International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075 (Online), Volume-9 Issue-7, May 2020

Performance Enhancement of IEEE 802.15.4e Deterministic and Synchronous Multi-Channel Extension

K Suresh, M. Ramesh Patnaik

Abstract**: *Deterministic and Synchronous multi-channel extension (DSME) is introduced to improve the network performance by providing dedicated slots. Thus, the network is divided into various slots to access the channel in the dedicated slots allocated to them. However, choosing the DSME slots is one of the major challenging tasks. In this article, we use fuzzy logic to estimate the optimum count of DSME slot per super frame by considering network size, collision probability, and modulation and coding schemes. Further, we analytically evaluate the collision probability, throughput, energy consumption and delay of DSME mechanism. Results show that the optimal number of DSME slots found using fuzzy logic significantly enhances the throughput and decreases the energy consumption. Finally, extensive simulations are conducted using ns-3 to validate the analytical results.***

Keywords: IEEE 802.15.4e, DSME, contention window.

I. INTRODUCTION

With the increase in low cost and low power wireless sensor devices, green communication has revolutionized the Internet of Things (IoT) [1]. To enhance the networking capability of IoT, IEEE 802.15.4 is introduced. Few of the standards recognized by IEEE 802.15.4 are ZigBee, IETF 6LoWPAN, Wireless HART and ISA100.11a because of their low power consumption [2,4]. It operates in 2.4GHz of ISM bands [3]. In industrial application like food processing, wireless controlled area networks, transfer of large amount of data with less energy consumption shows a significant impact on the performance of the network. As the available channel time in IEEE 802.15.4 is common to all the devices, there is a performance degradation due to severe contention. To overcome this problem IEEE 802.15 task group introduces IEEE 802.15.4e as an amendment to IEEE 802.15.4 [5]. The new standard introduces five different MAC modes, among which Deterministic and Synchronous multi-channel Extension (DSME) is used to provide deterministic time slots and to improve the reliability of the network [8].

Revised Manuscript Received on May 30, 2020.
* Correspondence Author
K Suresh*, Research Scholar, Department of Instrument Technology, Andhra University, VSP, India. Email: sureshvarma6277@gmail.com
M. Ramesh Patnaik, Associate Professor , Department of Instrument Technology, Andhra University, VSP, India. Email: ramesh_patnaik@yahoo.com

DSME uses multi-channel to enhance the throughput of the network. In [6], authors presented a detailed survey on the performance evaluation of IEEE 802.15.4e network. Authors in [7] dynamically tune the duration of the DSME slots. Among [10-14], several have been proposed a scheme to assess the IEEE 802.15.4e MAC modes.

One of the most challenging tasks is to determine the optimum count of DSME slots that can maximize the network performance [9]. Because choosing a lesser number of DSME slots increases the number of devices per group and rises the contention in the network. On the other hand, choosing a higher number of DSME slots results in wastage of channel resources. In this article, we exploit the fuzzy logic system (FLS) to find the optimum count of DSME slots. The FLS considers network size, collision probability, and modulation and coding schemes (MCSs) as inputs to find the optimal number of DSME slots as shown in Fig. 1. Then, we analytically assess the proposed scheme using collision probability, throughput energy consumption, and delay.

The article is structured as: Section II proposed the fuzzy based optimal slot selection scheme. Section III presents analysis to evaluate the collision probability, throughput, energy consumption and delay. 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 collision probability, throughput, energy consumption and delay of the network in dense IoT scenario.
- Fuzzy logic is used to find the find the optimum count of DSME slots that can maximize the network performance.
- The experiment findings show significant enhancement in the network performance using the optimum count of DSME slots.
- Finally, the analytical results are validated using ns-3 simulations.

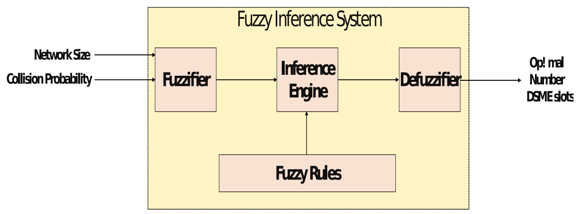

Fig. 1 Fuzzy Inference System to find optimal DSME slots

II. PROPOSED FUZZY INFERENCE SYSTEM

In this section, we exploit fuzzy logic to determine the optimal number of DSME slots rather than using the conventional analytical approach. As fuzzy logic is effective in decision-making, it is used to model the uncertainties of a system to get desired results. According to Boolean logic, an element belongs to a set with a degree of either 0 or 1. In fuzzy logic, every set has a mathematically represented membership function, and every membership function is defined by linguistic terms.

Fuzzification is defined as the process of mapping the input variable to their respective fuzzy set. As shown in Fig. 1, we have the following three inputs to the FIS to find the optimal number of DSME slots. (i) network size N, (ii) collision probability calculated using Eq. (3). Each input variable has multiple fuzzy sets defined by certain linguistic terms, and each fuzzy set is represented by a membership function. Due to computational efficiency and less complexity, we consider trapezoidal membership function.

Figure 2, Fig. 3, and Fig. 4 illustrates the membership functions of collision probability, network size and optimal DSME slots or groups (DSME slots and groups are interchangeably used in this article). Every membership function of both input and output variables follows the same trapezoidal function.

The core of FLS is fuzzy rules. Fuzzy rules are used to evaluate the degree of membership of input and output variables. To find the optimal number of DSME slots, we define hundred and four fuzzy rules. For every set of input variable, the AP finds the output based on the fuzzy rules. Some of the fuzzy rules are defined as follows:

- IF N=LOW, and Pc=LOW, and MCS=MC1 THEN $L_{opt} = Opt1$;
- IF N=Medium, and Pc=Medium, and MCS=MC2 THEN $L_{opt} = Opt2$;
- IF N=High, and Pc=High, and MCS=MC4 THEN $L_{opt} = Opt4$;
- IF N=Dense, and Pc=Dense, and MCS=MC8 THEN $L_{opt} = Opt8$;

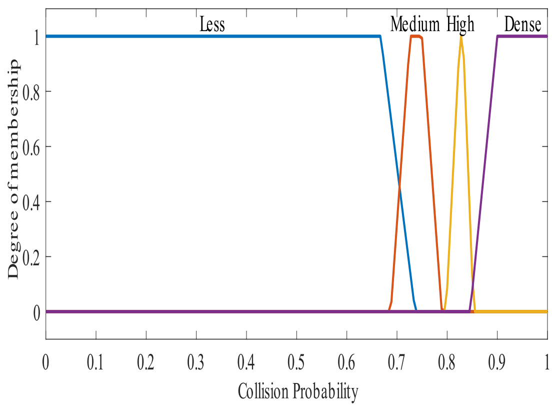

Fig. 2 Membership function of collision probability

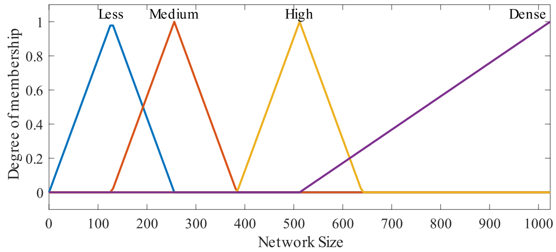

Fig. 3 Membership function of network size

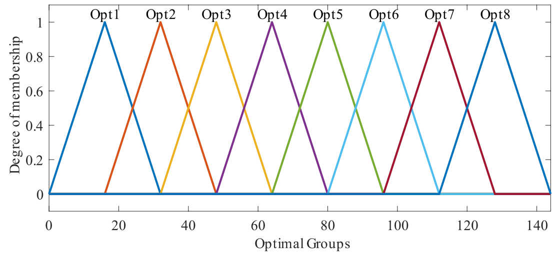

Fig. 4 Membership function of optimal group (or slots)

Each fuzzy rule is evaluated for every set of input variable and mapped to the corresponding fuzzy set of output variable. FLS computes the output using the COG method from the output of each rule.

III. 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,

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

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,

$$\tau_j = \sum_{i=0}^{m} b_{i,0} = \sum_{i=0}^{m} p_{c,j}^{i} b_{0,0}. \qquad (2)$$

Then, the conditional collision probability is given by,

$$p_{c,j} = 1-(1-\tau_j)^{g-1}. \qquad (3)$$

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,

$$P_{tr,j} = 1-(1-\tau_j)^{g}. \qquad (4)$$

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

$$P_{s,j} = \frac{g\tau_j\left(1-\tau_j\right)^{g-1}}{1-(1-\tau_j)^g}. \qquad (5)$$

A. Throughput

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

$$S_j = \frac{\begin{pmatrix}\text{Averageinformation}\\ \text{transmittedinamini-slot}\end{pmatrix}}{\text{Averagedurationofamini-slot}}, \qquad (6)$$

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

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

$$T_s = T_{PS\_Poll} + T_{E[P]} + 2T_{ACK} + 3SIFS + DIFS + 3\delta$$
$$T_c = T_{PS\_Poll} + DIFS + \delta. \qquad (7)$$

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.

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

$$T_{control} = \frac{8\times ControlFrame}{L_{sym}^{basic\_datarate}} \times T_{sym} + T_{PHY}. \qquad (8)$$

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:

$$\eta_j = \frac{E_b + E_f + E_s + E_c}{P_{tr,j}P_{s,j}E[P]}. \qquad (9)$$

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

$$E_b = E[B]\sigma P_{idle}, \qquad (10)$$

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

$$E[B] = \sum_{i=0}^{R} p_{c,j}^i(1-p_{c,j})\sum_{j=0}^{i}\frac{W_j-1}{2}. \qquad (11)$$

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,

$$P_{s,j}' = \frac{(g-1)\tau_j\left(1-\tau_j\right)^{g-2}}{1-(1-\tau_j)^{g-1}}. \qquad (12)$$

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

$$N_0 = \frac{E[B]p_{c,j}}{1-p_{c,j}}. \qquad (13)$$

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

$$N_t = \sum_{i=0}^{R} i p_{c,j}^i(1-p_{c,j}). \qquad (14)$$

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

$$E_s = P_{Tx}(T_{PS\_Poll} + T_{E[P]}) + P_{Rx}(T_s - T_{PS\_Poll} + T_{E[P]})$$
$$E_c = N_t[P_{Tx}(T_{PS\_Poll}) + P_{Rx}(T_c - T_{PS\_Poll})] \qquad (15)$$

Therefore, the total energy is given by,

$$E_T = E_b + E_f + E_s + E_c. \qquad (16)$$

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

$$\eta_j \approx \frac{E_T}{P_{tr,j}P_{s,j}E[P]}. \qquad (17)$$

C. Delay

The average delay (D_j) is time taken for a successful transmission. Therefore,

$$D_j = \mathbb{E}[B]\sigma + N_t(T_c - T_{ACK}) + T_c. \qquad (18)$$

IV. 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. The AP runs Fuzzy inference engine to find the optimal number of DSME slots *(K)*. Table 1 lists the parameters used to obtain the analytical and simulation results. We consider a network size of *g=256* devcices where the optimal number of DSME slots are found to be *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 5 shows the collision probability of DSME mechanism using the proposed fuzzy technique. The optimal number of DSME slots *K* that can maximize the network performance is found using the fuzzy based proposed scheme. In Fig. 5, the collision probability of DSME mechanism is evaluated using *K=32* and the results are compared with the non-optimal value *K= {4,8,16}*. It is observed that there is an increase in collision probability with rise in the devices. But the results justify the optimum count of DSME slots is found using fuzzy logic can significantly increase the performance of DSME mechanism. In Fig. 6, the throughput of DSME mechanism is evaluated using *K=32* and the results are compared with the non-optimal value *K= {4,8,16}*. It is observed that there is a degradation in throughput with rise in the network size due to increased contention in the network. But the results justify the optimum count of DSME slots found using fuzzy logic can significantly increase the performance of DSME mechanism. Figure 7 shows the energy consumption of DSME mechanism using the proposed fuzzy technique. The optimal number of DSME slots *K* that can maximize the network performance is found using the fuzzy based proposed scheme. In Fig. 7, the energy consumption of DSME mechanism is evaluated using *K=32* and the results are compared with the non-optimal value *K= {4,8,16}*. It is observed that there is an increase in energy consumption with rise in the network size due to increased contention in the network. But the results justify the optimum count of DSME slots found using fuzzy logic can significantly increase the performance of DSME mechanism. In Fig. 8, the delay of DSME mechanism is evaluated using *K=32* and the results are compared with the non-optimal value *K= {4,8,16}*. It is observed that there is an increase in delay with increase in the network size due to increased contention in the network. But the results justify the optimal number of DSME slots found using fuzzy logic can significantly increase the performance of DSME mechanism.

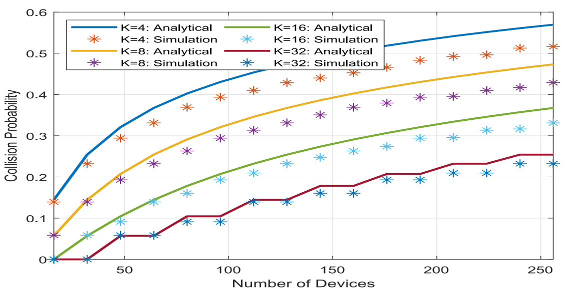

Fig. 5 Collision probability Vs. network size

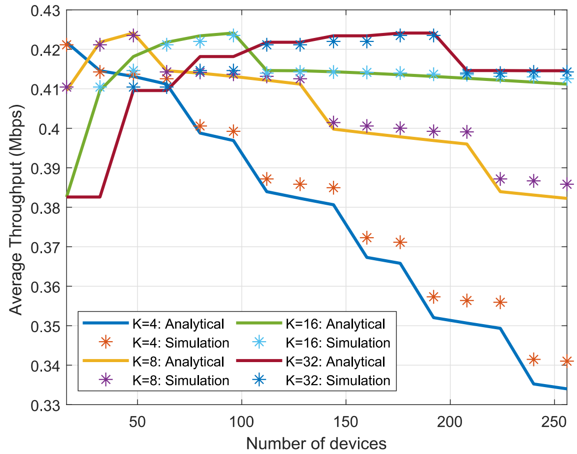

Fig 6. Throughput Vs. network size

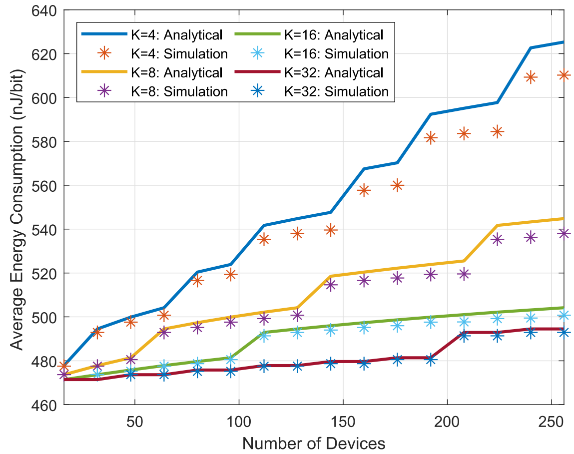

Fig. 7 Energy consumption Vs. network size

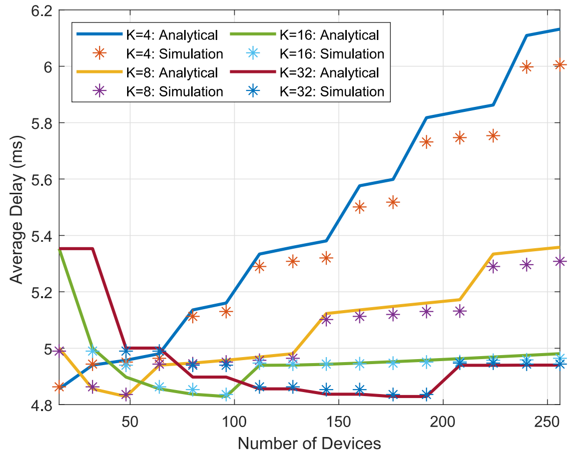

Fig. 6 Delay Vs. network size

V. CONCLUSION

In this paper, a FIS based optimal number of DSME slots scheme is proposed to decrease the collision probability, delay and energy consumption and to increase the network throughput. We have presented a simple mathematical model to evaluate the collision probability, throughput, energy consumption and delay of IEEE 802.15.4e DSME mechanism. From the results, presented scheme significantly enhances the DSME mechanism.

Finally, extensive simulation studies have been conducted to validate the analytical findings.

REFERENCES

1. J. Xu, Y. Andrepoulos, Y. Xiao and M. Schaar, "Non-Stationary Resource Allocation Policies for Delay-Constrained Video Streaming: Application to Video over Internet-of-Things-Enabled Networks," IEEE Journal on Selected Areas in Communications, vol. 32, pp. 782-794, 4 2014.
2. B. Velusamy and S. C. Pushpan, "An Enhanced Channel Access Method to Mitigate the Effect of Interference Among Body Sensor Networks for Smart Healthcare," IEEE Sensors Journal, vol. 19, pp. 7082-7088, 8 2019.
3. G. Patti and L. L. Bello, "A Priority-Aware Multichannel Adaptive Framework for the IEEE 802.15.4e-LLDN," IEEE Transactions on Industrial Electronics, vol. 63, pp. 6360-6370, 10 2016.
4. M. R. Palattella, N. Accettura, X. Vilajosana, T. Watteyne, L. A. Grieco, G. Boggia and M. Dohler, "Standardized Protocol Stack for the Internet of (Important) Things," IEEE Communications Surveys Tutorials, vol. 15, pp. 1389-1406, 2013.
5. K. Muraoka, T. Watteyne, N. Accettura, X. Vilajosana and K. S. J. Pister, "Simple Distributed Scheduling With Collision Detection in TSCH Networks," IEEE Sensors Journal, vol. 16, pp. 5848-5849, 8 2016.
6. H. Kurunathan, R. Severino, A. Koubaa and E. Tovar, "IEEE 802.15.4e in a Nutshell: Survey and Performance Evaluation," IEEE Communications Surveys Tutorials, vol. 20, pp. 1989-2010, 2018.
7. H. Kurunathan, R. Severino, A. Koubaa and E. Tovar, "DynaMO—Dynamic Multisuperframe Tuning for Adaptive IEEE 802.15.4e DSME Networks," IEEE Access, vol. 7, pp. 122522-122535, 2019.
8. H. Kapil and C. S. R. Murthy, "A Pragmatic Relay Placement Approach in 3-D Space and Q-Learning-Based Transmission Scheme for Reliable Factory Automation Applications," IEEE Systems Journal, vol. 12, pp. 823-833, 3 2018.
9. D. D. Guglielmo, B. A. Nahas, S. Duquennoy, T. Voigt and G. Anastasi, "Analysis and Experimental Evaluation of IEEE 802.15.4e TSCH CSMA-CA Algorithm," IEEE Transactions on Vehicular Technology, vol. 66, pp. 1573-1588, 2 2017.
10. F. Chiti, R. Fantacci and A. Tani, "Performance Evaluation of an Adaptive Channel Allocation Technique for Cognitive Wireless Sensor Networks," IEEE Transactions on Vehicular Technology, vol. 66, pp. 5351-5363, 6 2017.
11. Y. Al-Nidawi, H. Yahya and A. H. Kemp, "Tackling Mobility in Low Latency Deterministic Multihop IEEE 802.15.4e Sensor Network," IEEE Sensors Journal, vol. 16, pp. 1412-1427, 3 2016.
12. Y. Al-Nidawi and A. H. Kemp, "Mobility Aware Framework for Timeslotted Channel Hopping IEEE 802.15.4e Sensor Networks," IEEE Sensors Journal, vol. 15, pp. 7112-7125, 12 2015.
13. A. Aijaz and U. Raza, "DeAMON: A Decentralized Adaptive Multi-Hop Scheduling Protocol for 6TiSCH Wireless Networks," IEEE Sensors Journal, vol. 17, pp. 6825-6836, 10 2017.
14. N. Accettura, E. Vogli, M. R. Palattella, L. A. Grieco, G. Boggia and M. Dohler, "Decentralized Traffic Aware Scheduling in 6TiSCH Networks: Design and Experimental Evaluation," IEEE Internet of Things Journal, vol. 2, pp. 455-470, 12 2015.

AUTHORS PROFILE

K. Suresh, Associate Professor, ECE, Chaitanya Engineering College, VSP, has research interests lie mostly in the field of IOT, Sensors, Wireless Communication Systems and System Integration.

Dr. M. Ramesh Patnaik, Associate Professor, Department of Instrument technology, A.U. College of Engineering, Andhra University, is a fellow of the Institution of Engineers (India) and member of IETE and ISTE. He has quite a good number of publications is the field of fuzzy control, smart transmitters and general industrial control. His research interests lie mostly in the field of industrial control, fuzzy control, sensors and system integration