Enhancements of IEEE802.15.4e DSME Model of Wireless Sensor Networks

Sameer K. Alsudany, Student Member, IEEE, Said Boussakta, Senior Member, IEEE
and Martin Johnston, Member, IEEE
School of Engineering, Newcastle University, UK
E-mail: {s.k.k.alsudany1, said.boussakta, martin.johnston}@ncl.ac.uk

***Abstract*—Internet embedded sensor nodes have attracted the attention of researchers and industry due to their wide application. The main standard, IEEE802.15.4e 2012, introduces a deterministic and synchronous multi-channel extension (DSME) model. Three main issues should be tackled and improved with this model; a high energy consumption of end nodes during the contention access period (CAP), a long association and guaranteed time slot (GTS) earning times during a network initialization phase and a long network discovery time. These issues have been analysed and improved in a star topology wireless sensor network (WSN). Four scenarios with different numbers of nodes are investigated. Nodes numbers are set according to network saturation ratios (25%, 50%, 75%, and 100%). This paper proposes three enhancements for the performance of this model. Two new approaches are proposed to reduce the energy consumption of end nodes during the CAP period, a new association scheme during network initialization phase using a tight TDMA algorithm to minimize the time required for association and getting a GTS slot and reduce power consumption due to collisions, and a new technique to reduce network discovery time. Simulation results show significant improvements in reducing energy consumption and radio duty cycle (RDC) of end nodes by a factor of (71) and (77) respectively. Good improvements are also achieved in reducing association and GTS earning times by a factor of (8) on average. Finally, network discovery time has been reduced for fast association and further energy saving of end nodes.**

***Index terms*— DSME, GTS, IEEE 802.15.4-e, MAC scheduling, multi-superframe, wake-up command, WSN.**

I. INTRODUCTION

SMART sensor nodes can be deployed in different areas to construct a wireless sensor network (WSN). They can be utilized in different applications such as environmental monitoring, the military and healthcare sectors and industrial automation [1]. Nowadays, WSNs have become one of the main feeders of information to the Internet, especially since the emergence of the IoT (Internet of Things) [2] and the feasibility of transferring IPv6 packets over the medium access control (MAC) frame [3] using the 6LoWPAN adaptation layer [4]. Researchers in this field face various challenges due to the specific characteristics of sensor nodes. The limited energy source (battery-operated), low data rates, short-range communication, channel fading and interference and production costs are the main issues.

The popular standard IEEE 802.15.4 [5] represents the main infrastructure for the physical and MAC layers. Recently, the introduction of the newly amended IEEE 802.15.4e-2012 [6] has improved performance in terms of radio frequency (RF) link reliability, network capacity, packet latency and guarantees and determinism in packet transmission. Different superframe and slot frame structures, channel diversity modes (channel hopping and channel adaptation) and fast association, among others, are the main improvements achieved with the new amendment.

One of the main challenges of a WSN with a long lifetime is the energy consumption. Different components inside a sensor node can consume energy, but the main culprit is the wireless communication transceiver compared to other parts such as processing unit and memory. Sometimes, transmitting a single bit can consume as much as 1000 times the power utilized to compute a single instruction [7]. As the network operates, node energy is depleted and, as nodes become drained of energy, the coverage area begins to shrink and eventually the network becomes useless [8]. Therefore, power optimization is crucial in extending network lifetime.

The DSME model extends the legacy standard by reconfiguring the superframe structure and introducing channel diversity modes. It divides the superframe into a beacon slot, contention access period (CAP) and a contention-free period (CFP). Moreover, the beacon interval is divided into groups of superframes called a multi-superframe structure. According to the requirements of IEEE802.15.4-e, end nodes (battery-operated) inside the DSME network should keep their receivers ON during the CAP period, which can lead to higher energy consumption. Therefore, this issue should be addressed and optimized.

In the DSME network initialization phase, each node should associate with a PAN (Personal Area Network) coordinator and apply to earn a guaranteed time slot (GTS) before the beginning of transmitting its data. Nodes access their medium using a slotted CSMA-CA algorithm in which the number of collisions may increase for more than one reason. The main two reasons are, firstly, collisions that occur among different packets within the same process since nodes may transmit their commands packets at the same time. Different packets are transmitted in the association process such as association request, association response and acknowledgement packets.

In a GTS process, packets such as GTS request, GTS response, GTS notification and acknowledgements of different packets may be transmitted simultaneously and lead to more collisions. Secondly, interleaving between the association and GTS phases of different nodes may cause further collisions. When a node joins a network, it can ask for a GTS while other nodes are still in the association or GTS phases. Therefore the association and GTS long times during a network initialization especially in a network with a large number of nodes should be addressed and minimized.

The standard proposes that end nodes should scan the entire channels to discover a network and join it. This scan process can lead to a long waiting period and more energy consumption especially with a long beacon interval, therefore this long time should be addressed and minimized.

A. Contribution of this paper

This paper proposes three enhancements to the IEEE802.15.4e DSME model. The main contributions of our schemes can be summarized as follows:

1) Proposing two new approaches to control end nodes' receivers to reduce their energy consumption in a DSME network.
2) Proposing a new scheme to minimize the long time required for association and GTS earning processes during the initialization phase of a DSME network.
3) Proposing a new technique for network discovery.

The rest of this paper is organized as follows: relevant previous work is discussed in section II. Section III gives a brief background of the IEEE802.15.4e- DSME model. Section IV describes the main functions and enhancements of the proposed schemes. The implementation and analysis are given in section V. Results and discussion are presented in section VI. Finally, the conclusions and outcomes are indicated in section VII.

II. Related Work

Capone *et al*. [9] proposed three enhancements for the IEEE802.15.4 DSME model (Enhancement for Low-Power Instrumentation DSME Applications, ELPIDA). The first is the CAP wake-up in which an end node's transceiver is turned off during the CAP period. Secondly, since most traffic is sink-oriented, a sensor node falls into a sleep mode during down-stream traffic. Finally, a beacon look-up is used to overcome the clock jitter problem that affects end node's synchronization with the sink node. However, the CAP wake-up technique is not flexible enough to support different MAC wake-up schedules because it depends mainly on a single control bit (the frame pending field of the frame control of the enhanced beacon (EB)) to control the MAC duty cycle of end nodes. Also, it has a restriction when a coordinator node has data pending to its end nodes as it cannot use this field to inform these end nodes about pending data kept at the coordinator.

Sahoo *et al*. [10] proposed new methods for channel access and beacon scheduling to reduce network discovery time and energy consumption. Also, a new dynamic slot allocation for guaranteed retransmission and medium CCA implementation were proposed. The new channel access and beacon scheduling depend mainly on transmitting beacon frames in each superframe on different channels. Each node chooses a random channel to receive a beacon. This will partition nodes into different groups to access the medium in different superframes in the association process, thus leading to reduce number of collisions, association delay time and power consumption.

Juc *et al*. [11] analysed and compared the performance of two models of the IEEE 802.15.4 e standard; Time Slotted Channel Hopping (TSCH) and DSME. Three parameters were assessed in this analysis: energy consumption, throughput and transmission delay time. The results showed that, in low duty cycle applications, TSCH obtains higher throughput, shorter delay and lower power consumption. Meanwhile, DSME exhibits higher throughput, shorter delay and lower power consumption for high duty cycle applications.

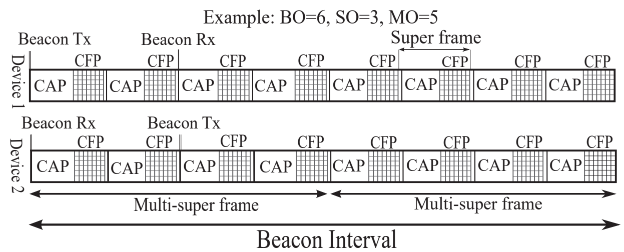

Fig. 1: DSME multi-super frame structure.

Alderisi *et al*. [12] presented a performance assessment for two models of the IEEE 802.15.4e standard: DSME and TSCH. The performance metrics were delay, reliability and scalability. Both protocols were proven to be robust against channel noise because of using multi-channel transmission technique; therefore, both can be considered as reliable protocols.

In [13], the relevance of IEEE 802.11ah and 802.15.4 in the context of IoT is examined, considering their various key aspects. Performances of both technologies in terms of association time, throughput and end-to-end delay are evaluated and compared, assuming realistic scenarios with a significantly large number of devices.

III. Background on the IEEE 802.15.4e-DSME model

In the DSME-enabled network, a PAN coordinator node transmits an EB every beacon interval (BI) to synchronize nodes with the superframe structure. Every beacon is broadcasted with a DSME PAN DESCRIPTOR IE (Information Element) which describes different parameters of the EB.

The DSME model can be considered as an enhanced and extended mode of the legacy IEEE 802.15.4 standard, as shown in Fig. 1. It enhances the performance of the legacy standard by utilizing the new multi-superframe structure, channel diversity, CAP reduction and group acknowledgements. The multi-superframe structure depends mainly on three parameters:

1) Superframe order (SO), which defines the length of the superframe duration (SD):
$$SD = aBaseSuperframeDuration \times 2^{SO} \quad (1)$$
2) Multi-super frame order (MO), which defines the multi-superframe duration (MD):
$$MD = aBaseSuperframeDuration \times 2^{MO} \quad (2)$$
3) Beacon Order (BO), which defines the duration between every two consecutive beacons transmitted by a PAN coordinator (BI):
$$BI = aBaseSuperframeDuration \times 2^{BO} \quad (3)$$

Octets: variable	1	1	2
MHR fields	Command Frame Identifier	Number of superframes	FCS

Fig. 2: Wake-up command structure.

These three parameters are related to each other according to:

$$0 \leqslant SO \leqslant MO \leqslant BO \leqslant 14 \quad (4)$$

Each superframe consists of 16 slots with equal size. Nine slots constitute the CAP period and seven slots form the CFP period. Therefore, a maximum of 7 devices can transmit during each superframe duration.

The multi-superframe structure is used for data transmission repetition. Therefore, every node can transmit every multi-superframe. EBs are transmitted at the start of slot 0 and repeated every beacon interval (BI). Commands frames are transmitted during the CAP period while data frames are transmitted during the CFP period.

In the DSME model, a node can follow five phases during its lifetime; network discovery, network association, GTS earning, data transmission and network disconnection.

IV. Enhancements of IEEE802.15.4e DSME model

Our system model enhances the performance of the IEEE802.15.4e DSME standard in more than one respect as follows:

A. Energy saving

The enhancement is related to the power consumption of end nodes during the CAP period of the EB superframes. As stated by the standard, end nodes should keep their receivers in the ON state during the CAP period. Therefore, two approaches have been developed to save nodes energy during the CAP period:

1) The CAP wake-up command: this approach is more flexible than others as it defines the wake-up time (ON) state per superframe inside a multi-superframe structure starting from the first superframe. The command structure consists of the following fields: (Fig. 2)
    a) Command Frame Identifier (0x1d): this is selected from the IDs that are reserved by the standard.
    b) Number of superframes: this defines the number of superframes inside each multi-super frame starting from the first one for the node's receiver to be in the ON state in the CAP period.
2) Control bit: Our proposed approach uses a reserved bit (unlike ELPIDA which uses the frame pending bit) in the same frame control field of the EB to implement the CAP wake-up. In this approach, end nodes turn their receivers OFF in all CAPs except in the beacon and the GTS slots when the control bit equals zero. When it is one, nodes turn their receivers ON in all CAPs.

Fig. 3(a) depicts a node in a data transmission phase with the standard model, while Fig. 3(b) depicts the same node

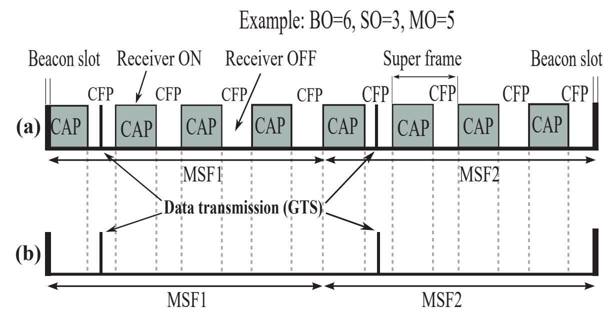

Fig. 3: Data phase: (a) Std. model, (b) Enh. model.

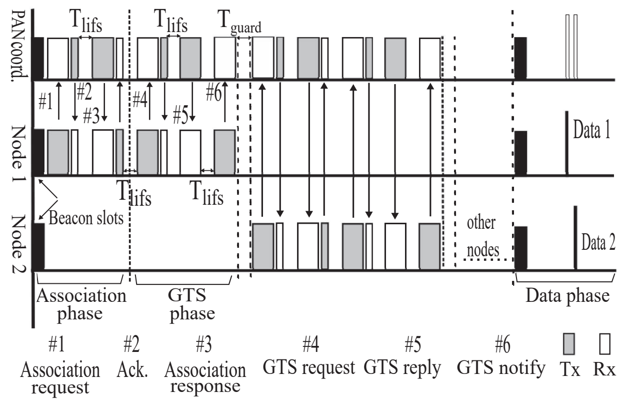

Fig. 4: Nodes' Association and GTS processes during an initialization phase.

in the proposed enhanced model using the CAP wake-up command with number of superframes field equals zero.

B. A New medium access scheme during the DSME network initialization phase

A tight TDMA algorithm is used to solve the two mentioned issues and minimize association and GTS earning times. The whole end nodes of a fully saturated network use only one beacon to implement these two processes and transfer its operation to the data transmission phase.

Fig. 4 depicts two nodes that associate and get GTSs slots consecutively after receiving a network discovery beacon. Each node performs the two processes successively. Therefore, collisions will be minimized significantly since nodes transmit their requests sequentially within their offset times. Any node fails to associate or earn a GTS slot, it can use the slotted CSMA-CA algorithm in the next beacons. After the network initialization phase is finished, nodes can use the slotted CSMA-CA algorithm to transfer their commands packets for network management.

C. A new DSME network discovery technique

In the standard model, nodes discover the DSME network through scanning the entire channels and receiving valid EBs from the PAN coordinator which can take long time. To minimize network discovery time, EBs are broadcasted with a fixed predefined channel and nodes are pre-configured with this channel before their deployment in a targeted area, so nodes can discover the network by receiving its first beacon from the PAN coordinator. Nodes that are unknown to the

TABLE I: Simulation Parameters

Parameter	Value
OS	Contiki 2.7 - Cooja Sim.
Module	Rime stack
Topology	Star
Scenarios (No. of nodes)	14, 28, 42, and 56
No. of channels	16
SO, MO, BO	3, 6, 7
Running time	1200s
No. of runs	50
Payload	6 bytes
Data traffic	Every multi-superframe
Seed number generator	Contiki seed number
Transceiver	CC2420
Mote	SKY mote

network can scan the entire channels.

V. IMPLEMENTATION AND ANALYSIS

The performance of the three models (the standard model, the work of Sahoo *et al*. [10] model and our enhanced model) has been investigated using the Contiki OS [14] with simulations conducted by the Cooja network simulator [15]. The test-bed of each sensor node is composed of a sky mote and the CC2420 transceiver [16]. Power trace tool [17] has been utilized to assess both models. Different scenarios were implemented with a star sensor network topology with (SO = 3, MO = 6 and BO = 7) and different numbers of nodes according to different newtork saturation ratios (14 (25%), 28 (50%), 42 (75%), and 56 (100%)). Table I describes the simulation parameters.

The CAP reduction enhancement is implemented using the CAP wake-up command with the number of superframes field equals zero, so all nodes keep their receivers OFF in a whole beacon interval (BI) except at the end of the EB for a beacon synchronization, beacon slot and its GTS for data transmission. The command is sent by the PAN coordinator after end nodes join the network.

The second enhancement uses the TDMA algorithm described in algorithm (1) to avoid collisions and get a perfect synchronization among different nodes in the network initialization phase, thus minimizing association and GTS earning times significantly. After that, end nodes go to a sleep mode except for a beacon synchronization and data transfer. Our algorithm proves that all end nodes within a full saturated network with a basic multi-superframe structure and thus for any other multi-superframe structure can associate and get GTSs within one beacon interval. According to the specification of the IEEE802.15.4e with a data transfer rate of (250 Kb/s, symbol rate of 62500 symbol/s):

$$minGTS = \frac{aBaseSlotDuration \times 2^{SO}}{R_s} \tag{5}$$

Where, R_s is the symbol rate. For $minGTS$, SO equals 0 and $aBaseSlotDuration$ equals 60 symbols. Therefore, $minGTS$ equals 0.96ms. The time duration required to transmit a full data packet with its acknowledgement can be found using (6):

$$GTS(data) = \frac{maxT_{packet} + T_{ack}}{R_s} \tag{6}$$

Where, $maxT_{packet}$ is the maximum physical packet size of the IEEE802.15.4e standard and equals (133 bytes (266 symbols), for the 2.4 GHz band, 1 byte equals 2 symbols) and T_{ack} is the time duration required to transmit an acknowledgement frame after receiving a data packet.

$$T_{ack} = \frac{aUnitbackoffperiod + T_{ta} + SHR + PHR + ACK}{R_s} \tag{7}$$

Where, T_{ta} (turn around) is the time required to switch the node transceiver from R_x to T_x and vice versa and corresponds to $aTurnarroundTime$ (12 symbols), SHR is the physical synchronization header and corresponds to $phySHRDuration$ (5 bytes), PHR is the physical header (1 byte) and ACK is the acknowledgement frame (5 bytes).
$T_{ack} = 20 + 12 + 5 \times 2 + 6 \times 2 = 54$ symbols.
$GTS(data) = 266 + 54 = 320$ symbols $= 5.12$ms.
To transmit one full data packet with its acknowledgement, $minGTS > GTS(data) \rightarrow 0.96\text{ms}\times 2^{SO} > 5.12$ms.
$SO = 3$, $minGTS = 0.96 \times 2^3 = 7.68\text{ms} > GTS(data)$.

In the DSME network, data transmission periodicity should be maintained by using a multi-superframe structure [6]. At least, two multi-superframe within a beacon interval should be utilized, $SD = 16 \times 7.68$ms$=$ 122.88ms and $minBI = SD \times 2 = 245.7$ms.
Where, $(minBI)$ is the minimum beacon interval that consists of two multi-superframe with a single superframe (SD) in each multi-superframe structure ($SO = 3, MO = 3$ and $BO = 4$) and transmit a full data packet of (133 bytes) with its acknowledgement in one GTS.

For a full saturated network, a maximum of (7) devices can transmit their data within each $minBI$ (one superframe for main data packet and one for data packet transmission periodicity). The time duration required by a node to associate and get a GTS slot using the TDMA algorithm (Fig.(4)) can be found using (8):

$$\begin{aligned} T_{ag} &= T_{areq} + 3 \times T_{ack} + 4 \times T_{lifs} + T_{ares} \\ &+ T_{greq} + T_{greply} + T_{ta} + T_{gnotify} + T_{guard} \end{aligned} \tag{8}$$

Where:
T_{areq} is the time required to send an association request from a node to a PAN coordinator.
T_{ares} is the time required to send an association response from a PAN coordinator to a node.
T_{greq} is the time required to send a GTS request from a node to a PAN coordinator.
T_{greply} is the time required to broadcast a GTS reply from a PAN coordinator to a whole network .
$T_{gnotify}$ is the time required to broadcast a GTS notification from a node to a whole network.
T_{lifs} is the time duration of a long interframe space to process a packet and corresponds to $macMinLIFSPeriod$.
T_{guard} is a guard time between any two consecutive nodes to implement a full association and GTS processes. Therefore,

$$\begin{aligned} T_{ag} &= 2 \times 28 + 2 \times 3 \times 54 + 2 \times 4 \times 40 + 2 \times 45 \\ &+ 2 \times 21 + 2 \times 21 + 2 \times 12 + 2 \times 21 + 75 \\ &= 1015 \text{ symbols} = 16.24\text{ms}. \end{aligned}$$

Therefore, $minBI(245ms) > 7 \times T_{ag}(113.68\text{m}s)$ and the

Algorithm 1 TDMA algorithm for the DSME model

function CALCULATE TIME OF ASSOCIATION
  Inputs $\leftarrow T_{areq}, T_{ares}, T_{greq}, T_{greply}, T_{gnotify},$
    $T_{lifs}, T_{ack}, T_{ta}, T_{guard}$
  Calculate: T_{ag}, T_{xag} using (8) & (9)
  Return: T_{xag}
end function
loop:
if *network discovery beacon is received* **then**
  Call "Calculate Time of Association".
  Implement Association & GTS processes (Fig.4)
  Switch to sleep mode and wake up only for beacon synchronization.
else
  goto *loop*.
end if
Wait for next beacons to start data transmission.

TDMA algorithm can be utilized efficiently as a network initialization technique in a multi-superframe structure of a full saturated DSME network. For a tight synchronization, each node should exactly calculate the starting time of its association process inside the network discovery beacon as in (9):

$$T_{xag} = T_{ag} \times (N_{id} - 1) \tag{9}$$

Where, T_{xag} is the beginning of node's association process and N_{id} is the node address.

VI. Results and Discussion

This paper focuses on three network performances; end nodes' energy consumption and their RDCs, association and GTS earning times in a network initialization phase, and network discovery time.

The CAP disabling scheme improves end nodes' energy consumption and their RDCs significantly using the CAP wake-up command approach to schedule the access of end nodes to the medium.

At the end of the simulation's running time (1200s), the whole end nodes of the standard model for the four scenarios (nodes 14, 28, 42, and 56) consume energy about 534J, 1090J, 1636J and 2148J respectively. Meanwhile, end nodes of the enhanced model deplete 7.15J, 15.25J, 23.2J and 31.2J respectively. Therefore, energy consumption is minimized by a factor of 71 on average, (see Fig. 5).

The second enhancement minimizes the association and a GTS earning times significantly by using the proposed TDMA algorithm. Using the slotted CSMA algorithm in the standard DSME model can increase the association and GTS times as nodes should compete for each other to get access to the medium during the CAP portion of each superframe (not a whole superframe duration) which increases the probability of collisions and, accordingly, increases the delay time of association or getting a GTS slot and leads to more energy consumption. The proposed model shows an improvement in minimizing the accumulative association and GTS times for the four different scenarios as compared to the other two models (the standard model and the work of [10] model) and as shown in Fig. 6. It spends about (0.28s, 0.56s, 0.84s and 1.12s) respectively. Meanwhile, the standard model spends

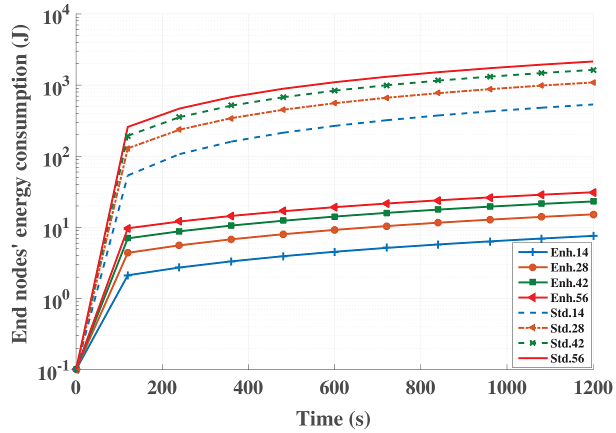

Fig. 5: Accumulated end nodes' energy consumption.

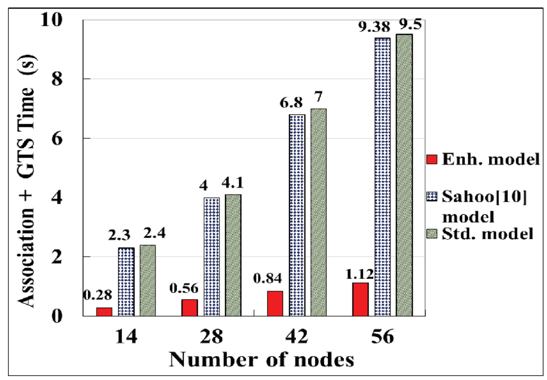

Fig. 6: Accumulated end nodes' association + GTS times.

about (2.4s, 4.1s, 7s and 9.5s) and the work of [10] spends about (2.3s, 4s, 6.8s and 9.38s). Therefore, association and GTS times are reduced by a factor of (8) on average. It is also clear that the other two models have spent about the same times since the numbers of collisions of the two models depend mainly on the number of nodes that access the medium at the same time and the duration of the superframe CAP. The Long CAP period minimizes the number of collisions and leads to about the same performance.

The third enhancement (network discovery technique) has its impact on minimizing network discovery time which leads to more energy saving and less network joining time. Fig.(7) depicts the improvement in network discovery time among the three models. The proposed technique minimizes network discovery time significantly since it can discover the EB of the PAN coordinator in the first valid beacon. Using three settings for the beacon order (6, 7, and 8); the network discovery time of whole nodes of the proposed technique is the same (6ms). Meanwhile, the work of [10] has spent fixed time about (1.96s). Its discovery time depends mainly on the value of the (SD) and the number of channels used to broadcast the EBs.

The highest network discovery time is consumed by the standard model (15.7s, 31.45s and 62.9s) respectively. It depends on the value of (BI) and the number of scanned channels by end nodes to discover the EBs.

Regarding end nodes' RDCs, the proposed model has the lowest RDC due to the effect of the three enhancements

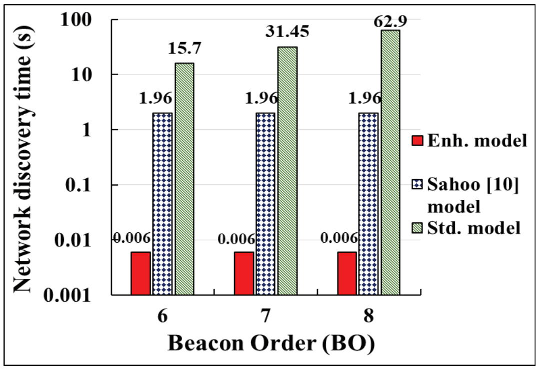

Fig. 7: Network discovery time (CHs=16 and SO=3)

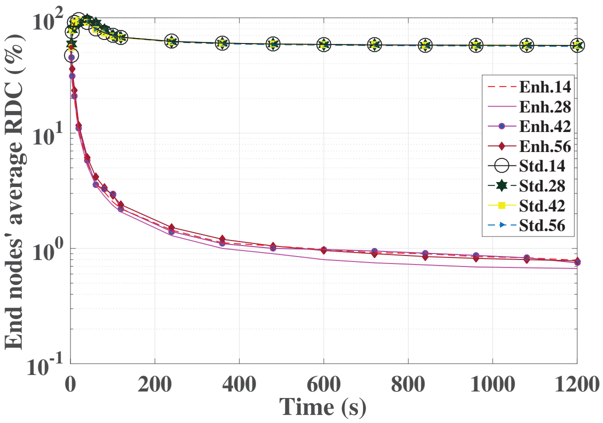

Fig. 8: Nodes' radio duty cycle (RDC)

as each one of them reduces the ON time of end nodes' receivers. Meanwhile, the accumulative RDC drops down after a very short period of operation to achieve very low values at the simulation end; 0.79%, 0.67%, 0.75% and 0.78% respectively. In contrast, the RDC of the standard model remains high in the network initialization phase and for a long period as compared to the proposed model due to a long channels scanning period and association and GTS earning times. After that, it decreases to reach about half its value at the initialization phase; 57.58%, 57.54%, 57.6% and 57.54% respectively. Therefore, the average RDCs of the four scenarios are reduced by a factor of 77 on average, (see Fig. 8).

VII. Conclusion

This paper considers three aspects related to the IEEE802.15.4e DSME model and introduces an enhancement to them. Three models are investigated; the standard model, the work of [10] and our enhanced model. The first issue is the energy consumption of end nodes during the CAP period which has been reduced by introducing two new approaches. One is more flexible and uses a new proposed wake-up command that can control end node's receiver within every superframe inside a multi-superframe structure. Simulation results exhibit a significant reduction in energy consumption of end nodes by a factor of (71) as compared to the standard model. The second drawback is a long association and GTS earning times of end nodes during the network initialization phase as the other two models use a slotted CSMA-CA algorithm. The proposed model introduces a new association and GTS earning mechanism in which a TDMA algorithm is implemented to separate the association and GTSs earning processes of consecutive nodes. Simulation results show a high minimization in these times by a factor of (8). The third issue which is a long network discovery time has been solved by using a new technique in which EBs are transmitted with a fixed pre-defined channel and end nodes are pre-configured with this channel during the pre-deployment process, thus end nodes can discover a network within the first valid EB. Simulation results show a high reduction in network discovery time of the proposed model as compared to the other two models. Ongoing and our future work includes investigating mobility of nodes inside the IEEE802.1.5.4-e DSME network.

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