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Load Aware Effective Backoff Scheme in Wireless Sensor Network

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ABSTRACT

Wireless sensors network is widely deployed in many areas such as smart homes and Internet of Things (IoT). However, since the limited energy source is a primary concern in the improvement and practical use of WSN, it is necessary to improve the energy efficiency. The backoff mechanism implemented in the WSN communication protocol is a key element in ensuring energy-efficient communication between sensor nodes. Many of the previous backoff approaches perform well on light to moderately loaded networks. However, on a heavily loaded network, the performance degrades significantly. In this paper, we devise a novel adaptive scheme which estimates network traffic using data arrival rate to improve the network throughput and the energy efficiency. We develop a Markov model for the proposed scheme with the provision of numerical analysis. The simulation results show that the proposed scheme significantly improves the energy efficiency and throughput.

Key Words : CSMA/CA, energy efficiency, backoff algorithm, optimization

Ⅰ. Introduction

Technological advances in micro-sensing enables wireless sensor network (WSN) deployed in various application scenarios such as home automation, IoT, and more. The WSN consists of a large number of sensor nodes, which are battery-powered with low computational power. To reduce the energy consumption plays an essential role in prolonging network life, as frequent replacement of batteries deployed in large areas is not cost-effective.

The IEEE 802.15.4's Medium Access Control (MAC) protocol employs the energy efficient carrier sensing multiple access with collision avoidance (CSMA/CA) for data transmission. To increase the energy efficiency, a sensor node with data to transmit conducts sporadically clear channel assessment (CCA) by sensing channel after the random backoff procedure is complete. This allows the node to enter a low-power mode during a random backoff delay, thus saves the energy. However, it increases the backoff index (BE) after every CCA failure and resets it to the minimum (MinBE) value on the data transmission or a packet drop, thus making it incapable of addressing high contention levels.

Therefore, to design the efficient protocols is a major challenge for WSN. Energy loss is primarily due to data collisions and idle listening. Guglielmo et al.[1] propose an algorithm that suggests a backoff should be carefully selected in order to increase the network performance. Cao et al.[2] develop a mathematical analysis model in which performance is particularly affected by the number of nodes,

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especially for a loaded network. Dahham at al.[3] demonstrate a backoff algorithm to increase the energy efficiency by decreasing collisions. Contention window (CW) size is updated based on the probability of collision and it applies a temporary backoff within an actual backoff period. However, the probability of collision alone cannot provide the contention level in the channel. In[4], authors suggest that the minimum and maximum BE (MaxBE) value should be set according to failed and successful transmissions. However, decreasing backoff value after consecutive collisions for a loaded network will result in more collisions, thus degrades the network performance. Batbayar et al.[5] develop the analytical model for an efficient backoff algorithm by calculating remaining backoff periods after conducting CCA operation. When remaining backoff is calculated, a node chooses the BE value that the idle period should be longer than the remaining backoff period. It is claimed that the BE value should be carefully chosen according to the network traffic. Because, the higher BE value can decrease the network throughput and the energy efficiency. Another cause of high energy consumption is the inability to access the channel for data transmission. A scheme in[6] is introduced to avoid collisions. The result shows that the channel sensing consumes significant amount of energy. Patel et al.[7] demonstrate a scheme which conducts an additional CCAs operation to improve the energy efficiency. This scheme works well for lightly loaded networks with fewer nodes, but as the traffic load or the number of nodes increases, the probability of data collisions increases, thus degrades the energy consumption performance for high density networks. Onwuegbuzie et al[8] suggests scheme that classifies data into high and low priority data by estimating backoff with expressions peculiar to the data priority class. However, this scheme is not suitable for sensor data type which falls under the same class. Scheme in[9] uses the predefined traffic classes (4) based on the existing patient's data classification. It prioritizes backoff period to each traffic class in every backoff during contention, thus improves energy consumption.

In this paper, to improve the throughput and the energy efficiency in IEEE 802.15.4, we propose a novel scheme called load aware (LA). LA estimates network traffic load by using only local information of the sensor nodes and adaptively chooses the MinBE value based on the data arrival rate. When a node's data arrival rate exceeds a certain threshold, the MinBE value is incremented by 1. This means that the backoff range is doubled, and reduces the chance of collisions when the network is densely populated. LA is proven to be capable of meeting high throughput while maintaining low energy consumption, and achieving great performance for a wide range of operating conditions for heavily loaded networks when compared with existing approaches.

The rest of the paper is organized as follows. Section 2 covers the system model, and section 3 represents the proposed scheme. Section 4 describes the analytical model of the proposed scheme in detail. Section 5 shows the performance evaluation of the proposed scheme. Finally, section 6 gives the conclusion.

Ⅱ. System Model

IEEE 802.15.4 operates in both beacon-enabled and non-beacon enabled modes. In this paper, we only consider the beacon enabled mode, in which the superframe is divided into contention access period (CAP), contention free period, and inactive period. During the CAP, a sensor node uses slotted CSMA/CA for accessing the channel that operates as a unit of slot time, called backoff period (BP). In order to evaluate MAC performance, we focus on the case that superframe duration is entirely dedicated to CAP. We assume that the network is homogeneous and the data arrive at each node according to a Poisson process with λ, then the arrival rate γ in a slot time T_{slot} is given by

$$\gamma = \int_0^{T_{slot}} \lambda e^{-\lambda t} dt \tag{1}$$

Since we aim to develop an efficient CSMA/CA scheme, we consider a single-hop uplink data transmission from N nodes. We assume that each node is non-saturated, and an error-free channel and no retransmission is allowed after a data collision or a failed attempt.

Ⅲ. Proposed Scheme

Performance of the network is greatly impacted by the traffic loads in the network. The traffic load is explicitly related to the data arrival rate of every node. Therefore, for a certain node to have the knowledge of the network traffic can have many implications. By applying LA scheme, each node estimates its own data arrival rate for every certain period (twarmup). Let p_c be a collision probability that data being transmitted on the channel suffers a collision with transmissions by other nodes.

We assume that in every new transmission attempt for the tagged node, regardless of previous number of collisions suffered, each packet is collided with independent probability p_c. In other words, there are at least one of the N − 1 remaining nodes senses the channel at the same time with the tagged node. Then probability of collision is $p_c = 1-(1-\phi)^{N-1}$, where ϕ is the probability that a node attempts to sense the channel at a random slot time. Also, ϕ is derived as a function of arrival rate γ, which is explained in section 4 for more detail. Therefore, we can see that probability of collision p_c and arrival rate γ has the explicit relationship. To estimate the arrival rate has the symmetric meaning of calculating the probability of collision. To reduce the probability of collisions in data transmission, LA needs to allocate an appropriate backoff to each node based on the network traffic load, i.e, data arrival rate. In order for a node to estimate its arrival rate, it sets the local counter to zero and increases by one during warmup period for every new data arrival and calculates the arrival rate by dividing the counter value by the warmup period. Then, calculating its arrival rate, a node sets the MinBE value depending on the calculated data arrival rate for the next data transmission. If the arrival rate exceeds certain thresholds, i.e. threshold1 or threshold2, the node increases the MinBE value by one or two. If the MinBE value increases by 1, i.e, doubles the backoff range, thus results in the reduction of possibility of collision when the network is densely populated and leads to greater energy efficiency.

Table 1. Simulation parameters

Parameter	Value
t_{warmup}	10 sec
t_{total}	3000 sec
MinBE	3
threshold1	0.01
threshold2	0.005
N	30

The pseudo code of the proposed LA is presented in Algorithm 1. To estimate traffic rate according to

Algorithm 1 Load Aware algorithm

```
Initialize arrival rate variable $rate_i$ and new packet counter $packet_i$ for every node in the network
for i=1: N do
  $rate_i$=0, $packet_i$(cnt)=0
end for
for t=0: $t_{total}$ do
  BE = MinBE
  update = false
  Estimate traffic rate during the given warmup duration
  if t < $t_{warmup}$ do
    send(data, BE)
    if packet received for ith node then
      $packet_i$(cnt)++
    end if
    update($rate_i$) = $packet_i$(cnt)/t
  else
    update = true
    $t_{warmup}$ = $t_{warmup}$ + t
  end if
  Adjust next initial MinBE based on traffic rate
  if update = true
    if $rate_i$ > $threshold_1$ then
      MinBE=+2
    else if $rate_i$ > $threshold_2$ then
      MinBE=+1
    else
      MinBE stays same
    update = false
  end if
end for
```

Algorithm 1, three sets of simulations are done to verify the accuracy of the estimation of the proposed scheme.

Simulation parameters are summarized in table 1. At first, 30 number of nodes try to estimate their traffic rate for 10 seconds of twarmup time. After estimating their traffic rate, every node sets the MinBE value according to the Algorithm 1. The values of threshold1 and threshold2 are predefined and chosen by the authors based on the many simulation experiments for optimization. After setting the MinBE value, each node tries to estimate the data arrival rate for every predefined warmup (twarmup) period again.

Figure 1 plot shows the result of the estimated arrival rates as arrival rate γ sets to 0.0016, 0.0096, and 0.01, respectively. The results for the lower rates show that the variance of the estimates is very low and accurate. However, fluctuation in estimations are high and prediction becomes poor as the traffic rate increases. This is because there is not enough sampling in the traffic rate estimation for a short amount of time.

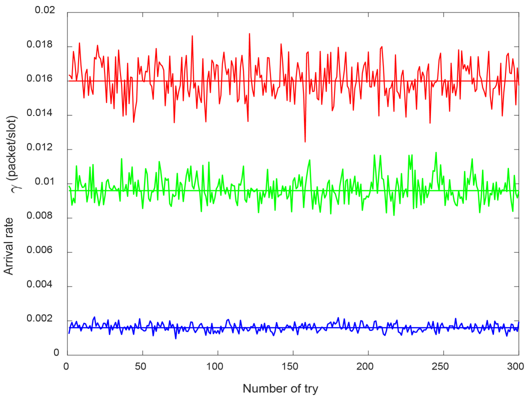

Fig. 1. Estimation of arrival rate

Ⅳ. Analytical model

In this section, we explain a brief description of an analytical model. Our scheme is characterized by two-dimensional Markov chain model $\{s(t), c(t)\}$ as shown in Figure 2. $s(t)$ is the stochastic process representing the backoff stages $s(t) \in \{0,1,\ldots,m\}$ or the transmission stage $(s(t) = -1)$, where m is the maximum number of CSMA backoffs defined by macMaxCSMABackoffs. And $c(t)$ is the stochastic process representing the backoff counter $c(t) \in \{0,1,\ldots, W_i - 1\}$, where W_i is the backoff window, initially $W_0 = 2^{MinBE}$ and $W_i = W_0 2^{\min(MaxBE - MinBE, i)}$, $i \in [0,m]$; and the MinBE and the MaxBE represent the minimum and maximum backoff exponent value, respectively. And $(c(t) = -1)$ and $(c(t) = -2)$ correspond to CCA1 and CCA2, respectively.

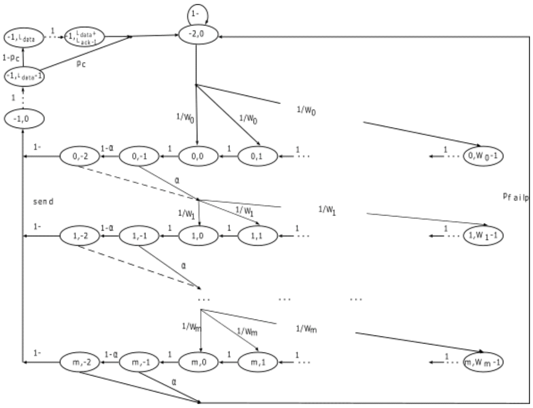

Fig. 2. Markov model of Load Aware Effective scheme

Let α be the probability of sensing channel busy for CCA1, and β the probability of sensing it busy for CCA2.

Then state transition probabilities in Markov model are given by

$$P\{i,k|i,k+1\} = 1, i \in [0,m], k \in [-1, W_i - 2] \tag{2}$$

$$P\{0,k|i,0\} = P_{suc}\gamma / W_0, i \in [0,m-1], k \in [-1, W_0 - 1] \tag{3}$$

$$\begin{aligned} P\{i,k|i-1,0\} = (\alpha + (1-\alpha)\beta)/ \\ W_i, i \in [1,m], k \in [-1, W_i - 1] \end{aligned} \tag{4}$$

$$P\{0,k|m,0\} = \gamma / W_0, k \in [0, W_0 - 1] \tag{5}$$

$$P\{-1,k+1|-1,k\} = 1, k \in [0, L_{data} - 1] \tag{6}$$

where P_{suc} is the probability of sensing channel idle for two consecutive CCAs, and is $P_{suc} = (1-\alpha)(1-\beta)$. L_{data} express the data size in slots. Equation 2 represents that the backoff counter decreases by one, and equation 3 represents the probability of returning back to initial backoff stage. Equation 4 presents the probability that a node senses the channel busy for CCA1 or CCA2, thus entering the next backoff stage with a selection of backoff delay from a range $[0, W_i - 1]$. The probability of starting a new transmission after reaching the maximum backoff stage is described in equation 5, and the probability of data being transmitted is described in equation 6. Moreover, when there is a collision in the channel, we assume that it takes 3 slot times to determine a collision.

Let $b_{i,k}$ be the steady state probabilities, $b_{i,k} = \lim_{t\to\infty}\{P(s(t) = i, c(t) = k\}$ where $i \in [-2, m]$, $k \in [-2, \max(L' - 1, W_i - 1)]$, and $L' = L_{data} + L_{ack} + L_{idle}$. Then by combining equations (2) through (6), we obtain $b_{i,k}$ as

$$b_{i,0} = P_{busy}^{i} b_{0,0},\, i \in [0, m] \tag{7}$$

$$b_{i,k} = (W_i - k)/(W_i)\, b_{i-1,0},\, i \in [1, m], k \in [1, W_i - 1] \tag{8}$$

$$b_{-2,0} = (1 - \gamma) b_{0,0} \tag{9}$$

where $P_{busy} = \alpha + (1 - \alpha)\beta$ is the probability of channel being busy. Summing all the steady state probabilities

$$\sum_{i=0}^{m}\sum_{k=0}^{W_i - 1} b_{i,k} + \sum_{i=0}^{m} b_{i,-1} + \sum_{i=0}^{m} b_{i,-2} \sum_{i=0}^{L'} b_{-1,i} + b_0 = 1 \tag{10}$$

Let ϕ be the probability that a node attempts to sense the channel at a random slot time, then

$$\phi = \sum_{i=0}^{m} b_{i,0} = (1 - P_{busy}^{m+1})/(1 - P_{busy}) b_{0,0} \tag{11}$$

Let P_{send} be the probability that a node successfully occupies the channel so transmits data, then

$$P_{send} = (1 - (1 - \phi)^N) P_{suc} \tag{12}$$

Let P_s be the probability of successful transmission, i.e., the probability that a node senses the channel idle for two consecutive time slots, and the others not; and let P_{cl} be the probability of collision within the network. Then they are represented as

$$P_s = N\phi(1 - \phi)^{N-1} P_{suc} \tag{13}$$

$$P_{cl} = 1 - P_s / P_{send} \tag{14}$$

The probability of sensing channel busy for CCA1, equals the probability that at least one of the remaining N-1 nodes sends the data which is calculated by

$$\alpha = P_{suc}(1 - (1 - \phi)^{N-1})(L_{data} + L_{ack}(1 - P_{cl})) \tag{15}$$

Similarly, the probability of sensing channel busy for CCA2, counts the probabilities that at least one of the remaining N-1 nodes starts transmitting during CCA2 and CCA1 senses empty slot between data and acknowledgement by the other nodes, and is expressed by

$$\beta = (2 - P_{cl})/(2 - P_{cl} + 1/(1 - (1 - \phi)^N)) \tag{16}$$

Three values of α, β and ϕ in equations (15), (16) and (11) are sufficient to drive performance metrics in our work, and we used Matlab tool to solve these nonlinear equations.

V. Performance evaluation

5.1 Throughput and Energy analysis

In this section, we analyze our proposed scheme performance in terms of network throughput and energy consumption. The network throughput is defined by the amount of data successfully delivered to the destination, thus expressed by

$$G = P_s L_{data} R \tag{17}$$

where the transmission rate R = 250 Kbps for

IEEE 802.15.4. To compute energy consumption, we need to derive probabilities of respective states, namely P_{tx}, P_{rx}, P_{cca}, and P_{idle}. All these probabilities are expressed by

$$P_{tx} = L_{data}\phi P_{suc} \tag{18}$$

$$P_{rx} = (L_{idle} + L_{ack})(1 - p_c)\phi P_{suc} \tag{19}$$

$$P_{cca} = \phi + \phi(1 - \alpha) \tag{20}$$

$$P_{idle} = 1 - P_{tx} - P_{rx} - P_{cca} \tag{21}$$

Then the total energy consumption is computed as the sum of the probabilities of each state multiplied by its corresponding energy consumption, and it becomes

$$E = P_{tx}E_t + P_{rx}E_r + P_{cca}E_{cca} + P_{idle}E_{idle} \tag{22}$$

5.2 Experinemtal results

Our proposed scheme is experimented by using a ns-2 simulator to validate our analytical model that derived in section Ⅳ. A WSN is assumed to consist of 30 and 50 nodes, and all nodes transmit data to a coordinator. Table 2 summarizes a simulation parameters that are used in analysis.

Figure 3 displays the comparison between the standard and the proposed scheme LA, [5], [3], and [4], which are named bat, zahraa and vut in the figure, respectively. In all cases, the analysis based on our Markov model matches quite well with the simulation results, essentially for a whole range of traffic load, only with a small mismatch of around 2% for a high traffic load. Moreover, LA represent better throughput performance than the standard, [5], [3], and [4] as the increase of traffic load.

Table 2. Simulation settings

	Parameter	Value
Data size	Ldata	10 slots (100 Bytes)
	Lack	2 slots (11 Bytes)
	Lidle	1 slot
	1 slot	0.32ms
	ACK timeout	3 slot
CSMA/CA setting	MinBE	3
	MaxBE	5
	macMaxCSMA	4
Power per state (mW)	E_R	40
	E_t	30
	E_{CCA}	40
	E_{idle}	0.8

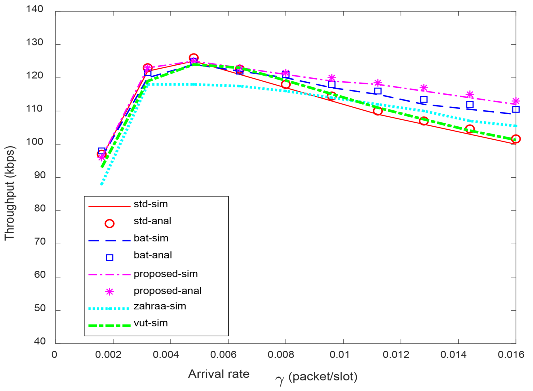

Fig. 3. Network throughput of 30 nodes

The improvement of proposed schemes owes to the estimation of the network traffic and reducing the collisions by increasing backoff range based on the calculated traffic rate.

The figure shows that LA improves throughput up to 10% over standard and [4] and 5% over [3] and 4% over [5]. Figure 4 depicts the comparison of energy consumption among the schemes.

When lightly loaded, there is no difference of energy consumption among all schemes, since all of them experience substantially no collision. However,

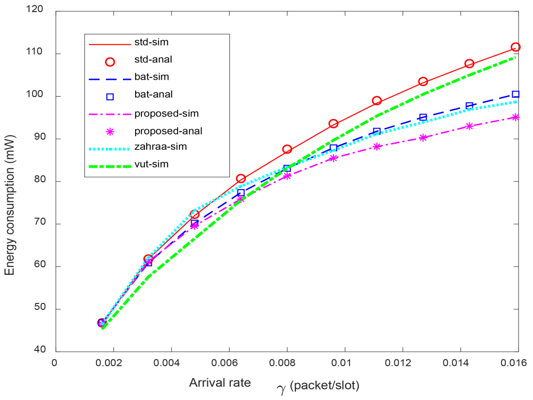

Fig. 4. Energy consumption of 30 nodes

as the contention level increases as the increase of traffic load, the probability of data collision among competing nodes for channel access increases. The reduction of energy consumption of proposed scheme is again due to the accuracy estimation of the traffic load as the increase of arrival rate, which results in the energy saving by 5% over [5] and up to 10% over standard and [4] and 3% over [3]. Figure 5 displays the comparison of network throughput for 50 nodes among standard and other schemes. In the same way, LA outperform the standard, [5], [4], and [3] as the congestion level increases. For the lower traffic load, [3] performs the worst among all schemes due to its backoff window selection. Figure 6 displays the energy consumption of all schemes for 50 nodes under different traffic load. As shown in the figure, energy efficiency for LA is up to 3% over [5], over standard and [4] is 10% as the increase of traffic load.

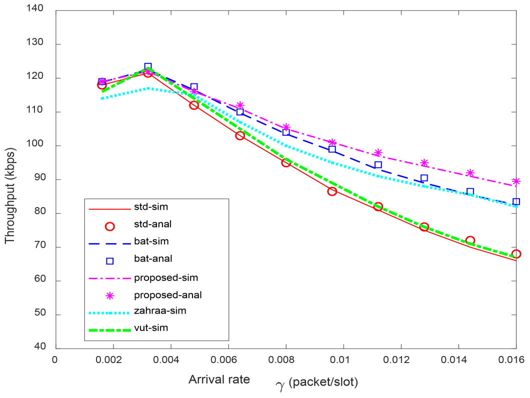

Fig. 5. Network throughput of 50 nodes

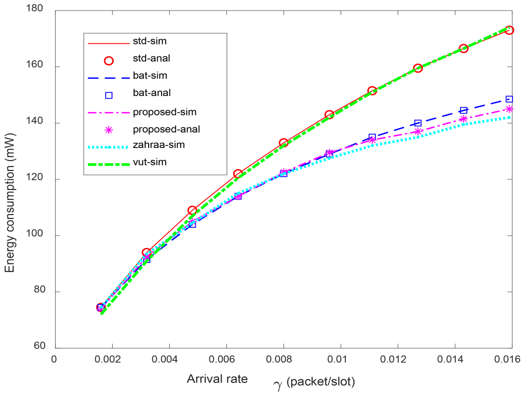

Fig. 6. Energy consumption of 50 nodes

Ⅵ. Conclusion

In this paper, in order to enhance the throughput performance and the energy efficiency, we propose a novel scheme, called Load Aware (LA), and develop its analytical model along with mathematical analysis. LA estimates the network traffic by calculating arrival rate and tunes MAC parameters accordingly. The performance of the proposed scheme LA is compared with previous studies. It shows that the propsed scheme outperforms [3-5] for a whole range of traffic rate.

Reference

[1] D. D. Guglielmo, A. B. 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. 66, no. 2, pp. 1573-1588, 2017.

[2] X. Cao, J. Chen, Y. Cheng, X. S. Shen, and Y. Sun, "An analytical MAC model for IEEE 802.15.4 enabled wireless networks with periodic traffic," *IEEE Trans. Wireless Commun.*, vol. 14, no. 10, pp. 5261-5273, 2015.

[3] Z. Dahham, A. Sali, and B. Ali, "An efficient backoff algorithm for IEEE 802.15.4 wireless sensor networks," *Wireless Pers. Commun.*, vol. 75, no. 4, pp. 2073-2088, 2014.

[4] A. Vutukuri, S. Bhattacharya, T. Raj, Sridhar, V. Geetha "Enhanced back-off technique for IEEE 802.15.4 WSN standard," *NetCom2013*, pp. 21-29, Jan. 2014.

[5] B. Khandish, E. Lee, H. Park, and J. B. Suk, "An efficient backoff scheme in wireless sensor networks," *ICUFN*, pp. 332-337, Prague, Czech Republic, Jul. 2018.

[6] M. Guennoun, M. Khanafer, and H. T. Mouftah, "Modeling of variable clear channel assessment mac protocol for wireless sensor

networks," *Computer Commun.,* vol. 59, pp. 67-83, 2015.

[7] N. R. Patel and S. Kumar, "Enhanced clear channel assessment for slotted CSMA/CA in IEEE 802.15.4," *Wireless Pers. Commun.,* vol. 95, no. 4, pp. 4063-4081, 2017.

[8] I. U. Onwuegbuzie, S. U. Razak, I. F. Isnin, S. J. Darwish, and A. L. Arafat, "Optimized backoff scheme for prioritized data in wireless sensor networks: A class of service approach," *Plos One,* vol. 15, pp. 1-31, 2020.

[9] F. Masud, A. H. Abdullah, A. Altameem, A. S. Gaddafi, and F. Muchtar, "Traffic class prioritization-based slotted-CSMA/CA for IEEE 802.15.4 MAC in Intra-WBANs," *Sensors,* vol. 19, no. 3, 2019.

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