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Allocating resources to the Internet of Things network based on IEEE 802.15.4

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Abstract
IEEE 802.15.4 is a standardized protocol stack equipped with rich capabilities for pervasive and ubiquitous computing for Wireless Personal Area Networks (WPANs). In IEEE 802.15.4, a super-frame structure is regulated by beacon interval. Where beacon order (BO) defines the length of a beacon interval and super-frame order (SO) depicts the active portion. These MAC parameters play a vital role in the network in terms of throughput, network delay, and energy depletion. When a collision occurs during the contention for channel access in super-frame structure, devices increase the backoff exponent (BE) thus leads to excessive energy consumption. Therefore, this paper presents a dynamic algorithm that adjusts the SO and BE parameters. BE plays a vital in reducing the contention among nodes that are trying to contend for the channel access during communication. Thus, reduces the collision, end-to-end delay of communication, and energy consumption. The proposed algorithm computes the required SO based on the network traffic and number of nodes. Secondly, the proposed algorithm adjusts the BE parameter in the subsequent beacons in order to reduce the contention and enhance the packet delivery ratio. Analysis reveals that the proposed algorithm outperforms the IEEE 802.15.4 as it adjusts the SO and BE parameters dynamically based on the knowledge of the network configuration.

INTRODUCTION

Wireless sensor network (WSN) is formed by small nodes communicating in a meaningful way with a sink. WSN is essential in each and every field including; health sector, industrial areas, asset tracking, forest monitoring, agriculture fields monitoring and rescue [1][2]. IEEE 802.15.4 standard defines low data rate wireless connectivity for sensor devices that consume the least energy. Both academia and industry are greatly involved in the use of IEEE 802.15.4 recently, due to its low power and low-cost solutions [3], [4].

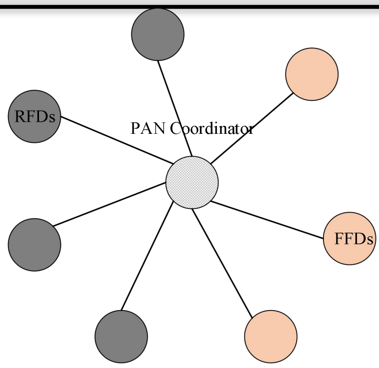

Fig. 1. Star topology

IEEE 802.15.4 supports one-hop star topology within the range of 10-20 meter, exceeding this limit it becomes a self-configuring multi-hot network. A low rate wireless personal area network can be formed by the three different devices: a PAN coordinator, Reduced Function Devices (RFDs) and Full Function Devices (FFDs). FFDs have more capabilities and power resources as associated to RFDs. Furthermore, FFDs manage the whole network operations including beacon transmission, however, RFDs are only limited to data transmission and beacon reception. On the other hand, an RFD can only communicate with a PAN coordinator. The data exchange between devices and a coordinator uses short addresses (i.e. 16bit short address). Fig. 1 shows star topology that can be constructed using the IEEE 802.15.4 standard.

In the beacon-enabled network of IEEE 802.15.4, the PAN coordinator uses a super-frame structure for data communication. In IEEE 802.15.4, a super-frame structure is regulated by beacon interval, where beacon order (BO) defines the length of a beacon interval and super-frame order (SO) depicts the active portion. Currently, IEEE 802.15.4 uses fixed parameters for each application, thus results in degraded network performance. In this paper, we propose a dynamic algorithm which adapts itself based on the number of nodes and the data these nodes carry. The proposed algorithm adjusts the SO parameter along with backoff exponent (BE). BE plays a vital in reducing the contention among nodes that are trying to contend for the channel access during communication. Thus, reduces the collision and end-to-end delay of communication.

The rest of this paper is outlined as follows: Section II presents the related work. Section III outlines the super-frame structure. Network model and the proposed algorithm is presented in section IV. Simulation analysis of both proposed and IEEE 802.15.4 algorithms are presented in section V, whereas the last section completes this paper.

Related Work

This section discusses the detailed relevant work done in the area of super-frame parameter analysis.

The duty cycle algorithm (DCA) [5]primarily adjusts only the SO parameter during the communication in order to lower the consumption of energy and increase the success ratio in the beacon-enabled network. After assicaition the algorithm is triggered at the PAN coordinator, where it adjusts the SO parameters dynamically based on the size of the queue and queuing delay. Furthermore, DCA is not considering the deadlines for the traffic flows during the adjustment period of the super-frame structure. By only adjusting the SO parameter and leaving BO as fixed can create problems such as contention and association between a number of nodes. By using fixed BI the association time can increase if the value of SO is small as compared to BO. Thus, reducing the performance of network throughput, network delay, and the network goes through severe collision. Another works that focuses on the dynamic SO adjustment is the dynamic super-frame adjustment algorithm (DSAA) [6].It only alters the SO and keeping the BO fixed in order to increases the success ratio. The purpose of the DSAA algorithm is to lower the energy depletion and to enhance the network operation more efficient during communication. The algorithm works at the PAN coordinator and tries to adjust SO parameter by considering the collision rate during communication and computes the occupancy ratio of the active portion based on the number of flows. DSAA computes the collision rate at the PAN coordinator based on the received packets from nodes and calculates the expected SO for the next beacon interval. The DSAA algorithm makes use of these value at the PAN coordinator to a pre-defined threshold and tries to adjust the SO parameter accordingly. Adjustment delay scheme (ADES) [7] aims to improve the performance of IEEE 802.15.4 by adjusting the medium control access for multiple end devices based on the backoff exponent. ADES adjusts the backoff exponent in order to reduce the collision probability of ongoing transmission. The algorithm works at the PAN coordinator, where it adjusts the delay if the coordinator finds a busy channel condition. ADES does not show the results using simulation it only shows the analytical results. By adjusting the backoff exponent and network delay it improves the network performance. Another dynamic SO based algorithm is presented in[8], which improves the success ratio of packets by adjusting dynamically the SO parameters. The PAN coordinator first calculates the received number of data packets transmitted by the end devices during communication and then compared it with a pre-defined threshold. If the network requirements are not met, then the PAN coordinator tries to adjust the SO parameter. The algorithm follows a simple approach that does not consider other parameters such as a number of end devices, collision, and network delay.The Adaptive Duty Cycle Algorithm (ADCA) [9] algorithm primary goal is to select a best SO for each beacon interval during the ongoing transmission based on the inactive period. In the ADCA algorithm, if the inactive portion contained in the BI is more than the active portion, then the PAN decreases the SO parameters for the next beacon interval.

Overview of super-frame

This section briefly discusses the super-frame structure used by the beacon-enabled mode of IEEE 802.15.4.

The beacon-enabled mode is mainly based on the use of a super-frame structure. The super-frame structure has two periods: Active period and Inactive period. Active period is also called super-frame duration (SD), which is based on SO. It is further divided into 16 slots of equal length. Whereas, Beacons Interval (BI) defines the duration between two successive beacons, which is based on BO as shown in Fig. 2.

Equation (1) [10] is used to calculate the super-frame structure.

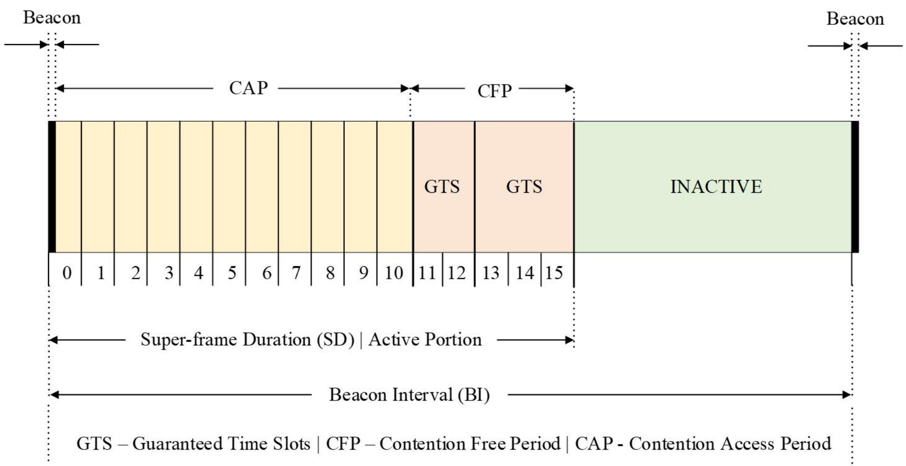

Fig. 2. IEEE 802.15.4 based super-frame structure

$$aBaseSuperFrameDuration = aBaseSlotDuration \times aNumSuperSlot, \tag{1}$$

where $aBaseSlotDuration$ is the time duration of a slot, whereas $aNumSuperSlot$ represents the total number of slots contained in the BI.

$$BI = aBaseSuperFrameDuration \times 2^{BO} \quad (0 \leq BO \leq 14) \tag{2}$$

$$SD = aBaseSuperFrameDuration \times 2^{SO} (0 \leq SO \leq BO \leq 14) \tag{3}$$

$$Sleep\ Period = BI - SD \tag{4}$$

$$Duty\ Cycle = DC = \frac{SD}{BI} \tag{5}$$

Joint Superframe Adjustment and Backoff exponet Algorithm

In this section, we explain the network model of our proposed algorithm.

During the transmission first step in the proposed algorithm is to compute the $SO_{required}$ based on the number of nodes and its data rate using equation (6).

$$SO_{required} = (SN * PktSent * PktSize * PktTime) \tag{6}$$

$$PktTime = \frac{PktSize}{250} \tag{7}$$

Equation (6) used to calculate the required SO for the next transmission, where SN is the number of number active nodes taking part in the communication, $PktSent$ is the total number of packets being transmitted during the active period of particular node, $PktSize$ presents the size of packet in bytes, whereas $PktTime$ shows the time required it takes for the complete transmission from source to destination and is computed using equation (7).

Separately from $SO_{required}$ received ratio parameter is also included in order to accurately determine the size of the active portion in the super-frame structure and is calculated using equation (8)

$$Recv_{ratio} = \frac{PktRcvd}{PktSent}, \tag{8}$$

where $PktRcvd$ in equation (8) finds the received ratio at the PAN coordinator for every BI.

Proposed algorithm working

The proposed algorithm works at the PAN coordinator and runs every time before the transmission of every beacon interval. Before the transmission of BI, the coordinator computes the required SO ($SO_{current}$) based on the end nodes and their contents (data rate and delay requirements). If the $SO_{required}$ is greater than the $SO_{current}$ for the next BI, then $SO_{required}$ is immediately changed to the $SO_{required}$ in order to satisfy application requirements. Otherwise, the received radio is checked, if it meets the application requirements (i.e., greater than the threshold of 90%) then it continues the transmission with $SO_{required}$ and no further changes required. While, on the other hand, if the received ratio is lower than a pre-defined threshold, the proposed algorithm rises both SO and backoff exponent (BE) . However, the proposed algorithm cannot go beyond the minimum SO and maximum SO in order to ensure the association problem (i.e., minimum SO=2; maximum SO=8). The change in BE is important in order to reduce the contention.

In the contention access period, each node communicates with its PAN coordinator using CSMA/CA. Each node has to wait for an amount of time called the backoff slots in order to avoid collision and it is represented as aUnitBackoffPeriod = 20 symbols. Each node chose a random BE in the range of $[0, 2^{BE} - 1]$ slots, where BE is the backoff exponent and its default values is set to 3. In our proposed algorithm, when a particular condition is true a node gets an updated BE values and tries to reduce the chances of collision.

Algorithm 1: Proposed algorithm for the adjustment of both SO and BE

Triggered at the PAN coordinator at each BI

Input: SO_{min} = 2, $BO_{min} = 6, BO_{max}$= 10, BE_{min} = 3, BE_{max} = 8

Output: Modified superframe structure and Backoff exponent

PAN coordinator computes the $SO_{required}$ using equation (6)

if $SO_{required}$>$SO_{current}$

$SO_{current}$ = $SO_{required}$

else

PAN coordinator computes the receive ratio using equation (8)

if (RR >= TH)

$SO_{current}$ = $SO_{required}$

else

if ($SO_{current}$<SO_{max} and SO_{max}<= BO_{max})

$SO_{current}$ = $SO_{current} + 1$

else

if (BE_{min}<BE_{max})

BE = BE + 1

else

BE = BE – 1

else

$SO_{current}$ = $SO_{current} - 1$

end if

end if

Algorithm 1: Proposed algorithm for the adjustment of both SO and BE

Triggered at the PAN coordinator at each BI

Input: SO_{min} = 2, SO_{max}= 8, BO_{max} = 8, BO_{max}= 10, BE_{min} = 3, BE_{max} = 8

Output: Modified superframe structure and Backoff exponent

PAN coordinator computes the $SO_{required}$ using equation (6)

if $SO_{required}$>$SO_{current}$

$SO_{current}$ = $SO_{required}$

else

PAN coordinator computes the receive ratio using equation (8)

if (RR >= TH)

$SO_{current}$ = $SO_{required}$

else

if ($SO_{current}$<SO_{max} and SO_{max}<= BO_{max})

$SO_{current}$ = $SO_{current} + 1$

else

if (BE_{min}<BE_{max})

BE = BE + 1

else

BE = BE – 1

else

$$SO_{current} = SO_{current} - 1$$

end if

end if

Performance Assessment

This performance assessment of IEEE 802.15.4 and proposed algorithms in terms of energy consumption, network delay, and throughput is presented in detail. The simulation is carried out by using NS-2 [11]. This study aims to compare the performance of MAC parameters (both SO and BE) based on network load in a star topology. The simulation scenario covers an area of 15 meters, where 15 number of nodes are placed randomly. Whereas, the PAN coordinator is placed in the middle as shown in Fig. 3.

Furthermore, the source nodes are dynamic, during the communication the nodes are turned ON and OFF to observe the network performance. Here, ATMEL [12] energy model is used and the rest of the simulation parameters are shown in Table 1.

Figure 4 represents the energy consumed during the 500 seconds of simulation in which 10 number of source nodes report the data to the PAN coordinator collectively at 100kbps. IEEE 802.15.4 has fixed duty cycle, therefore when BI is high (at a larger value of BO) then SD is half of BI and network devices spend more time in an inactive state, as a result, energy consumption is low, but it severely degrades the network throughput. On the other hand, our proposed algorithm outperforms the IEEE 802.15.4 in terms of energy consumption. It is due to its dynamic nature where it adjusts the SO and BE if the network conditions are not met.

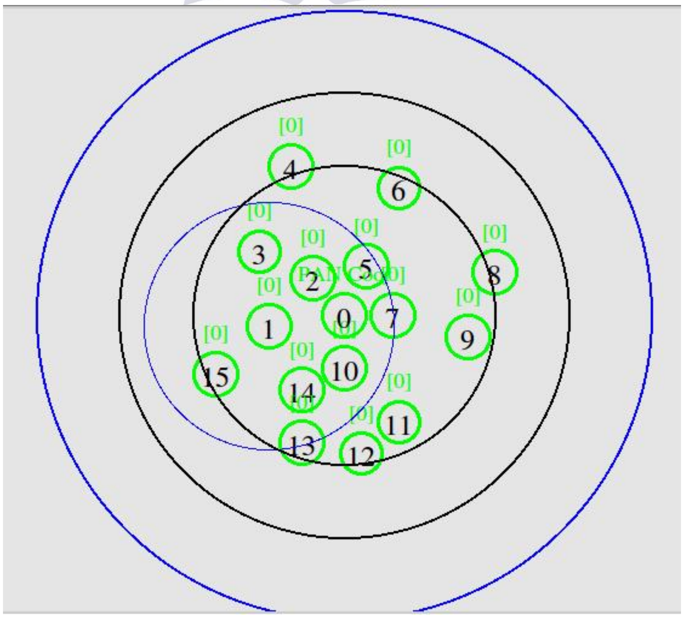

Fig. 3. Simulation environment.

TABLE 1. SIMULATION SETTINGS

Considerations	**Value**
Simulation time (s)	500
Simulation range (m)	15
BO_{min}	8
SO_{min}	2
Traffic type	CBR
Size of packet (B)	60
Source nodes (transmitting nodes)	6, and 10
Nodes data rate (kbps)	100
Simulation energy model	ATMEL MOTE [12]
macMaxCSMABackoff	5
BE_{min}	3
BE_{max}	8
$BE_{\mathrm{aUnitBackoffPeriod}}$	20 symbols
Considerations	**Value**
Simulation time (s)	500
Simulation range (m)	15
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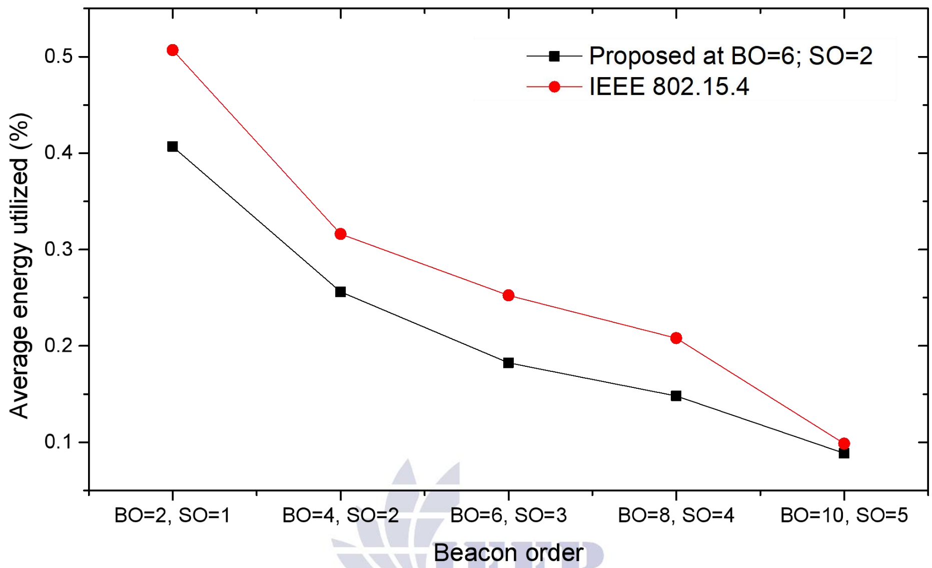

Figure 4. Average energy utilized in percentage for the proposed and IEEE 802.15.4 algorithm

Figure 5 shows throughput for the proposed algorithm and IEEE 802.15.4, respectively at 100kbps. Higher throughput is observed for the proposed algorithm due to the adjustment of SO and BE as a result it increases the active portion when the network throughput requirements are not met. Nodes in the network contend for the channel access simultaneously and get collision, therefore, BE is important to be adjusted dynamically with SO to enhance overcome the contention problem and hence enhances the network throughput. IEEE 802.15.4 performance is worse in terms of throughout it is due its fixed active duration, due to the short active period the nodes contend for the channel at the same time and thus collisions occur and therefore decreases the network throughput.

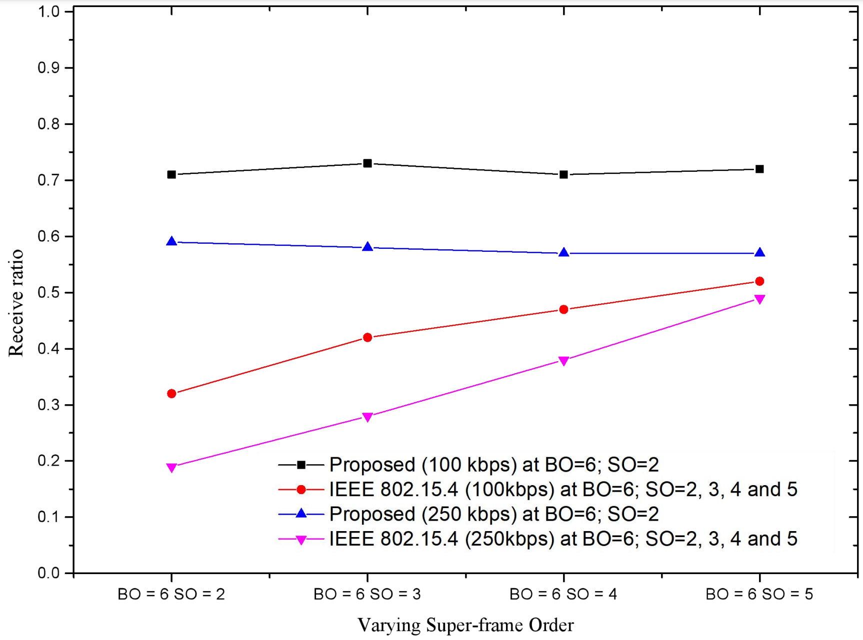

Figure 5. Average receive ratio of the proposed algorithm and IEEE 802.15.4

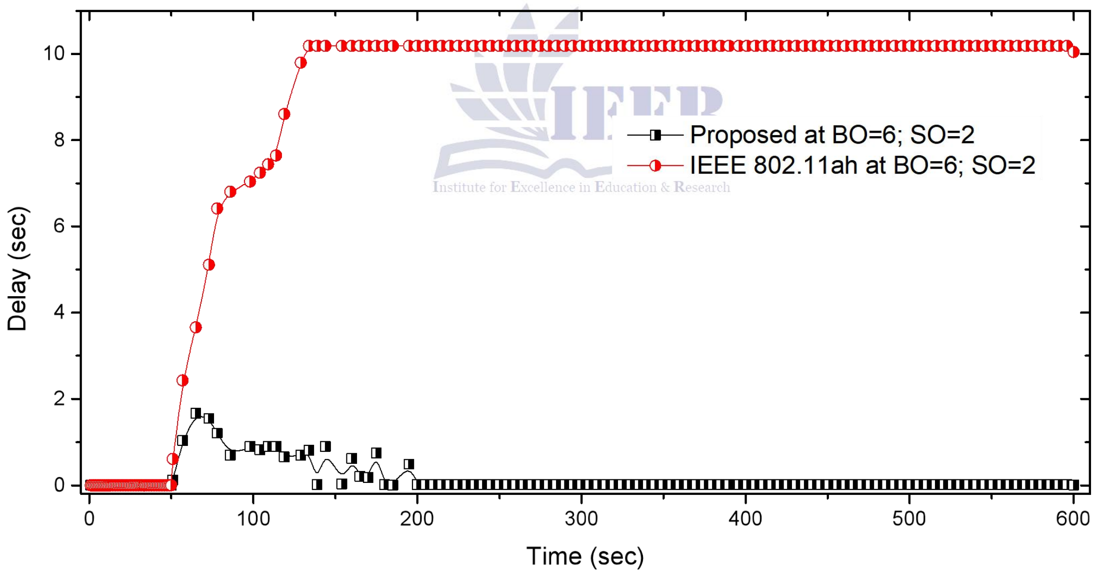

Figure 6. Average delay at run time for the proposed algorithm and IEEE 802.15.4

The delay for BO=6, SO=2 at 100kbps for the IEEE 802.15.4 and the proposed algorithm is presented in Figure 6. High latency perceived for the standard, due to frequent beacon transmission and lower active portion which results in degraded network performance. However, latency is mainly based on the active period. Lower the active portion, higher end-to-end delay is observed as compared to our proposed algorithm. For better network performance, it is recommended to use the ideal values of both BO and SO to maintain the tradeoff. Network administrator chooses the best values of BO and SO prior to network deployment. However, a larger value of SO can result in higher throughput and less delay. It is evident in Figure 3, that due to small super-frame duration all source nodes compete to occupy a channel for data transmission. As a result, a collision occurs which results in higher end-to-end latency. On the other hand, our proposed algorithm adjusts the SO based on application requirements and hence reduces the end-to-end delay when compared to IEEE 802.15.4.

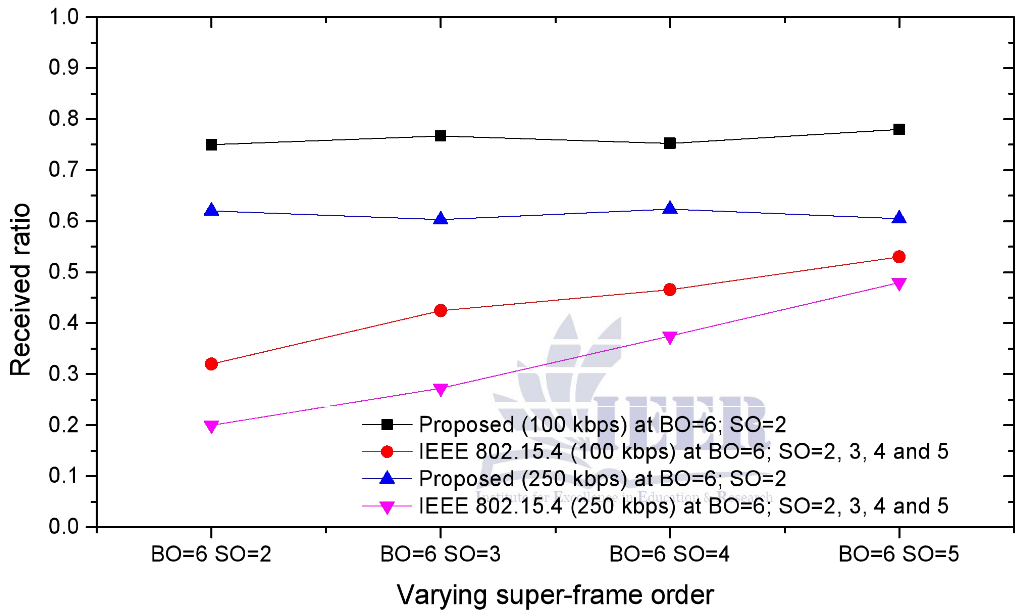

Figure 7. Average receive ratio of the proposed algorithm and IEEE 802.15.4

Figure 7 showsthe achieved throughput of the proposed algorithm and IEEE 802.15.4, respectively at 100kbps and 250 kbps. The proposed algorithm controls the SO (increases or decrease based on the network receive ratio) while IEEE 802.15.4 SO is fixed during the entire communication. From, Figure 7 it is clear the SO management plays vital role in the enhancement of throughput while the throughput increases by increasing the SO by one for the case of IEEE 802.15.4. Therefore, IEEE 802.15.4 unable to achieve a satisfied throughput being with fixed super-frame structure.

Conclusion

This paper presented a dynamic algorithm that adjusts both the SO and BE parameters simultaneously. BE plays a vital in reducing the contention among nodes that are trying to contend for the channel access during communication. Thus, reduces the collision, end-to-end delay of communication, and energy consumption. Simulation analysis shows that a large SO compared to BO results in high success ratio and less delay, but incurs high-energy consumption. Whereas, by picking a large BO as associated with SO results in less energy consumption, higher latency and less throughput are observed for the IEEE 802.15.4.

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