

Improvement of Network Utility and Energy Efficiency in DSME based Internet of Things Networks

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Abstract: This paper provides a comparison between IEEE 802.11 and IEEE 802.15.4e standards in the context of Internet of Things (IoT). These emerging standards are the amendments of IEEE 802.11 and IEEE 802.15.4 to support IoT based applications. The 802.11 has a channel access scheme, Distributed coordination function (DCF). On the other hand, IEEE 802.15.4e introduces five MAC behavior mode. Among these five modes, DSME is well suited for IoT. A comparison between these two standards is discussed in this paper by using an analytical model and are validated through ns-3 simulations. Results show that the DSME show significant improvement in the performance of DSME when compared to the legacy IEEE 802.11 DCF.

Keywords: DSME, DCF, IEEE 802.11 DCF.

I. INTRODUCTION

Internet of Things (IoT) is a paradigm shift in the era of Internet and this technology is progressing very fast in today's technology world. The term IoT is first coined by Kevin Ashton in 1999. According to analysts, there may be around 50 billion devices connected to the Internet by 2020 [1]. IoT literally means things that can communicate over the Internet. Things include not only computers, electronic devices, sensor and actuators but also people, trees, and animals. Fig. 1 show a scenario of IoT where many devices are communicating over Internet. This makes IoT a cross platform for things to communicate at anytime, anywhere and with anything.

There are wide range of IoT applications that are classified based on their type of network coverage, and heterogeneity [2]. The main objective of IoT is to enable communication between any physical or virtual things around the world. Many communication protocols like Zigbee, Bluetooth, RFID etc., came up to support IoT applications but failed due to less coverage, low data rates, delay, low reliability and scalability. Though the networks like GPRS, LTE, and WIMAX have large coverage and high throughput, they are expensive in their deployment. Recently, IEEE has proposed IEEE 802.15.4e and IEEE 802.11ah protocols as a solution to support Internet of Things.

Several standards have been proposed by many international bodies. One among them is IEEE 802.15.4 [3] which is widely used in Wireless Sensor Networks (WSN's). This protocol although standardized in 2006 have undergone several Amendments. This protocol mainly defines the PHY layer and MAC layer of the protocol stack. IEEE 802.15.4e [4] is introduced in 2012. This amendment introduced a number of modifications.

The published research works focus on either IEEE 802.15.4e or IEEE 802.11ah as a proposed MAC protocol for IoT. Wun-Cheol *et al.* presented detailed perform analysis of DSME mode to find energy consumption, throughput and reliability [5].

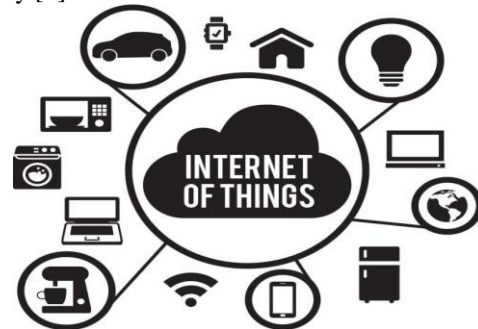


Fig. 1. Scenario of Internet of Things

A similar analytical model is also presented in [6] and [7] for LLDN and TSCH modes. Domenico *et al.* in [5] address a clear overview of all the MAC layer modes in 802.15.4e, but they didn't discuss about issues like coverage and scalability to enhance IoT applications. In [8] Maria *et al.* proposes 802.15.4e based IoT protocol stack. To support IoT, the authors in [9] gave a survey on standardization effort for 6TiSCH and its expected outcomes. As an extension [10] and [11] provide 6TiSCH architecture and its centralized and distributed operation.

The article is structured as: Section II presents overview of IEEE 802.15.4e based optimal slot selection scheme. Section III presents analysis to evaluate throughput, energy consumption. Section IV discusses the results and discussion. The summary of the paper is presented in Section V. The summary of this paper is as follows:

- An analytical model is developed to evaluate the throughput, energy consumption of the network in dense IoT scenario.
- The experiment findings show significant enhancement in the network performance using the DSME than the legacy IEEE 802.11.

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- Finally, the analytical results are validated using ns-3 simulations.

II. IEEE 802.15.4e

IEEE 802.15.4 has a number of limitations such as unbounded delay, limited communication reliability, no protection against interference and fading and need of intermediate relay nodes in multi-hop network. Because of these issues, IEEE 802.15.4 is unsuitable for IoT based applications which need to support timeliness, scalability and reliability. In 2008 IEEE formed 802.15.4 TaskGroup4e with an objective to modify the 802.15.4 to overcome the limitations.

This amendment defines five MAC behavioral modes for various applications. These modes are Time Slotted Channel Hopping (TSCH), Deterministic and Synchronous Multi-Channel Extension (DSME), Low Latency Deterministic Network (LLDN), Radio Frequency Identification Blink (BLINK), Asynchronous Multichannel Adaptation (ACMA). LLDN mode provides very low and deterministic latency for industrial automation. DSME mode synchronizes all the stations and runs on beacon enabled personal area network. To integrate IEEE 802.15.4e and IoT, a 6TiSCH [10] workgroup was formed by Internet Engineering Task Force (IETF) to enable IPv6 over TSCH mode [10] which will be described later in this paper.

Time Slotted Channel Hopping: TSCH mainly targets application for industrial automation and process control. It supports multihop and multichannel communication through TDMA. More details about TSCH is provided in Section III-A

Deterministic and Synchronous: Multi-Channel Extension: DSME mode is meant to support most of industrial and consumer application, where very stringent delay requirements are necessary [12]. The super frame structure in DSME mode has both contention access period based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and contention free period based on Time Division Multiple Access (TDMA). Multihop and mesh networks are supported in this mode.

Low Latency Deterministic Network: LLDN mode [13] is used in industrial automation where very low latency is required. This mode only supports star topology.

Asynchronous Multichannel Adaptation: AMCA is applied in largely deployed networks like Wireless Smart Utility Systems (WSUN's), Wireless Controls Systems (WCS's) [14]. It is based on non-beacon enabled mode of IEEE 802.15.4. In this asynchronous network, any two stations communicate on the same frequency channel by simple exchanging HELLO packets.

Radio Frequency Identification Blink: Blink mode is to provide identification for item or people identification [15]. The devices share their ID without any association process and acknowledgment based on ALOHA protocol.

In this paper, more emphasis is given to DSME mode because it is the promising candidate for IoT. This mode is intended to support many IoT applications.

III. PROPOSED GROUPING SCHEME

In this section, fuzzy logic system (FLS) that uses fuzzy c-means (FCM) clustering algorithm to group the devices

with similar transmission requirements and to allocate each group with a DSME slot whose duration adaptively varies according to the transmission requirements of the devices.

Initially, every device in the network listens to the periodically broadcasted beacons and undergoes association procedure with the AP. Prior to the association, each device estimates the required channel access time during its full functionality using,

$$\Delta_n = \sum_{i=0}^R W_i \sigma + E[T_{s,n}] + \Delta_{f,n}. \quad (1)$$

Algorithm 1 Grouping scheme

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1: Inputs:
2:  $\epsilon = 0.01$ ;  $\backslash \backslash$  Convergence value
3:  $U$ ;  $\backslash \backslash$  Randomly initialized partition matrix of size  $K \times N$ 
4:  $l = 0$ ;  $\backslash \backslash$  Number of iterations
5:  $z = 2$ ;  $\backslash \backslash$  Fuzziness parameter
6: for each device do
7:    $A(n) = \Delta_n$ ;
8: end for
9:  $\backslash \backslash$  Classifying  $A(n)$  using FCM
10: while  $|U^{(l+1)} - U^{(l)}| \leq \epsilon$  do
11:    $C_k = \frac{\sum_{i=1}^n (u_{ki})^z d_i}{\sum_{i=1}^n (u_{ki})^z}$ ,  $k \in [1, K]$ ;  $\backslash \backslash$  Calculate K-centroids corresponding to K-groups
12:    $u_{ki} = \sum_{j=1}^k \left[ \frac{(d_i - C_k)^{\frac{2}{z-1}}}{(d_j - C_k)^{\frac{2}{z-1}}} \right]^{-1}$   $\backslash \backslash$  Each element of partition matrix  $U$ 
13: end while
14: AP forms each row of the matrix  $U$  into a group with average transmission requirements given by  $C$ ;
15:  $T_{slot,k} = \beta_k T_R$ ;  $\backslash \backslash$  The duration of the DSME slot of each group
16:  $\beta_k = \frac{C_k}{\sum_{i=1}^K C_i}$ ;

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The first term in Eq. (1) is the duration of the back-off counter. $E[T_{s,n}]$ is the duration between transmission of a packet till reception of the acknowledgment frame. $\Delta_{f,n}$ is the duration in which the back-off counter freezes due to overhearing of other transmission. Therefore,

$$\Delta_{f,n} = R(E[T_{s,n}] + SIFS + T_{ACK_timeout}). \quad (2)$$

Here, $T_{ACK_timeout}$ is the duration of acknowledgment timeout. Having estimated the transmission times, each device communicates Δ_n with the AP using the additional field of short MAC header in the association request frame. According to Algorithm 1, the AP sorts all the transmission requirements of the devices into an array $A(n)$. Then, the AP uses FCM to classify the devices into K groups according to their channel access requirements. Having grouped the devices into K groups, the AP assigns each group with a DSME slot whose duration is a function of the channel requirements of the respective group. Thus, the duration of the k^{th} DSME slot is given by,

$$T_{slot,k} = \beta_k \times T_{RAW}, \quad (3)$$

where β_k is the scaling factor that depends on the traffic requirements of each group. Therefore,

$$\beta_k = \frac{C_k}{\sum_{i=1}^K C_i}. \quad (4)$$

IV. SYSTEM MODEL

We assume fully connected and saturated network. We consider an error-free channel and assess the uplink performance of the network. The channel is divided into slots of duration σ . We consider a network of size g in which all the devices contend for the channel access using legacy DCF mechanism [2]. Channel is sensed for DIFS duration before initiating the counter. The back off stage is selected from $[0, W_0-1]$, where W_0 is the minimum contention window. For every packet transmission, W_0 is initialized to zero and for collision, it is doubled up to the maximum contention window (CW_{max}) [9]. An i^{th} back-off contention is given by,

$$W_i = \begin{cases} 2^i \times W_0; & 0 \leq i \leq m-1, \\ 2^m \times W_0; & m \leq i \leq R, \end{cases} \quad (5)$$

where m is the maximum W_0 and R is the maximum retries. A device gets the transmission opportunity when the W_0 is zero. In between two consecutive transmissions, the device initiates the back-off counter followed by DIFS duration.

According to the model presented in, the probability of transmission in j^{th} slot is given by,

$$\tau_j = \sum_{i=0}^m b_{i,0} = \sum_{i=0}^m p_{c,j}^i b_{0,0}. \quad (6)$$

Then, the conditional collision probability is given by,

$$p_{c,j} = 1 - (1 - \tau_j)^{g-1}. \quad (7)$$

τ_j and $p_{c,j}$ can be obtained by solving Eqs. (5) and (6). Let

$P_{tr,j}$ is transmission probability in a j^{th} slot,

$$P_{tr,j} = 1 - (1 - \tau_j)^g. \quad (8)$$

$P_{s,j}$ is the successfully communication of a packet in a j^{th} slot,

$$P_{s,j} = \frac{g\tau_j(1-\tau_j)^{g-1}}{1-(1-\tau_j)^g}. \quad (9)$$

A. Throughput

The saturation throughput S_j of a j^{th} slot can be calculated as,

$$S_j = \frac{\left(\frac{\text{Average information}}{\text{transmitted in a mini-slot}} \right)}{\text{Average duration of a mini-slot}}, \quad (10)$$

$$= \frac{P_{tr,j} P_{s,j} E[P]}{(1 - P_{tr,j})\sigma + P_{tr,j} P_{s,j} T_s + P_{tr,j} (1 - P_{s,j}) T_c}$$

where $E[P]$ is the size of data packet, T_s and T_c are successful time and collision time,

$$T_s = T_{PS_Poll} + T_{E[P]} + 2T_{ACK} + 3SIFS + DIFS + 3\delta$$

$$T_c = T_{PS_Poll} + DIFS + \delta. \quad (11)$$

Here δ is the propagation delay, T_{PS_Poll} is the duration of PS_Poll frame, T_{ACK} is the duration of ACK frame, and $T_{E[P]}$ is the data transmission time. The time taken to transmit the payload $T_{E[P]}$ is a function of data rate

corresponding to the MCSs, that can be calculated using Eq. (11). Similarly, the duration of other packets is calculated by Eq. (11). It is noteworthy to point out that, $basic_datarate$ is used to transmit the control frames and PHY header. $L_{sym}^{basic_datarate}$ are the bits per symbol.

$$T_{E[P]}(Rate) = \frac{8 \times (E[P] + MAC)}{\frac{Rate}{basic_datarate} \times L_{sym}^{basic_datarate}} \times T_{sym} + T_{PHY},$$

$$T_{control} = \frac{8 \times ControlFrame}{L_{sym}^{basic_datarate}} \times T_{sym} + T_{PHY}. \quad (12)$$

B. Energy consumption

The energy consumption in DCF mechanism, can be in either a back-off state, freezing state, or a transmission state.

Thus, each device consumes energy in four parts:

- E_b is the energy consumed during the back-off process.
- E_f is the energy consumed when a device freezes its back-off counter.
- E_s and E_c are the energies consumed due to a successful transmission and collision.

Therefore, the energy consumption is defined as:

$$\eta_j = \frac{E_b + E_f + E_s + E_c}{P_{tr,j} P_{s,j} E[P]}. \quad (13)$$

The average energy consumed during the back-off process is given by,

$$E_b = E[B] \sigma P_{idle}, \quad (14)$$

where $E[B]$ is the average number of back-off slots which is given by,

$$E[B] = \sum_{i=0}^R p_{c,j}^i (1 - p_{c,j}) \sum_{j=0}^i \frac{W_j - 1}{2}. \quad (15)$$

In a slot, among the g devices, a node overhears a transmission when one of $g-1$ devices is successfully transmitting in the j^{th} slot. Therefore, the success probability is given by,

$$P_{s,j}' = \frac{(g-1)\tau_j(1-\tau_j)^{g-2}}{1-(1-\tau_j)^{g-1}}. \quad (16)$$

The average number of transmissions overheard by a device during the back-off process is given by,

$$N_0 = \frac{E[B] p_{c,j}}{1 - p_{c,j}}. \quad (17)$$

Therefore, the energy consumed by a device due to overhearing the other devices during the back-off process is given by,

$$N_i = \sum_{i=0}^R i p_{c,j}^i (1 - p_{c,j}). \quad (18)$$

Then the energy of successful transmission and collision is given by,

$$E_s = P_{Tx}(T_{PS_Poll} + T_{E[P]}) + P_{Rx}(T_s - T_{PS_Poll} + T_{E[P]})$$

$$E_c = N_t[P_{Tx}(T_{PS_Poll}) + P_{Rx}(T_c - T_{PS_Poll})] \quad (19)$$

Therefore, the total energy is given by,

$$E_T = E_b + E_f + E_s + E_c. \quad (20)$$

Finally, the energy consumption per bit η_j is given by,

$$\eta_j \approx \frac{E_T}{P_{tr,j} P_{s,j} E[P]}. \quad (21)$$

V. RESULTS AND DISCUSSIONS

Analytical and simulation results are presented in this section. The analytical model presented in Section II is evaluated using MATLAB. The analytical results are validated using the open source network simulator ns-3. In this paper, we consider a network of size g uniformly deployed around the AP. Table 1 lists the parameters used to obtain the analytical and simulation results. We consider a network size of $g=256$ with $K=32$.

Table 1. Parameters used for analysis

Parameter	Value
basic_datarate	650 Kbps
delta	1 us
T_sym	40\ us
sigma	52 u s
SIFS	160 u s
DIFS	264 us
P_Tx	255 mW
P_Rx	135 mW
P_idle	1.3 mW

Figure 2 compares the throughput performance of IEEE 802.15.4e DSME with the IEEE 802.11 DCF mechanism. It is shown that the throughput decreases by varying the number of devices. With the increase in the network size the throughput slightly decreases for DSME mechanism, whereas the throughput of DCF mechanism is drastically decreased. Because the increase in the network size means is increase in the contention in the network. Due to the increase in the contention, the number of collisions experienced by a packet increase which increase the collision probability of as device and decrease the probability of successful transmission. In the DSME mechanism, due to the allocation of dedicated time slots, the contention among the network devices is spreads across the DSME time slots where as the no such mechanism is available in DCF mechanism. But for smaller network size the number of devices accessing the DSME slots is less hence results in the ineffective utilization of the medium, whereas the DCF outperform the DSME mechanism. But for large network size, due to the decrease in the number of collisions the DSME outperforms the DCF mechanism.

Figure 3 compares the energy consumption of DSME mechanism with the IEEE 802.11 DCF mechanism. The results show that with the increase in the network size the number of collision increase, consuming more energy. Hence, the energy consumption increases with the increase in the network size. In DSME mechanism due to the spread of contention among the devices, the energy is very less when compared to the DCF mechanism. Whereas the DCF

mechanism consumes more energy due to the severe contention.

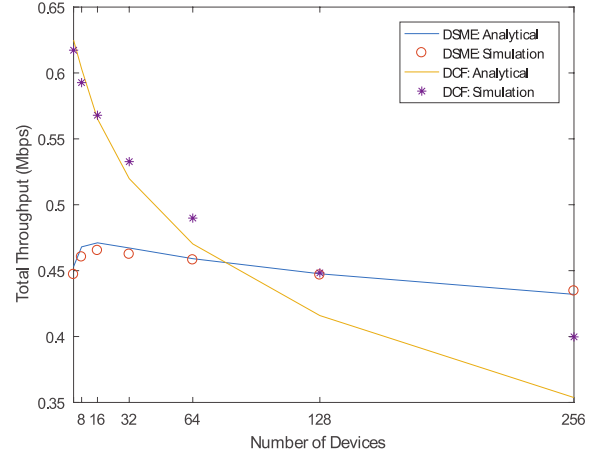


Fig. 2 Throughput for various devices

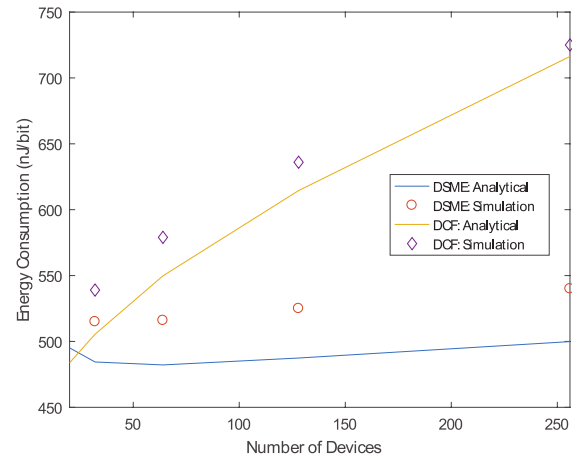


Fig. 3. Energy consumption for various devices

VI. CONCLUSION

In this paper, a we compare the throughput and energy consumption of a DSME mechanism with the IEEE 802.11 DCF mechanism using a mathematical model developed using probability theory. The results show the DSME mechanism outperform the DCF mechanism. Because of the spread in the contention into various DSME time slots. Finally, the results are validated using ns-3 simulations.

REFERENCES

1. I. Standard and I. C. Society, IEEE Standard for Local and metropolitan area networks — Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs) IEEE Computer Society Sponsored by the, vol. 2006, no. September. 2006.
2. I. Standard and I. C. Society, IEEE Standard for Local and metropolitan area networks — Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs) IEEE Computer Society Sponsored by the, vol. 2011, no. September. 2011.
3. W.-C. Jeong and J. Lee, "Performance evaluation of IEEE 802.15.4e DSME MAC protocol for wireless sensor networks," Proc. First IEEE Work. Enabling Technol. Smartphone Internet Things, no. 10035380, pp. 7–12, 2012.
4. C. Ouanteur, D. Aissani, L. Bouallouche-Medjkoune, M. Yazid, and H. Castel-Taleb, "Modeling and performance evaluation of the IEEE 802.15.4e LLDN mechanism designed for industrial applications in WSNs," Wirel. Networks, 2016.

5. D. De Guglielmo, S. Brienza, and G. Anastasi, "IEEE 802.15.4e: A survey," *Comput. Commun.*, vol. 88, pp. 1–24, 2016.
6. R. de Vegt, "Potential Compromise for 802.11ah Use Case Document," IEEE 802.11-11/0457r0, Mar. 2011.
7. IEEE P802.11ac. Specification framework for TGac. IEEE 802.11-09/0992r21. January 2011.
8. T. R. Alexander Gluhak, Ericsson Serbia Michele Nati, "A Survey on Facilities for Experimental Internet of Things Research," *Ieee Wirel. Commun.*, no. December, pp. 2–10, 2010.
9. IEEE 802.11ah/D5.0, "Draft for Information Technology — Telecommunications and Information Exchange between Systems — Local and Metropolitan Area Networks — Specific Requirements — Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications — Amendment 6: Sub 1 GHz License Exempt Operation."
10. B. Divya Darshini, A. Paventhan, H. Krishna, and N. Pahuja, "Enabling real time requirements in industrial IoT through IETF 6TiSCH," 2016 Int. Conf. Internet Things Appl. IOTA 2016, pp. 121–124, 2016.
11. M. R. Palattella et al., "Standardized protocol stack for the Internet of (important) things," *IEEE Commun. Surv. Tutorials*, 2013.
12. D. De Guglielmo, B. Al Nahas, S. Duquennoy, T. Voigt, and G. Anastasi, "Analysis and experimental evaluation of IEEE 802.15.4e TSCH CSMA-CA Algorithm," *IEEE Trans. Veh. Technol.*, vol. XX, no. XX, pp. 1–1, 2016.
13. P. Thubert, T. Watteyne, M. R. Palattella, X. Vilajosana, and Q. Wang, "IETF 6TSCH: Combining IPv6 connectivity with industrial performance," *Proc. - 7th Int. Conf. Innov. Mob. Internet Serv. Ubiquitous Comput. IMIS 2013*, pp. 541–546, 2013.
14. N. Accettura and G. Piro, "Optimal and secure protocols in the IETF 6TiSCH communication stack," *IEEE Int. Symp. Ind. Electron.*, pp. 1469–1474, 2014.
15. D. Evans, "The Internet of Things, How the Next Evolution of the Internet is Changing Everything", White paper, Cisco Internet Business Solutions Group (IBSG) (2011).

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