

A Novel Channel Access Mechanism for IEEE 802.15.4e to Promote Internet of Things



Chebrolu Phaneendra Kumar, Bandi Kiran Kumar

Abstract: IEEE 802.15.4e defines the specification of PHY layer and MAC layer. Although distinguished by its popularity and strength for Wireless Sensor Networks (WSNs), it still suffers from several limitations that deteriorates its performance. One such restriction is a high collision probability that degrades the performance of a dense network. In this article, we develop a Slotted Access Window (SAW) mechanism, a medium access technique to mitigate high collision probability and energy consumption in dense and battery constrained networks. An accurate analytical model is presented to assess the effectiveness of SAW mechanism and validated using the ns-3 simulator. Finally, results show that the SAW mechanism significantly improves the throughput, energy efficiency, and delay in contrast to the default medium access mechanism.

Index Terms: Wireless Sensor Network, IEEE 802.15.4e, LLDN, Internet of Things, Slot Allocation Window, MAC Layer.

I. INTRODUCTION

Wireless Sensor Network (WSNs) is slowly evolving as the Internet of things. It was predominantly used in military operations to track soldiers and to detect intruders. Since then, it is widely spread to the various sector, including medical, industrial, agriculture, environmental, and disaster monitoring applications. Nowadays, with the sophisticated design of sensors and actuators, this paradigm is attracting the industry in various aspects.

There are various design concerns in WSNs. One such constraint is energy efficiency. Because most of the sensor and actuator system in WSN is powered by static power sources and in most of the cases, replacement of the battery is an expensive task or even impossible. However, there are additional constraints, such as reliability, stringent delay, and scalability. To detect critical events in industrial automation, the data transmission should ensure high reliability else results in disaster. Similarly, there are many industrial applications with stringent delay constraints, for example, Wireless Controlled Network, where even 50ms of delay is also intolerable. Finally, scalability is an essential factor in vast networks. An excellent wireless communication standard is necessary to support the above-said constraints. Recently there have been many communication standards (Bluetooth, Wi-Fi, ZigBee, etc.) introduced to support the requirements of the WSN.

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Among all IEEE 802.15.4e is mostly marketed well and among several MAC modes in IEEE 802.15.4e, the performance of LLDN network are extensively assessed using mathematical models. We also propose Slot Allocation Window, a medium access technique to reduce the collisions. To do so, we group the network device into the various group and allow them to contend in the specified time slot, thereby decreasing the collision among the devices and increasing the performance of the network. The remainder of the article is as per the following: Section II presents the literature on IEEE 802.15.4e. Section III briefs about IEEE 802.15.4e. Section IV presents the proposed channel access scheme. In Section V, throughput, energy consumption, and delay are assessed using a mathematical model. Section VI discusses the results. Finally, section VII concludes the paper.

II. LITERATURE SURVEY

Many works in the literature assessed the performance IEEE 802.15.4e. Domenico et al. in [1] explained the drawback in the legacy 802.15.4 standard with suitable simulations. Chen et al. in [2] briefly describes the various MAC mode introduced in IEEE 802.15.4e and presents a state diagram for TSCH CSMA/CA. Berger et al. in [3] uses relay node and decrease the energy consumption. Patti et al. in [4] proposes multichannel LLDN to enable communication between the nodes in the different channel, i.e., to increase the scalability of the network. Dairz et al. in [5] proposes an enhancement to LLDN mode and evaluate the performance of LLDN analytically. Achim et al. in [6] suggests a retransmission mode to save the energy consumption by 33% and reduces the packet loss by 40%.

Many works are reported to assess the performance of LLDN. In [7], Bianchi proposed a mathematical model to find the throughput of DCF mechanism. Extending Bianchi work, authors in [8] finds the throughput of a error prone network. Similarly, in [8] authors derive a closed-form expression from finding the packet delay using the Markov chain model. Madani et al. in [10] considers the backoff freezing and busy channel to estimate the collision probabilities more accurately. Similar to the previous work, Motamedi et al. in [11] evaluate the DCF in noisy wireless networks. They also present models the slotted CSMA/CA to find various metrics under saturation conditions. They provide an analytical model in the star topology for saturated and unsaturated conditions. Performance of IEEE 802.15.4 is assessed in various situations. In [12], authors propose an adaptive algorithm to minimize the power consumption. In [13], a hybrid MAC is proposed, and authors in [14] consider fading channels in their evaluations.

Mainly, this work focuses on assessing LLDN mode under saturation condition using various parameters. We also present a novel channel access mechanism to reduce the contention in the network and provide deterministic time slots to the network devices. The results show the SAW scheme outperform the legacy standard. All the analytical results are validate using extensive ns-3 simulations.

III. OVERVIEW OF IEEE 802.15.4E

The LLDN MAC mode targets the application which requires low and deterministic delay like Wireless Controlled Network. LLDN mode aims to provide a delay of 5-50ms. To provide deterministic delays, the mode enables only star. The structure of super frame consists of the periodically transmitted beacon, management time slots, uplink timeslots and bidirectional timeslots.

In LLDN mode individual devices use dedicated times slots whereas devices contend in the shared timeslots using simplified CSMA/CA i.e., Distributed Coordination Function (DCF) as shown in Fig 1. In simplified CSMA/CA, each device initializes backoff stages, contention window and back off exponent. A value in between $[0, 2^{BE} - 1]$ is chosen by each device. After the expiration of the backoff counter, a CCA operation is performed. If the channel is not idle, the NB is incremented along with changes in BE else the contention window is decremented. If CW is zero, then a device initiates packet transmission. Finally, if thebackoff stage exceeds maximum value, the packet transmission is a failure.

IV. PROPOSED SCHEME

In this section, we present the Slot Allocation Window (SAW) algorithm to reduce the contention in the network and improve its performance. In this proposed scheme the coordinator initializes the SAW algorithm as shown in Algorithm I. Initially, the coordinator randomly chooses N group heads and allow them to broadcast the pilot message to the rest of the network. Each node measure the signal strength form the corresponding group head. Finally, each node joins with a group head with maximum signal strength. The coordinator allows the group of devices to contend deterministically in a time slot.

V. ANALYTICAL MODEL

This section presents an analytical framework to evaluate the throughput, delay, and energy efficiency using a discrete chain Markov chain model [18]. Let the network which is free from error has N devices. Let $E = \{p(t), c(t), g(t)\}$ are the states of discrete time markov chain that represents the stochastic process of the back-off stage, back-off counter and transmission or retransmission process.

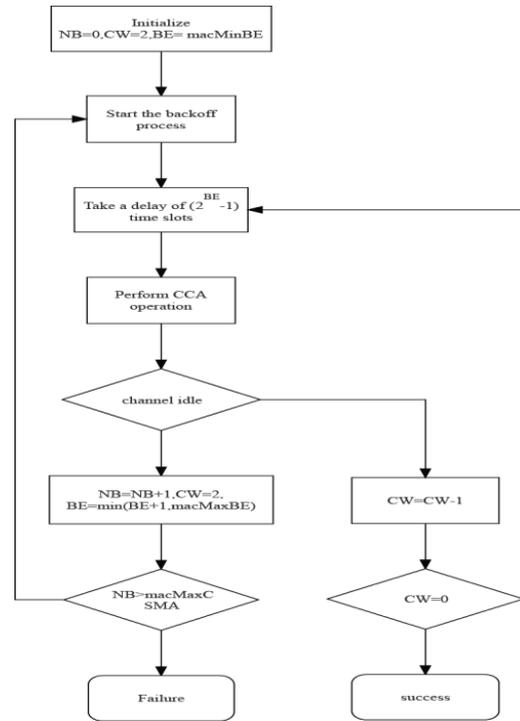


Fig.1: CSMA/CA Mechanism

FOR each SAW period **DO**

AP chooses a random node (Group Head) in each;
AP informs about group head in Beacon Frame;

FOR each node **DO**

IF it is group head **THEN**

| Send pilot tone to the network devices;

ELSE

| Listen to pilot tone from the group head;

END

END

Group the node around each group head by measuring signal strength;

FOR each node **DO**

IF it is group head **THEN**

| Send grouping information to the Coordinator;

END

END

END

ALGORITHM 1: SLOT ALLOCATION WINDOW ALGORITHM

Since we know the back of counter doubles for every m_b , the contention window is given by

$$W_i = \begin{cases} 2^i \times W_0 & i \leq m_b - m_0 \\ 2^{m_b - m_0} \times W_0 & m_b - m_0 \leq i \leq m \end{cases} \quad (1)$$

where m_b represents the back-off stages, m_0 is the minimum number m_b , and m is the maximum retry limits.

The following are the transition probabilities:

$$P\{i, k, -1 / i, k + 1, -1\} = 1 \quad (2)$$

$$P\{i, -1, -1 / i, 0, -1\} = 1 - \alpha \quad (3)$$

$$P\{i, k, -1 / i - 1, 0, -1\} = \frac{\alpha}{W_i} \quad (4)$$

$$P\{i, k, -1 / -1, -1, -1\} = \frac{\beta}{W_i} \quad (5)$$

$$P\{i, -2, 0 / i, -1, -1\} = 1 - \beta \quad (6)$$

$$P\{0, -2, 1 / 0, -2, 0\} = P_c \quad (7)$$

$$P\{0, k, -1 / 0, -2, 0\} = \frac{(1 - \lambda)(1 - P_c)}{W_o} \quad (8)$$

$$P\{-1, 0, 0 / 0, -2, 0\} = \lambda(1 - P_c) \quad (9)$$

$$P\{0, k, -1 / m, 0, -1\} = \frac{(1 - \lambda)\alpha}{W_o} \quad (10)$$

$$P\{-1, 0, 0 / m, 0, -1\} = \lambda\alpha \quad (11)$$

$$P\{0, k, -1 / m, -1, -1\} = \frac{(1 - \lambda)\beta}{W_o} \quad (12)$$

$$P\{-1, 0, 0 / m, -1, -1\} = \lambda\beta \quad (13)$$

$$P\{0, k, -1 / 0, -2, 1\} = \frac{(1 - \lambda)}{W_o} \quad (14)$$

$$P\{-1, 0, 0 / 0, -2, 1\} = \lambda \quad (15)$$

The probability of decrementing the back-off counter by one is given by (2). Equation (5) and (8) is the probability of the channel being empty. The probability of initializing a new back of counter is given by (6), and (7). Equation (9) is retransmission probability. Resetting the back-off counter is given by (10). Similarly, the probability of resetting the back-off timer to zero after reaching the maximum retry limit is given by (12) and (14). Going to the first back-off stage after a retransmission is given by (11), and the probability to go to idle state is given by (12), (13), (14) and (15). Using the equation (2)-(15), the closed form expression is given by

$$b_{i,k} = \frac{W_i - k}{W_i} b_{i,0} \quad i \in [0, m], \quad k \in [0, W_i - 1] \quad (16)$$

using (5) and (7) we get the following equation:

$$b_{i-1,0,-2}(\alpha + (1 - \alpha)\beta) = b_{i,0,-1}$$

$$b_{i,0,-1} = (\alpha + (1 - \alpha)\beta)b_{0,0,-1} = x^i b_{0,0,-1} \quad 0 \leq i \leq m,$$

Where $x = \alpha + (1 - \alpha)\beta$. Owing to the chain regularities and imposing the normalization condition:

$$\sum_{i=0}^m \sum_{k=0}^{W_i-1} b_{i,k,-1} + \sum_{i=0}^m b_{i,-1,-1} + b_{-1,0,0} + \sum_{j=0}^1 b_{0,-2,j} = 1 \quad (17)$$

Solving the above expression results in $b_{0,0,-1}$ given by

$$b_{0,0,-1} = \left[\begin{array}{l} \frac{1}{2} \left(\frac{1 - x^{m+1}}{1 - x} + W_0 \frac{1 - (2x)^{m+1}}{1 - 2x} \right) \\ + (1 - \alpha) \left(\frac{1 - x^{m+1}}{1 - x} \right) \\ + \frac{\lambda}{1 - \lambda} + (1 - P_c)(1 - x^{m+1}) \end{array} \right]^{-1} \quad m \leq m_b - m_0$$

Therefore, the probability of packet transmission is given by

$$\tau = \sum_{i=0}^m b_{i,0,-1} = \frac{1 - x^{m+1}}{1 - x} b_{0,0,-1} \quad (18)$$

The probability of packet collision is given by

$$p = 1 - (1 - \tau)^{n-1} \quad (19)$$

The probability that the channel is busy during the CCA1 is given by,

$$\alpha = (1 - \alpha)(1 - \beta)[L(1 - (1 - \tau)^{n-1})] + L_{GACK} \frac{n\tau(1 - \tau)^{n-1}}{1 - (1 - \tau)^n} (1 - (1 - \tau)^{n-1}) \quad (20)$$

Where L and L_{GACK} are duration of data packet and acknowledgement. The busy probability of CCA2 operation is given by,

$$\beta = \frac{1 - (1 - \tau)^{n-1} + n\tau(1 - \tau)^{n-1}}{2 - (1 - \tau)^n + n\tau(1 - \tau)^{n-1}} \quad (21)$$

Solving equations (18), (20) and (21) gives α, β, τ . Let P_{tr} be the probability that a device transmits in the time slot.

$$P_{tr} = 1 - (1 - \tau)^n \quad (22)$$

P_s is the probability of a successfully transmitted packet and is given by,

$$P_s = \frac{n\tau_j(1 - \tau)^{n-1}}{1 - (1 - \tau)^n} \quad (23)$$

A. Average Throughput

The average throughput is the amount of data transmitted for one slot. Therefore,

$$S = \frac{P_{tr} P_s E[L]}{(1 - P_{tr})\sigma + P_{tr} P_s T_s + P_{tr}(1 - P_s)T_c} \quad (24)$$

where, T_s is successful transmission time, T_c is duration of collision and σ is an idle time slot.

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

$$T_c = T_{PS_Poll} + DIFS + \delta \quad (25)$$

B. Energy Consumption per bit

The energy consumed for transmission and collision is given by,

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

$$E_c = P_{Tx}(T_{PS_Poll}) + P_{Rx}(T_c - T_{PS_Poll}) \quad (26)$$

Therefore, the average energy consumed in a time slot is given by

$$E_T ; (1 - P_{tr})\sigma P_{idle} + P_{tr} P_s E_s + P_{tr}(1 - P_s)E_c \quad (27)$$

Therefore, the energy consumption per bit η is given by,

$$\eta \approx \frac{E_T}{P_{tr} P_s E[P]} \quad (28)$$

C. Average Delay

A collision occurs due to multiple transmission by the devices in the same slot result in the unnecessary delays. Therefore, the delay is given by

$$D = \frac{(1 - P_{tr})\sigma + P_{tr}P_sT_s + P_{tr}(1 - P_s)T_c}{P_{tr}P_s} \quad (29)$$

VI. RESULTS AND DISCUSSIONS

This section analyzes IEEE 802.15.4e network using the channel access technique proposed in the previous section. All the analytical results are obtained using MATLAB and validated using ns3 simulations. We consider a network of size $N = \{128, 256\}$ divided into various groups of size $G = \{4, 8, 16, 32\}$. The variables using in the analysis are listed in Table. 1

Fig. 2 analyzes the collision probability of the proposed scheme using different group sizes. We divide the network into multiple groups. The results show that the collision probability reduces with rise in the group size. Because in a network 256 devices divided into various groups, the stations in each group decrease by increasing the group size. Since the number of devices per group decrease, the contention among them also decrease. The graph in the figure shows that SAW can significantly reduce the contention in the network and enhance the network performance.

Fig. 3 assess the SAW scheme performance. The network is divided into various groups. As shown in figure, increasing the group size increases the throughput up to a specific value and slightly decrease further. Because a small group has large number of devices of per group, hence they can effectively contend the channel without wasting the time slots. Therefore the effective throughput is slightly reduced for the large value of a number of groups. However, when compared with the legacy channel access mechanism, the SAW outperforms.

TABLE 1: PARAMETERS USED TO OBTAIN RESULTS.

| Parameter | Value |
|-----------|------------------|
| W0 | 8 |
| mb | 5 |
| m0 | 3 |
| m | 4 |
| L | 8 bytes |
| LO | 0.35 |
| LGACK | σ |
| timeout | LGACK +IFSPeriod |
| Ptrans | 30 mW |
| Pidle | 0.8 mW |
| Precev | 40 W |

Similarly, Fig. 4 depicts the energy consumed in the network using the proposed scheme for various group size. The results show the energy consumption gradually decreases by increasing the group size and remains constant for a further rise in the group size. The reason behind this phenomenon for the number of groups less than 64 the effective number of the device per group are large thereby consuming energy in transmitting the data packet as well as the back-off process.

But for the groups greater than 64 devices per group are less. Hence most of the time that devices spend time in back-off process thus consumes negligible energy. Finally, Fig. 5 shows delay performance of the proposed scheme for different group sizes. As shown in figure, increasing the group size decrease the delay in the network, but for the larger number of groups, the delay again increases. For example, for a network of size 256 devices divided into 128 groups, each group has two devices to contend in a time slot. Hence most of the contention for backoff increase in the delay. However, when compared with the performance legacy standard the SAW mechanism shows better results.

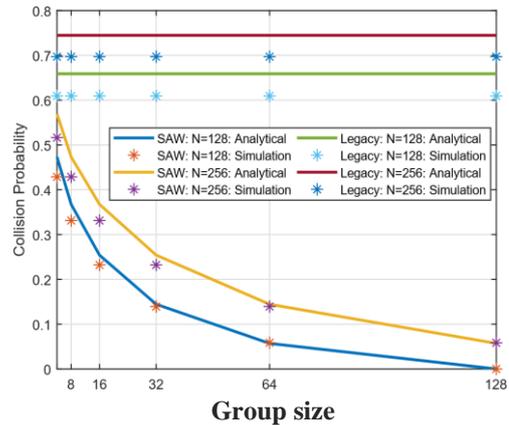


Fig. 2: Collision Probability performance

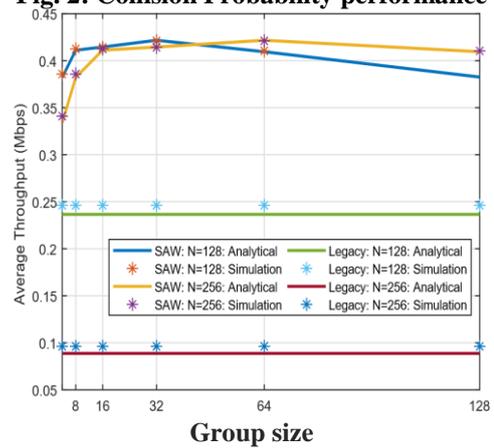


Fig. 3: Throughput performance

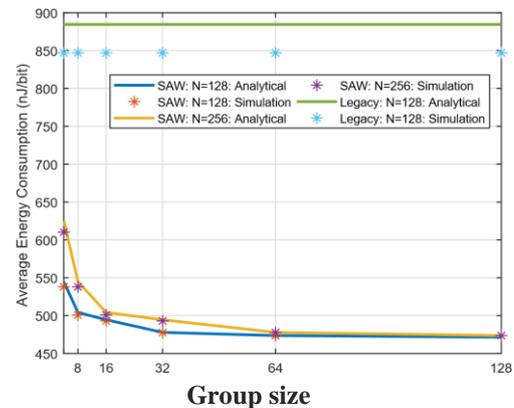


Fig. 4: Energy Consumption per bit performance

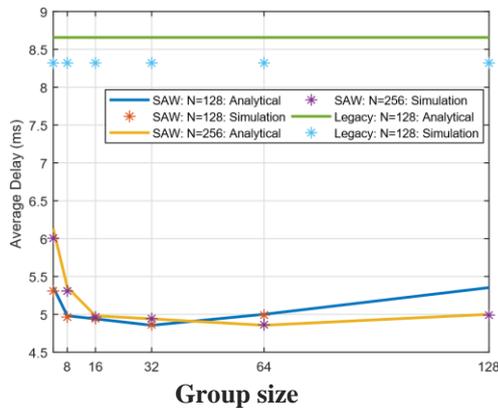


Fig. 5: Delay performance

VII. CONCLUSION

In this paper, we have developed a novel channel access mechanism to split the network in the smaller group and allow each to contend in a deterministic time slot, thereby by reducing the collision among the devices and increasing the performance of the network. We have presented an analytical framework to find network performance. Results show improvement in the network performance in contrast to the legacy IEEE 802.15.4 network. Finally, all mathematical analysis is validated by simulation studies in ns-3

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