_{CCA_2} is the time required in CCA_2.

From (7) and (13), it can be observed that a frame consumes more time in performing CCAs. The time spent waiting in the backoff stage in IEEE 802.15.4 CSMA/CA is purely random can either be longer or shorter than the next communication link to a destination in TSCH mode. However, the TSCH retransmission backoff mechanism introduces a longer transmission time (11) through the waiting period of a random number of shared links. This can be generally longer than a similar retransmission mechanism in IEEE 802.15.4 CSMA/CA as the backoff timer is only dependent on the value of BE (binary exponential backoff).

The energy consumption in TSCH CSMA/CA (9) is lower than IEEE 802.15.4 CSMA/CA (14) due to the additional CCA prior to transmission attempt. Also, transmissions in dedicated communication links (10) consume considerably low energy. Retransmissions in IEEE 802.15.4 CSMA/CA is a repetition of the entire CSMA/CA transmission mechanism. However, in TSCH retransmission, energy consumption after performing CCA (12) is still lower than 802.15.4 based CSMA/CA. Therefore, energy consumption during transmissions is lower in TSCH mode compared to IEEE 802.15.4 MAC.

VI. RESULTS AND DISCUSSION

In this section, the IEEE 802.15.4 MAC, DSME and TSCH MAC modes are evaluated and compared based on their QoS performance metrics like latency, throughput and cost in terms of energy. We consider an IEEE 802.15.4 network topology, as shown in Fig. 4 with c1, c2, c3, c4, c5 and c6 acting as coordinators, while rest of nodes (21 devices) are the end-devices. The superframe configuration of the coordinators are given in Table 2. For, DSME and TSCH, let the number of available channels be three (for ease of computation and comparison with 802.15.4 MAC). Let each device generate four frames per BI. For TSCH, we consider a timeline equivalent to four BI of c1 (coordinator with longest BI). The schedules for 802.15.4 MAC, DSME and TSCH are built using LBS [18], DSME [62] and [55]. We consider a timeslot (TSCH) to be 10 milliseconds long.

TABLE 3. QoS performance measurement.

MAC modes	Throughput (kbps)	Latency (ms)	Cost (J)
IEEE 802.15.4	0.22	245.76	0.43
DSME	0.25	185.76	0.47
TSCH	0.27	120	0.52

We evaluate the QoS performance metric for all the three MAC modes in MATLAB We use the expressions derived from the Markov model to compute the latency and energy consumed in transmission for 802.15.4 MAC and TSCH. DSME follows a similar transmission procedure to the 802.15.4 MAC, but it primarily relies on DSME-GTS for low-latency transmissions. Therefore, while building the transmission schedule, we allow frames to be transmitted using the available DSME-GTS and the remaining frames (if any) through the CAP. Throughput is computed based on the number of frames received within the four BIs (equivalent time for TSCH). The amount of energy consumed for achieving the desired latency and throughput is computed based upon the number of transmissions incurred. This includes overhead in the transmission of control messages for schedule computation and GTS allocation request/response, and channel switching.

Table 3 shows the measured throughput, latency and cost values. Next, we vary the number of nodes and record the throughput, latency and the cost in terms of energy as shown in Fig.7, Fig. 8 and Fig. 9. Within the considered timeline, we observe (Fig. 7) that the throughput difference between the MAC protocols is significant. The network complexity and channel contention increase with size, resulting in a longer delay in transmissions. Thus, the average throughput decreases marginally in the network, degrading the performance of the MAC protocols. TSCH outperforms the other MAC protocols due to dedicated multichannel transmission links that ensure no retransmission and collision in the channel. Also, both 802.15.4 and DSME MAC modes utilize slotted CSMA/CA in their respective CAP period, which induces backoff delay with the increase in channel contention.

Fig. 8 shows the latency comparison between the MAC protocols. Both TSCH and DSME facilitate low-latency through the multichannel approach and the presence of dedicated links in terms of timeslots and DSME-GTS. However, 802.15.4 MAC has limited GTS slots and the primary transmission mechanism is slotted CSMA/CA. With the increase in network size, the delay time increases with the increase in the hop number and retransmission of frames.

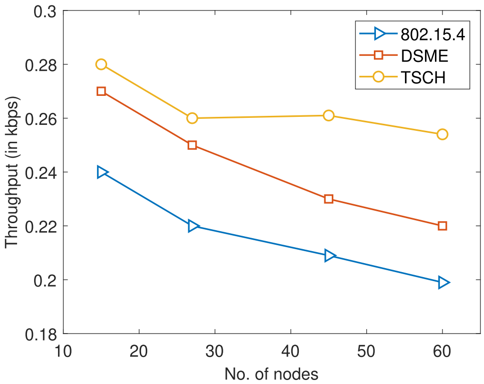

FIGURE 7. Performance of MAC protocol in terms of throughput.

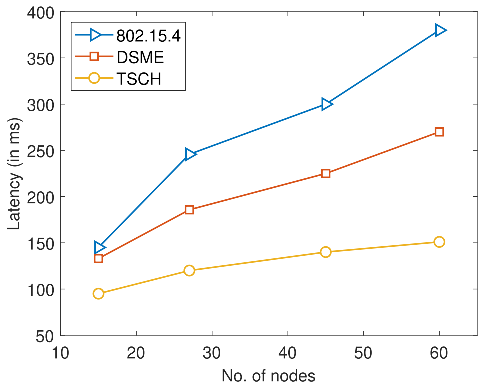

FIGURE 8. Performance of MAC protocol in terms of latency.

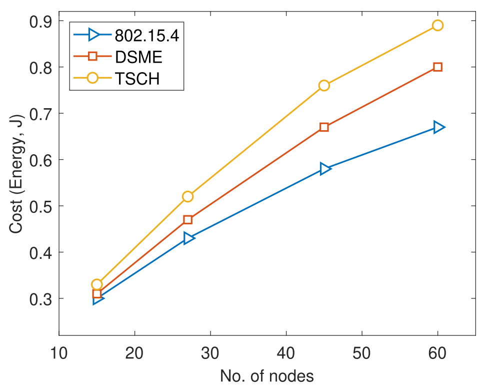

FIGURE 9. Performance of MAC protocol in terms of energy consumption.

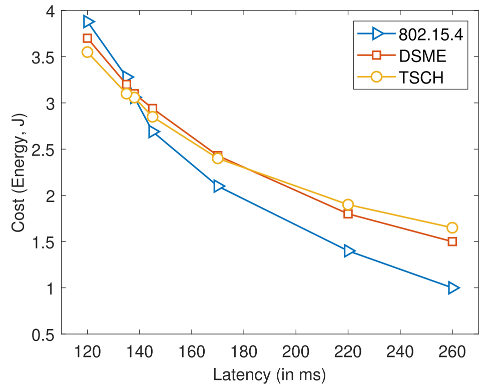

FIGURE 10. Performance of MAC protocol in terms of energy consumption and latency.

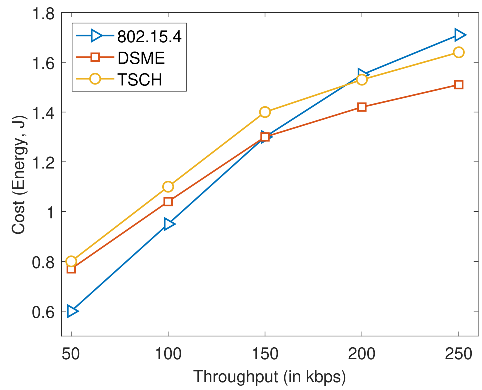

FIGURE 11. Performance of MAC protocol in terms of energy consumption and throughput.

TABLE 4. Simulation parameters.

Parameters	Values
Beacon order	8
Superframe order	2
Multisuperframe order	2
Slot duration	0.010 millisecond
Slotframe length	101 symbols
Initial Energy	10 J
Energy consumed to receive a frame	0.003 J
Energy consumed to transmit a frame	0.006 J
Energy consumed during sleep-state	0.000 030 J

Although TSCH and DSME achieve high throughput and low latency compared to 802.15.4 MAC, the associated cost is higher in terms of energy consumption. Fig. 9 shows the cost in energy consumed by the MAC protocols. Due to the simplicity in transmission and the presence of the sleep cycle in the 802.15.4 MAC superframe structure, devices considerably reduces their power consumption. Devices in TSCH based networks may sleep in between their transmissions links and generally remain active for data transmissions. The 802.15.4 MAC primarily focuses on energy-efficient mechanisms to operate various network functions and is suitable for applications with relaxed throughput and latency. Fig. 10 and Fig. 11 show the associated cost in achieving a desired level of latency and throughput respectively. For relaxed latency and throughput, 802.15.4 MAC consumes lower energy compared to DSME and TSCH. However, in the process of achieving low-latency or high throughput, the 802.15.4 MAC increases its active period (thereby decreasing the sleep period) to accommodate more incoming frames. This results in higher cost compared to TSCH and DSME modes after a certain level of desired latency and throughput.

Next, we conduct experiments on OMNeT++ [74] simulator and 6TiSCH [75] simulator for DSME and TSCH based networks, respectively, to evaluate their performance.

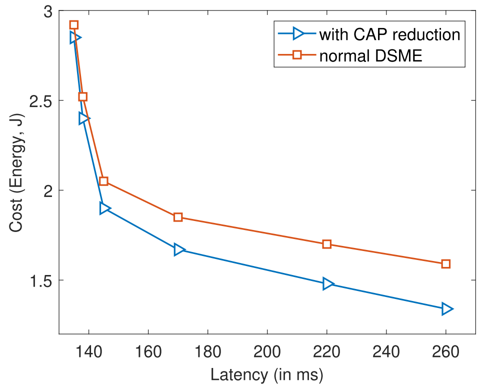

FIGURE 12. **Performance of DSME based networks in terms of latency and incurred cost.**

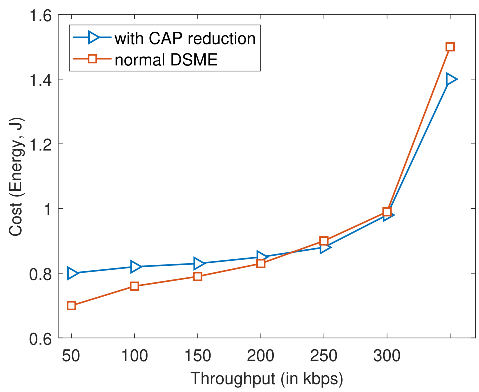

FIGURE 13. **Performance of DSME based networks in terms of throughput and incurred cost.**

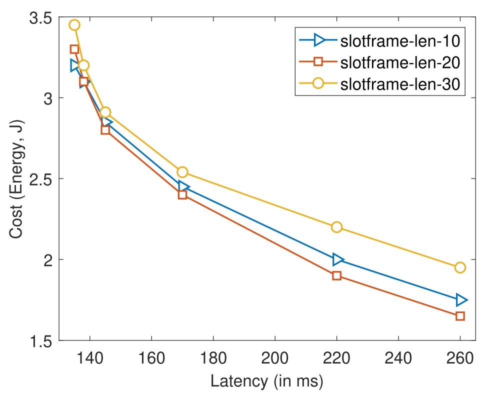

FIGURE 14. **Performance of TSCH based networks in terms of latency and incurred cost.**

This is done due to unavailability of a single simulator modeling all the three MAC modes. OpenDSME [76], an open-source portable implementation of IEEE 802.15.4 DSME, is imported in the OMNeT++ to realize the DSME MAC mode. We use an IEEE 802.15.4 network topology as shown in Fig. 4. We set the same simulator parameters, wherever feasible for both the simulators. Table 4 presents the parameter values of the simulation.

First, we use OMNeT++ to simulate our DSME based network. We consider both CAP reduction and normal DSME

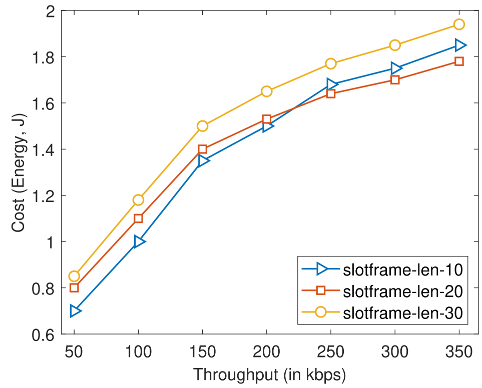

FIGURE 15. **Performance of TSCH based networks in terms of throughput and incurred cost.**

in our experiment. From Fig. 12 and Fig. 13, it can be noticed that with CAP reduction, higher throughput and lower latency can be achieved as transmissions take place through the DSME-GTS only. However, this results in considerably higher energy consumption than normal DSME. Also, with stringent requirements of latency and throughput, power consumption increases. The devices have to remain active for a longer duration to ensure transmissions to/from other devices. Therefore, in such cases, the network needs to operate in higher duty-cycles.

Secondly, to evaluate the performance of TSCH based networks, we simulated three different scenarios with slotframe lengths of 10, 20 and 30 timeslots. Fig. 14 shows the increase in power consumption with lower latency guarantees. The frequent slot allocation for the devices is required to maintain strict latency throughout the network, resulting in higher energy consumption. Similarly, high throughput results in higher consumption of energy, as shown in Fig. 15. Higher throughput demands an increase in the number of frame transmission within the same amount of time. This is achieved by scheduling frequent, dedicated links with minimal empty timeslots. This also minimizes retransmission of frames, which in turn assists in reducing latency.

VII. SUITABLE MAC MODES FOR VARIOUS APPLICATIONS

In this section, we present QoS features considered by each of the MAC modes and the different industrial applications suited to these MAC behaviors. The 802.15.4 MAC was initially designed for all LR-WPANs and wireless sensor networks that are typically comprised of resource-constrained devices. It is one of the widely adopted standards for realizing IP based IoT applications that have flexible throughput and latency requirements. Network topologies operating the 802.15.4 MAC are currently used in oil/refinery industries, agricultural implementation, factory automation, smart city, smart home applications, etc. However, to support specific QoS requirements of applications, several new MAC behaviors were designed in IEEE 802.15.4e. The RFID Blink mode is used for tracking and identification purposes. It is also integrated with WSNs for tagging and identifying

TABLE 5. List of the supported features by the MAC modes.

MAC	Latency	Reliability	Robustness	Scalability	Scheduling	Energy Efficiency	Supported Topology	Suitable Applications
IEEE 802.15.4	No	Yes	No	Yes	Straightforward for star, difficult for cluster-tree	Yes	Star, cluster-tree	Applications with flexible throughput/ latency
BLINK	No	No	No	No	Not applicable	Yes	Star	Object/Personnel Identification, location and tracking
AMCA	No	No	Yes	Yes	Not applicable	No	Star, cluster-tree	Smart utility, infrastructure monitoring, process control
LLDN	Yes	Yes	No	No	Straightforward	No	Star	Terrain surveying, factory automation, cargo, airport logistics, automated dispensers, automated packaging
DSME	Yes	Yes	Yes	Yes	Complex	No	Star, cluster-tree	Industrial automation, process control, and health-care monitoring
TSCH	Yes	Yes	Yes	Yes	Highly Complex	No	Star, cluster-tree	Oil and gas refineries, food and chemical products, pharmaceutical products, water treatments

goods [77], [78]. These networks can have very long network lifetime.

The AMCA MAC mode is suited for non-beacon PANs and targets large deployments like infrastructure monitoring networks, smart utility networks, etc. These applications require multi-channel and link adaptations [79] to communicate between several devices without compromising on network performance. However, they operate in the non-beacon mode of operation, resulting in considerable energy dissipation. This is because the devices remain active throughout their lifetime without the support of any synchronization mechanism.

Further, DSME MAC was designed to cater to the requirements of applications with low and deterministic latency, energy efficiency, scalability, and high reliability and robustness. Considering the criticality of exchanged data, applications like industrial automation and process control are highly sensitive to any loss of data. Also, health-care monitoring systems need to guarantee low-latency for data transmissions. Further, many applications like outdoor surveillance require large and dense deployment. DSME MAC mode provides the solution to all such QoS requirements through the presence of a high number of GTSs, which is achieved through a multi-channel approach. Also, the channel adaptation feature in DSME increases the robustness of the network.

The LLDN mode target applications demanding centralized control, low-latency, and robustness. For example, terrain survey [80] capturing large geographical areas will best be served with the LLDN mode of MAC behavior. This MAC mode is based on star topology supporting the connectivity of more than 100 devices to the central device. Single hop communication also helps in achieving low and deterministic latency. Data frames are re-transmitted for failed transmissions. ACK frames and retransmissions increases the reliability of networks operating MAC modes like IEEE 802.15.4, DSME, LLDN, and TSCH.

Finally, TSCH MAC mode is designed to serve applications requiring high reliability and time-critical assurances. It is suitable in sensor-actuator networks in oil and gas refineries where strict safety assurances are to be met and maintained for both human and environmental safety. Other applications are equipment and process monitoring like food and chemical products, pharmaceuticals, water treatment, etc. Such networks are prone to interference from other similar networks that negatively affect the performance of the wireless devices. TSCH, with its frequency hopping mechanism, mitigates the effects of such interference and fading link qualities, thus, improving the robustness of the network. Also, the absence of a long sleep period for the devices restricts network lifetime. We summarize a list of supported QoS and applications suited to the IEEE 802.15.4 MAC, RFID Blink, AMCA, LLDN, DSME, and TSCH MAC modes of IEEE 802.15.4e in Table 5.

The new MAC modes will have superior performance in terms of latency, throughput, reliability, and robustness. However, performance guarantees of the new MAC modes should not result in its application by default. Simple and ease of implementation of IEEE 802.15.4 MAC have been shown to perform better in applications with non real-time requirements. For example, an application with deterministic and low-latency requirements may consider either DSME or TSCH MAC over 802.15.4 MAC. However, if the network is prone to interference and has distinct deadlines for different data traffic flows, TSCH is more suited than DSME. Although a better performance in such a network scenario is achieved, energy consumption can be higher than DSME MAC. LLDN MAC may not be suitable if the application requires devices to be connected in a multi-hop scenario. Further, if the network desires for a reasonable lifetime, AMCA will not be a suitable option for the power-constrained, battery-operated devices. Delayed data can either be useless or detrimental to the deployed geographical area. Thus, the choice of MAC plays a critical role in determining the overall network performance and safety of the application. On the other hand, for a network with relaxed throughput and latency requirements, the IEEE 802.15.4 MAC will be better suited than the DSME or TSCH modes in terms of energy consumption. This is also observed from Fig. 10 and Fig. 11. Applications like industrial monitoring and control have dynamic traffic requirements at different phases of operation. The duty-cycle of the devices and the transmission schedule needs to be adapted for optimal power consumption. Overhead in duty-cycling followed by updating the transmission [18] schedule is comparatively lower in 802.15.4 MAC than DSME and TSCH based networks. Networks that primarily require to operate under very low duty-cycle have benefited through the use of 802.15.4 MAC, allowing long network lifetime.

VIII. CONCLUSION AND FUTURE WORK

In this paper, we have presented an analysis of DSME and TSCH MAC and primarily compared against the IEEE 802.15.4 MAC. The multi-channel approach in DSME and TSCH allows dedicated and reliable communication between devices. These MAC modes are suitable for networks hindered with interference from other wireless networks as well as suited for applications with deterministic or low latency requirements. However, it introduces the design of complex synchronization schedules as well as GTS management in multi-hop networks to maintain low latency QoS requirements. Frequent channel adaptations for multiple communications and lack of a complete sleep period may increase the energy consumption of such a network setup. In addition, a Markov model for TSCH CSMA/CA and retransmission is proposed to estimate energy consumption and transmission time. Finally, we present a summary of the supported QoS features of different MAC modes along with their suitable application areas. A trade-off of choosing a particular MAC mode over others is to be made based on the QoS requirements of an application.

The IEEE 802.15.4-2015 standard has been recently ratified and do not specify the implementations of several mechanisms, like DSME-GTS allocations and TSCH link scheduling. Also, the challenges highlighted in the paper may delay the adoption of 802.15.4e as the de-facto communication standard for future IoT applications. Nevertheless, the revised standard aims to achieve highly reliable and efficient communication for applications with specific QoS requirements. As a future work, we intend to develop a DSME-GTS as well as TSCH slot scheduling mechanism for multi-hop networks operating with different traffic flows.

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