

DELAY-AWARE SUPERFRAME CONTROL IN CLUSTER-TREE WPANS

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Abstract

The IEEE standard for Wireless Personal Area Network (WPAN) is IEEE 802.15.4, which aims to provide low data rate, low power consumption, and a low-cost solution. Another important feature this standard can support is low-duty-cycle operation, which is well-suited to low-power devices. Due to the fixed-duty-cycle operation of IEEE 802.15.4, delay is always a primary concern, leading to low throughput. Therefore, an efficient algorithm is required to overcome the existing problem. In this paper, we propose a delay mitigation algorithm that adjusts the super-frame structure. The PAN coordinator dynamically adjusts the SO parameter of cluster heads based on packet receive ratio, data rate, number of cluster heads, and delay observed at cluster heads. Detailed simulation analysis of the proposed algorithm is compared with the standard IEEE 802.15.4, which shows better results in terms of latency, packet delivery ratio, and throughput.

I. INTRODUCTION

A wireless sensor network typically consists of several sensor nodes that can measure, sense, and gather information from the surroundings. Possible observed parameters are wind direction, humidity, temperature, pressure, and speed [1, 2]. A WSN can be infrastructure-based or ad-hoc. In an infrastructure-based WSN, some nodes form a relatively static infrastructure and are responsible for relaying traffic for other nodes. Smart Dust [1] is an example of the network in this mode. While in an ad-hoc network, sensor nodes collaborate via one or multiple hops without an infrastructure. As the deployment of an ad hoc network is less costly, the ad hoc mode is adopted by many WSN applications. However, managing the network resources and quality of service provisioning in such networks is more difficult than in an infrastructure-based network [2, 3]. Some WSNs may combine the infrastructure-based and ad-hoc modes, where clusters of sensor nodes are interconnected via some central access points referred to as cluster heads (CHs), and all the data packets gathered by sensor nodes are eventually transmitted by the CHs to the sinks. The formatter will need to create these components, incorporating the applicable criteria that follow certain physical quantities, a

microprocessor, a power supply, a radio transmitter, and a receiver. A sensor node may change in size and cost, relying on the functional requirements and the resources of the individual sensor nodes, such as computational speed, memory, and energy [4].

ZigBee Alliance explains different network topologies above the IEEE 802.15.4 physical and MAC layers: the mesh topology, the star topology, and the cluster-tree topology. In a mesh topology, some of the nodes relate to more than one adjacent node in the network, and packets detuning their path to the destinations according to the routing algorithm. Due to its cost and complexity, the mesh topology is usually used with a small number of nodes [5]. The star topology is easy to design and implement; all the devices in a star topology network are connected to central nodes, and the failure of each device or connection does not affect the entire network as long as the central nodes function well. The cluster-tree topology combines some small star topology networks together, in which a root node is associated with one or different lower-level nodes, and every node in the network has a unique number of child nodes associated with it in the hierarchy [6].

The topology of a WSN affects many network features and qualities, such as capacity, latency,

and scalability. Both the star and cluster-tree topologies can utilize beacon frames to move devices to their parent node, and thus reduce the power consumption of the devices by minimal operations [6, 7].

There are two types of devices in IEEE 802.15.4 networks: Full Functional Device (FFD) and Reduced Functional Device (RFD). FFD can be a coordinator because of more computational properties, power resources, and support for utmost networking functionalities. On the other hand, RFDs cannot be coordinators because of limitations in terms of computational power resources and networking functionalities. FFDs can communicate with each other and can be cluster heads; RFDs can only communicate with FFDs and cannot be cluster heads. The IEEE 802.15.4 standard supports topologies: Star

topology, peer-to-peer topology, and cluster tree topology, as shown in Figure 1.

II. IEEE 802.15.4 OVERVIEW

This standard is designed for Low-Rate Wireless Personal Area Networks (LR-WPAN). This standard fulfills the requirements of applications, which are characterized by low data rate communication and have limited power resources. This standard is more suitable for low-power wireless communication than Wi-Fi and Bluetooth. The IEEE 802.15.4 standard addresses two layers: the physical layer and the medium access layer. The physical layer contains the Radio transceiver and low-level control mechanism. The MAC layer defines to transfer and access mechanism of data over the physical layer.

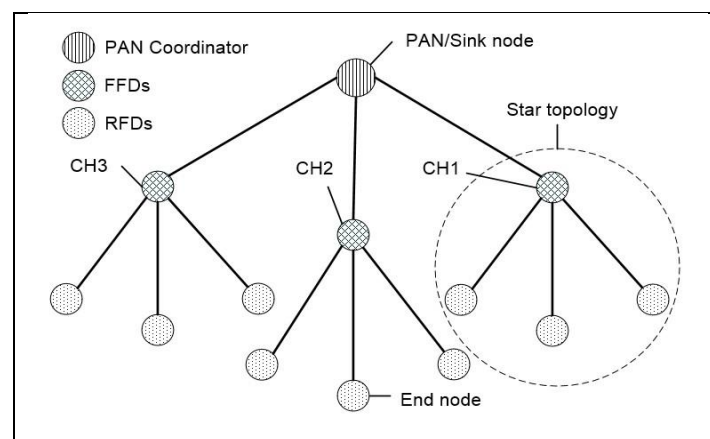


Figure 1. Network Topologies of IEEE 802.15.4

Cluster tree topology is suited for networks to cover an area larger than a star topology. In Cluster tree topology, there is a PAN coordinator, which is a sink node, and FFD Cluster heads are also FFD, and end devices are RFDs. Sensor nodes are the end devices that sense the data from the target and transmit it to the cluster heads. Cluster heads, upon reception of data from end devices, forward it to the sink node. There are several clusters in the cluster tree topology. Each cluster has a cluster head, which is FFD.

Cluster tree-based networks are used in many applications, like smart environments, home automation, WBANS, and industries. Cluster tree topology is useful in networks where the data rate of communication is low and where low-power-consumption devices are required.

The IEEE 802.15.4 standard has two modes of operation: beacon-enabled mode and non-beacon-enabled mode. In beacon-enabled mode, periodic beacons are transmitted from the PAN coordinator and cluster heads to cluster heads and end devices, respectively. In beacon frames, information about the super-frame structure is transmitted, which is associated with the duty cycle of cluster heads and end devices. Duty cycle is fixed in the standard, but it can be varied by changing Beacon Order BO or Super-frame Order SO.

IEEE 802.15.4 operates both in BE mode and BLM. In BE mode, the PAN node transmits beacons at regular intervals of time. The beacon message contains information about the super-frame and duty cycle. The duty cycle is fixed, but

it changes with increasing and decreasing the values of BO and SO.

The IEEE 802.15.4 standard has two modes of operation: beacon-enabled mode and non-beacon-enabled mode. In beacon-enabled mode, beacon frames are broadcast from PAN and coordinators for synchronization, which is

why beacon-enabled mode is used in infrastructure-based networks. Examples of beacon-enabled mode are cluster tree and star topology. Mesh topology is an example of a non-beacon-enabled mode and infrastructure with fewer networks. Modes of IEEE 802.15.4 are illustrated in Figure 2.

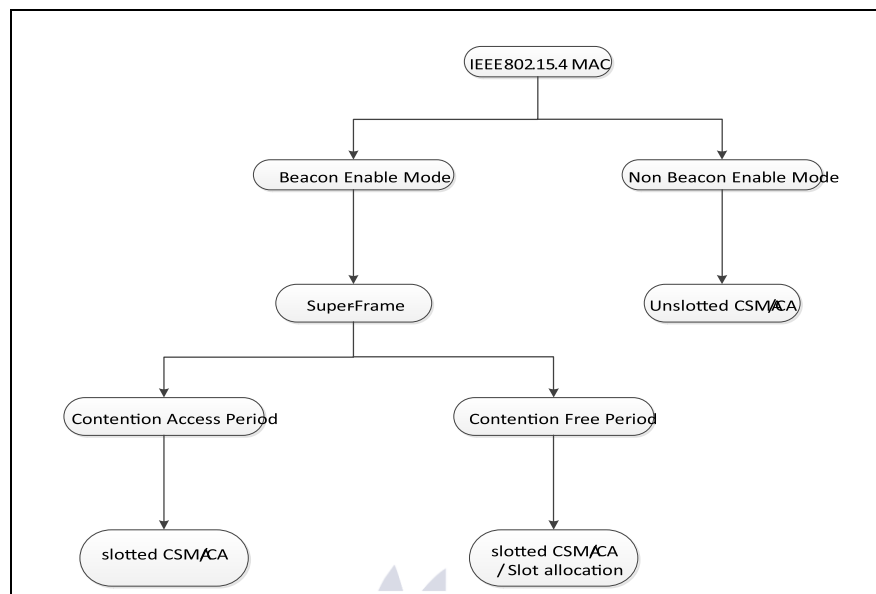


Figure 2. Operational Modes of IEEE 802.15.4

There are 16 time slots in the active period of the super-frame, and every slot has a minimum of 60 symbols in each. BI and SD can be calculated from the following equations [8]:

$$aBaseSuperFrameDuration = aBaseSlotDuration * aNumSuperframeSlot \quad (2.1)$$

$$BI = aBaseSuperFrameDuration * 2^{BO} \quad (0 \leq BO \leq 14) \quad (2.2)$$

$$SD = aBaseSuperFrameDuration * 2^{SO} \quad (0 \leq SO \leq BO \leq 14) \quad (2.3)$$

$$DutyCycle(DC) = SD/BI \quad (2.4)$$

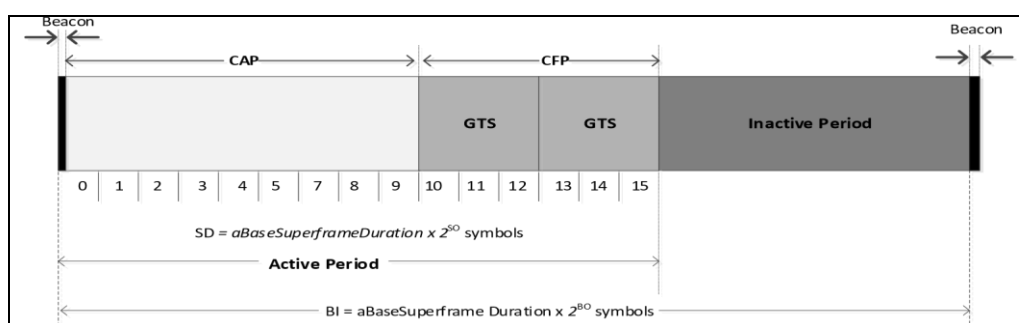


Figure 3. Super-frame Structure of IEEE 802.15.4

III. RELATED WORK

This section presents the literature review of dynamic super-frame adjustment schemes in cluster tree and star topologies. In recent years, many research efforts have targeted the improvement of network performance (throughput, delay, and energy consumption) [9-11]. Generally, research has focused on star

topology-based networks, but in recent years, the large-scale deployment of WPANs has triggered performance issues in cluster tree-based networks [12].

In [2], the appraisal of SO (Super frame order) is fitted by the PAN (personal area network) coordinator, relying on various models, including energy consumption, queue size, and

data rate. However, [4] uses a static BI (Beacon interval) that can result in higher energy utilization if fewer BO (Beacon Order) are utilized. Even using negative network capacity, nodes will be affected to periodically wake up and observe the beacon. In [4], the authors address the delay minimization problems by proposing different ideas during the Contention Access Period (CAP), whereas improvements in the Guaranteed Time Slot (GTS) mechanism are proposed in [5] to optimize the traditional CSMA/CA mechanism and introduce a timing group division method for quick communication in minimizing delays. In [6], the author exhibited QoS improvement in IEEE 802.15.4 in terms of reduction in latency. These developments are achieved by adopting an enhanced Binary Power Back (BPB) off algorithm, which avoids destruction. Energy-efficient clustering scheme (EECS) [13] is another distributed and load-balanced clustering algorithm. According to the cluster formation stage of this algorithm, sensors with more than one potential Cluster Head (CH) choose the CHs by considering not only the distance to the CH but also the number of hops from that CH to the sink. Moreover, there is very little work done in [3, 4], considering WSNs with heterogeneous devices. A practical deployment for a WSN is to distribute a number of FFDs as the CRs and several RFDs as the sensor nodes, all in various places. The FFDs then form an infrastructure for the network with a certain topology. Since the cluster-tree topology has more efficient scalability than the star topology and is more effective for large-scale sensor networks, it is captivating more attention [3, 4]. Sensor nodes should be placed in the extended area among several clusters so that the sensor nodes can select different CRs to consider. In that case, the association relation between sensor nodes and the CRs is effective as it influences the network performance. Some work on sensor node associations in IEEE 802.15.4 networks can be found in [16, 17]. The Simple Association Process (SAP) [11] and the Fast Association mechanism (FAM) [8] are introduced, respectively, to decrease the association delay in practical IEEE 802.15.4 networks.

The idea is that the active duration of the sensor nodes in every cluster is gathered with the same timing offset. This MAC protocol can reduce the

latency and

determine the congestion complications in inter-cluster communications. Besides, the authors of [18] present a novel MAC protocol for delay-sensitive data in a multi-hop mesh network, in which the nodes use local mechanisms to determine an adaptive transmission schedule and manage the delay.

Some other research [15] in delay-sensitive applications in multi-hop wireless mesh networks has been developed, which presents an approach to finding collision-free TDMA agendas with reduced scheduling delay, in which the composers formulate an optimization problem to find a sending order with the min-max moratorium in a set of multi-hop paths, and further devise an algorithm to superimpose tree topologies and handle it with an adjusted Bellman-Ford algorithm to find reduced delay schedules in polynomial time.

There has been some work focusing on modeling and estimating the delay performance in WSNs [11, 16]. In [3], the authors analyze the average minimum delay for collecting data in networks with different topologies and the effect of several factors, such as packet size, sending range, and channel establishment, on the delay execution. End-to-end delay analysis in WSNs is investigated in [5]. A closed-form expression for the delay distributions in a WSN employing data aggregation is derived in [17], and a stochastic end-to-end delay bound to predict the attainment of a WSN deployment is derived.

In [19], a QoS-aware inter-cluster routing protocol for IEEE 802.15.4 networks is recommended. It consists of various functions like the hello protocol module, packet classifier, reliability module, and routing service module. Utilizing the Packet classifier, the packets are divided into data and hello packets. IEEE 802.15.4 endorses the use of static duty cycle operation, which results in high energy utilization and end-to-end delay. Therefore, an efficient algorithm is needed to adapt the duty cycle operation to overcome the end-to-end delay and energy consumption [20].

Recent research on IEEE 802.15.4-based WPANs has focused on improving network performance, particularly throughput, delay, and energy efficiency in both star and cluster-tree topologies. While earlier work primarily addressed star networks, the increasing

deployment of large-scale WPANs has highlighted performance challenges in cluster-tree structures. Several studies propose dynamic adjustments to super frame parameters, enhancements to CAP and GTS periods, and modifications to CSMA/CA to reduce energy consumption and minimize delay. Additional work explores QoS improvements, energy-efficient clustering, heterogeneous WSN deployments, and optimized sensor coordinator associations to enhance scalability. Delay-sensitive MAC protocols, collision-free scheduling, and both analytical and stochastic delay models have been developed to better support multi-hop and large-scale networks. Overall, the literature indicates a need for adaptive duty-cycle mechanisms and dynamic

super frame management to reduce energy usage and end-to-end delay in IEEE 802.15.4 networks.

IV. Methods/Experimental

This section briefly describes the proposed scheme called Delay Mitigation in Cluster Tree. The algorithm is based on a Tree topology based on IEEE 802.15.4. The flow chart of the proposed algorithm is shown in Figure 4.

The proposed algorithm follows these steps.

Step1. The proposed algorithm computes the expected duration based on node flows and their data rate as computed by equations (5), (6), and (7), respectively.

$$ExpSD_{CHn} = (TX_{dev} * Dev_{pkt} * Size_{pkt}) * TX_{time} + TX_{Delay} \quad (5)$$

$$TX_{time} = \frac{Size_{pkt}}{250} \quad (6)$$

$$TX_{Delay} = 2 * ACK + IFS + (2 * CCA) + BACKOFF_{proc} \quad (7)$$

Equation (5) computes the expected super-frame order and is termed $ExpSD_{CHn}$, where TX_{dev} is the number of active nodes taking part in the communication, Dev_{pkt} is the packet transmission rate of each node, and $Size_{pkt}$ is the size of a single packet. Equation (6) calculates the time for a single packet transmission from source to destination. Equation (7) (Ranjit & Shin,

2013), computes the transmission delay expected for a single packet, including ACK transmission.

Step2. In the proposed algorithm, other parameters like throughput and received ratio are also introduced, which are explained in the remaining sections based on Equation (8).

$$Thr_{network} = \frac{(R_{pkts} * Size_{pkt} * 8)}{1000} \quad (8)$$

Equation (8) calculates the throughput $Thr_{network}$, where R_{pkts} are the total number of packets,

$Size_{pkt}$ is the size of the packet in bits, and 1000 is the simulation run time.

$$R_R = \frac{R_{pkts}}{CHn_{pkts} * Tot_{pkts}} * 100 \quad (9)$$

Equation 9 estimates received ratios (R_R) at each cluster head and PAN coordinator. R_{pkts} are the packets received by each cluster head and PAN

coordinator. CHn_{pkts} are the total number of source nodes in each cluster, and Tot_{pkts} are the sum of all packets generated by each cluster.

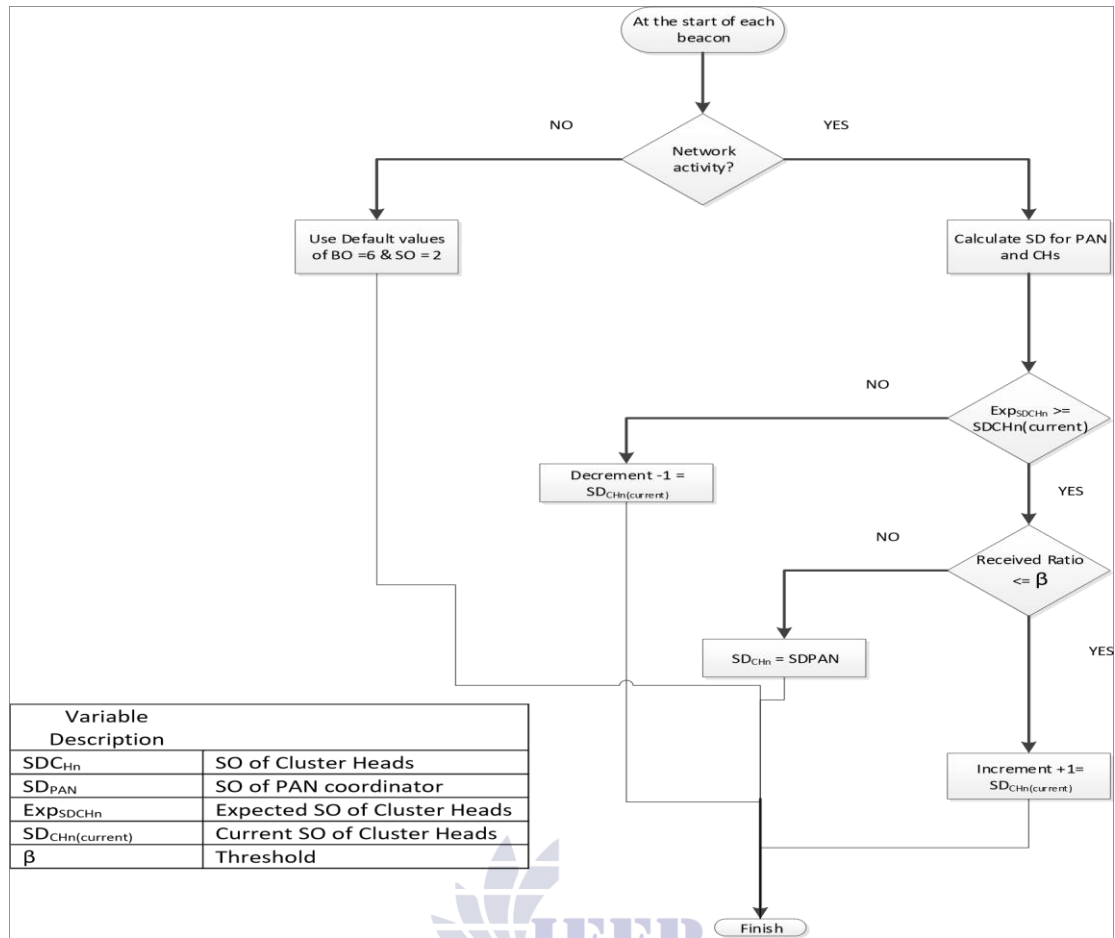


Figure 4: Flow chart of the Proposed Algorithm

$ExpSDCHn$ is calculated at the end of every BI, which is explained in the former section. $ExpSDCHn$ is then compared with $SDCHn_{current}$, which is the current SO of coordinators. If $ExpSDCHn$ is greater than $SDCHn_{current}$, then the received ratio is checked against the threshold. In case it exceeds the received ratio, then $SDCHn_{current}$, the beacon is transmitted without any change, which means the network requirements are satisfied. Otherwise, it is incremented by 1 to enhance the throughput and decrease the end-to-end delay. If $ExpSDCHn$ is less than $SDCHn_{current}$, then $SDCHn_{current}$ is decremented by 1. In the former case, if there is no network activity, the network works based on the default values. The detailed flowchart of the proposed algorithm is available in Figure 4.

V. SIMULATION RESULTS AND ANALYSIS

Simulation analysis of the proposed algorithm is discussed and compared with the IEEE 802.15.4 standard. The comparison is based on

parameters like packet delivery ratio, throughput, and end-to-end delay. Network Simulator (NS2) is used for simulation analysis. Network configuration is based on two clusters in our network, and the PAN coordinator is placed in between these clusters, as shown in Figure 7. Beacons are transmitted by the PAN coordinator at the start of each super-frame, and cluster heads, after reception of these beacons, transmit their own beacons to their respective clusters. In beacons, the active and inactive period is defined according to which nodes can schedule their duty cycle, nodes can communicate during the active period (CAP), and can go to sleep mode during the inactive period to save power and enhance network lifetime.

In this section, a short simulation of fixed BO and SO at PAN and coordinators is presented. The purpose of this simulation study is to analyze the impact of static BO and fixed SO on the network performance in a cluster tree network. The experimental cluster topology is shown in Figure 5. In the simulation, we

consider 1 PAN coordinator, 5 cluster heads, and 5 transmitting nodes in a 50-meter coverage area. There are two different scenarios in which the results are carried. In scenario 1, the BO is kept fixed at 6, whereas the SO is varied from 2 to 6. However, the BO and SO for coordinators are kept fixed at 3 and 2, respectively. In the second scenario, the BO is kept fixed at 6, whereas the SO is varied from 2 to 6. Conversely, the BO and SO for coordinators are kept fixed at 4 and 3, respectively. The results are extracted

by using the NS2 simulator. To have realistic simulation results, we adapted the energy model of the ATMEL Mote for the end devices. The rest of the simulation settings are shown in Table 1. The simulation is performed 10 times, and the average values are shown. In the remainder of this section, evaluation results for network throughput, network lifetime, packet drop, and latency of communication are presented.

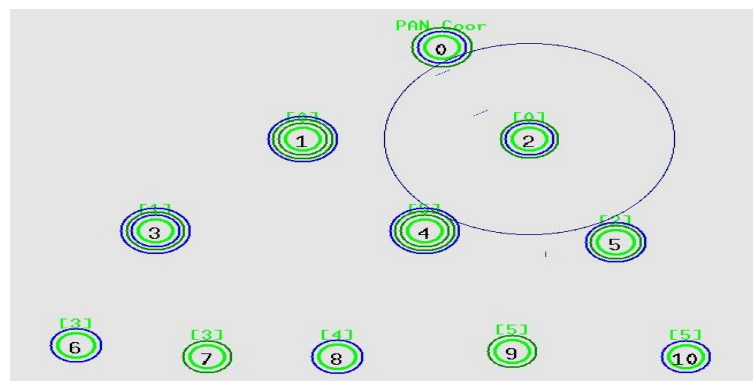


Figure 5. Fixed Network Environment

Table 1. Fixed Network Parameter Impact Settings

Parameter	Description
Simulation time	100 s
Radio range	50 m
Frequency band	2.4 GHz
BOPAN	6
SOPAN	2-6
BO _{CH}	6
SO _{CH}	2-6
Traffic type	CBR
IFQ length	50
Packet size	60 B
No. PAN coordinator	1
No. Cluster Heads (Coordinators)	5
Number of Transmitting nodes	5
Data rate (kbps)	20kps per node
Energy Model	Atmel Mote [12]

Figure 6 shows the throughput observed at the PAN coordinator at 100kbps in total (20kbps per end device). In this figure, the value of BO is kept fixed at 6 due to synchronization issues. Higher values of BO result in node disassociation; therefore, to avoid such a

situation, BO is fixed at 6. On the other hand, SO varied from 2 to 5 to observe the network performance. It can be seen from the figure, the throughput at BO=6, SO=6 is the best due to the large SD duration providing 54.72kbps out of 100kbps.

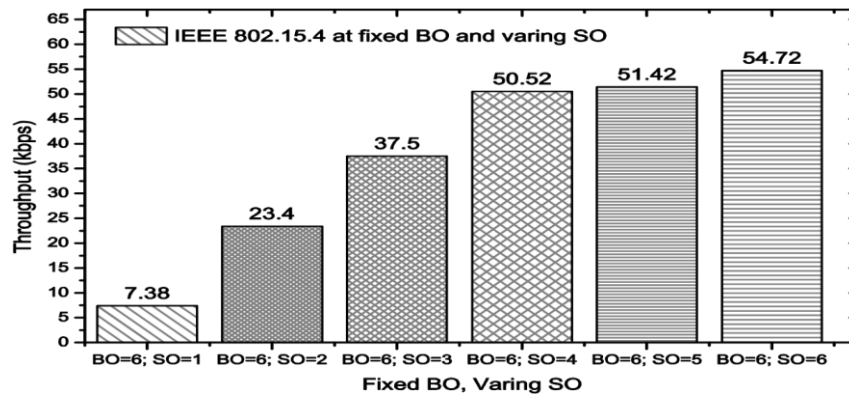


Figure 6. Average Network Throughput under Fixed BO and SO

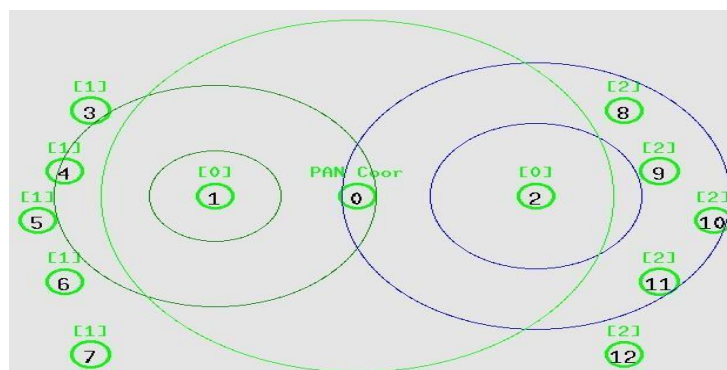


Figure 7. Simulation Scenario

Table 2. Simulation Parameters

Parameters	Values
Simulation time	1000 sec
Frequency band	2.4 GHz
Data rate (kbps)	28, 56, 84, 112, 140 and 224
IFQ length	50
Traffic type	CBR
Packet size	70 B
Radio range	15 m
Number of Clusters	2
Number of Source nodes	10
Number of total nodes	13
Transmit Mode	12.3 Ma
Receive mode	14 Ma
Beacon Order	6
Super-frame order	2, 3, 4, and 5
Sleep mode	0.2 μ A
Idle mode	0.5 Ma
Initial energy	4 joules

V.I. Throughput

Figure 8 shows the throughput of IEEE 802.15.4 and the proposed algorithm. Network load is controlled by turning ON and OFF the source nodes of clusters. So, when the simulation begins, network traffic gradually increases by turning cluster source nodes ON, due to which

the throughput of the proposed algorithm and IEEE 802.15.4 increases gradually. The proposed algorithm provides better results than the standard 802.15.4 because the proposed algorithm dynamically adjusts SO based on data rate and the number of cluster source nodes. The performance of the standard is better for

BO = 6, SO = 5, because the duty cycle is increased, thus more CAP duration is available

for traffic. Table 2 shows the throughput results at different data rates.

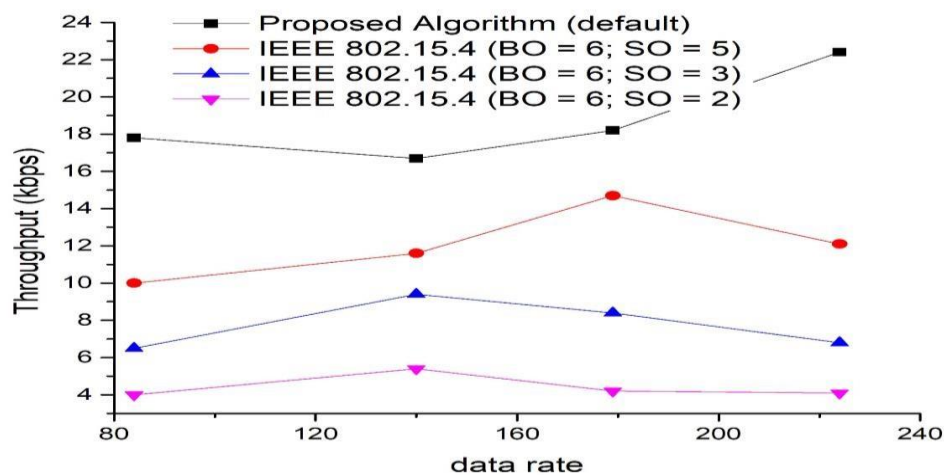


Figure 8. The throughput of the proposed algorithm and IEEE 802.15.4

V.II. End-to-End Delay

Figure 9 shows the end-to-end delay at the PAN coordinator for IEEE 802.15.4 and the proposed algorithm. Standard using fixed SO values; as a result, it produces a higher end-to-end delay in

our scenario. The standard uses SO = 2, 3, 5, and BO=6. The proposed algorithm performs better because of dynamic SO adjustment and achieves lower latency, stability, and cost-effectiveness.

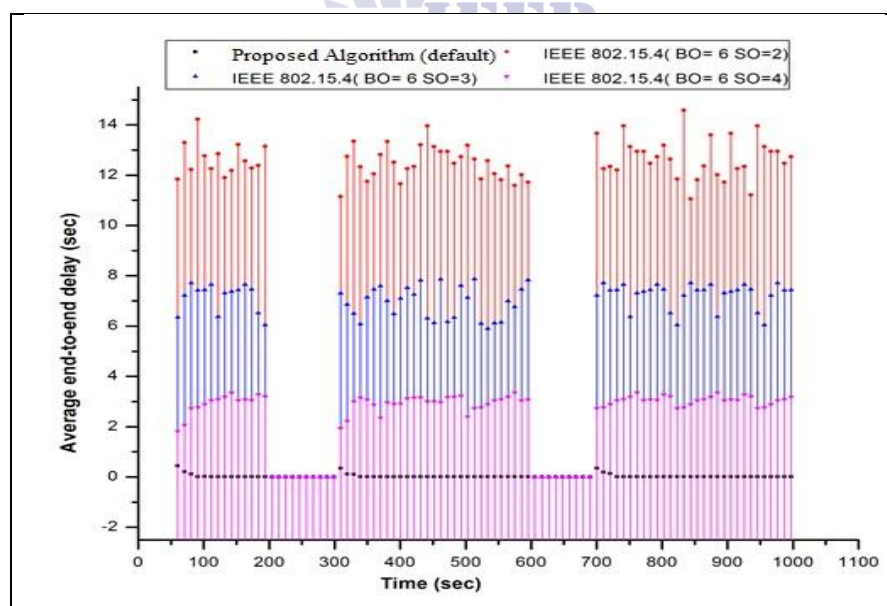


Figure 9. End-to-End Delay of IEEE 802.15.4 and the Proposed Algorithm

V.III. Packet Receive Ratio

Packet Delivery Ratio (PDR) is the quantitative relationship of total packets sent by source nodes to the total packets received at the PAN coordinator. Figure 10 shows the average packet delivery ratio at the PAN coordinator.

Performance of the standard at BO = 6, SO = 2, 3, 4, and 5 is compared with the proposed algorithm, proposed algorithm dynamically adjusts the SO parameter, and its performance is better than the standard. Performance of the proposed algorithm and the standard algorithm

in terms of packet delivery ratio at different data rates is summarized in Table 2.

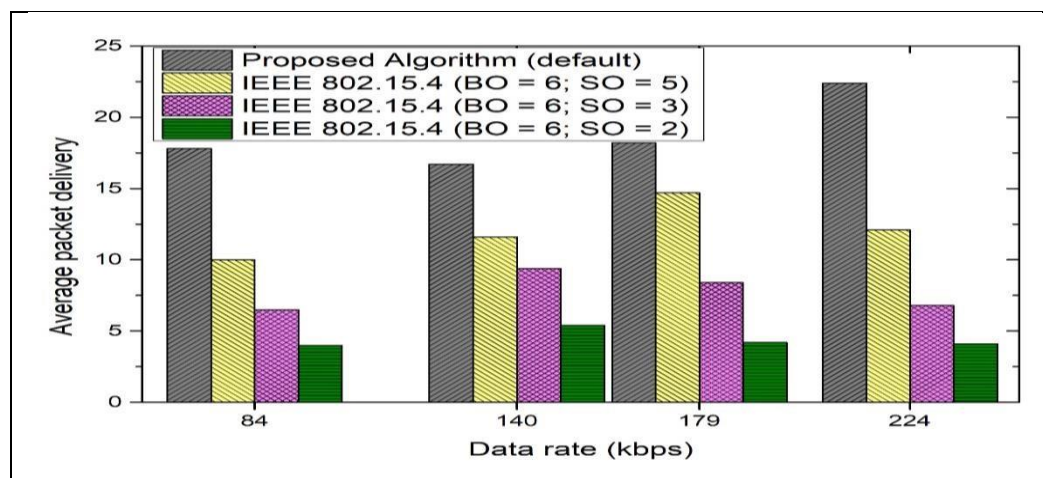


Figure 10. Packet delivery ratio

VI. CONCLUSION

In the existing work, the dynamic adjustment of the super-frame is not targeted to enhance throughput and decrease end-to-end latency for cluster tree topology-based networks. In this work, we proposed an algorithm that adjusts the SO parameter dynamically to fulfill the requirements of applications in terms of throughput, latency, and PDR. The IEEE 802.15.4 standard is modified in the proposed algorithm, and dynamic adjustment of SO is implied at the PAN coordinator to meet application requirements. In the proposed algorithm, after the expiry of every BI, the estimated SO is calculated, and the SO of cluster heads is adjusted during data transmission. Simulation results demonstrate that the proposed algorithm performs better than the standard IEEE 802.15.4. In the future, this work can lead to adjusting both BO and SO parameters dynamically in cluster tree-based wireless personal area networks.

DECLARATION

We hereby declare that the work presented in this research paper is our original work and has not been submitted, in whole or in part, for publication or assessment in any other journal or conference. All sources of information used in this study have been duly acknowledged, and any ideas or data taken from other works have been properly cited.

COMPETING INTERESTS

The authors declare that they have no competing financial or non-financial interests that could have influenced the work reported in this manuscript.

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AUTHORS CONTRIBUTION

WL and JL participated in the technical review and manuscript revision. MA and SJ performed the core algorithm development and simulation analysis. JK participated in the initial draft preparation. All authors conceived the idea and designed the study, and all authors read and approved the final manuscript.

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