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DYNAMIC SUPER FRAME ADJUSTMENT FOR DELAY MITIGATION IN IEEE 802.15.4 CLUSTER-TREE WIRELESS SENSOR NETWORKS

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Article Info

Abstract

The standard IEEE 802.15.4 is the most popular standard covering the use of Wireless Personal Area Networks (WPANs), which is mostly aimed at helping to deliver low data rates, low power Utilization, and affordable communication. Despite these, the standard has a fixed duty-cycle scheme that can cause latency and low throughput, especially in cluster-tree and multi-hop network architectures. To overcome these constraints, a dynamic delay-mitigation algorithm is proposed in this paper to adaptively adjust the super frame structure. The suggested method allows the PAN coordinator to make a Super frame Order (SO) of cluster heads dynamically, depending on the real-time network parameters such as the ratio of packet reception, traffic load, data rate, number of active nodes, and delay observed. Much simulation evidence indicates that the proposed scheme leads to significantly better network performance than the standard IEEE 802.15.4 protocol in terms of end-to-end interruption, packet delivery ratio, and throughput.

Keywords: *Wireless Sensor Networks; IEEE 802.15.4; Cluster Tree Topology; Super frame Order; Duty Cycle; Delay Mitigation.*

1. Introduction

Wireless Sensor Networks (WSNs) are composed of a large number of low-power sensor nodes capable of sensing environmental conditions, performing local data processing, and transmitting information wirelessly. Sensor nodes are commonly deployed for the measurement of physical parameters such as temperature, humidity, atmospheric pressure, and wind speed. WSNs may be deployed in infrastructure-based or ad hoc formats depending on the deployment conditions. Infrastructure-based WSNs make use of comparatively fixed nodes in order to create a communication backbone, unlike ad hoc WSNs, where multi-hop communications without centralized control are used. Their numerous applications in real-life scenarios like smart agriculture, environmental monitoring, automation in industries, and healthcare, which are facilitated by their adaptability, low cost of deployment, and their capability to be used in harsh or remote conditions, are known to make ad hoc WSNs popular in real-life applications [6]. Although those have advantages, ad hoc WSNs have severe issues in managing resources and providing Quality of Service (QoS), especially in dynamic and heterogeneous traffic conditions. Limitations of energy, computing, and memory also make it even more difficult to provide reliable data within a delay constraint. In order to overcome these weaknesses, hybrid and hierarchical architectures have been introduced, but most importantly, cluster-based networks. Such architectures use clusters of sensor nodes, with Cluster Heads (CHs) receiving, aggregating, and pushing data of other member nodes to a sink or Personal Area Network (PAN) coordinator. Such a hierarchical structure helps in increasing scalability, minimizing redundancy of transmissions, and extending network lifetime [1].

A sensor node is typically composed of sensing units, a microcontroller, memory, a power source, and a radio transceiver. Nonetheless, the capabilities of nodes cannot be homogeneous; Full Function Devices (FFDs) may be more powerful in processing power and energy resources, but Reduced Function Devices (RFDs) are low-capability end nodes. This heterogeneity dictates the need to have energy-efficient and delay-aware communication mechanisms that can guarantee consistent performance and scalability [2]. Based on the IEEE 802.15.4 standard, the ZigBee Alliance can be used to support various network topologies such as star, mesh, and cluster tree. Star topology is easy to implement and insignificantly scalable, whereas mesh topology is strong at the expense of being more complex and consuming more energy. Cluster tree topology leverages the advantages of hierarchical structuring while providing improved scalability, which is why it is especially appropriate when using a large-scale WSN [3], [4]. Because the network topology has a direct impact on the latency, throughput, and energy efficiency, adaptive communication strategies are needed. Though IEEE 802.15.4 is specified to be used with low-power, its fixed-duty cycle design can tend to exhibit poor performance with variable traffic loads, which has led to the development of adaptive super frame mechanisms figure 1.

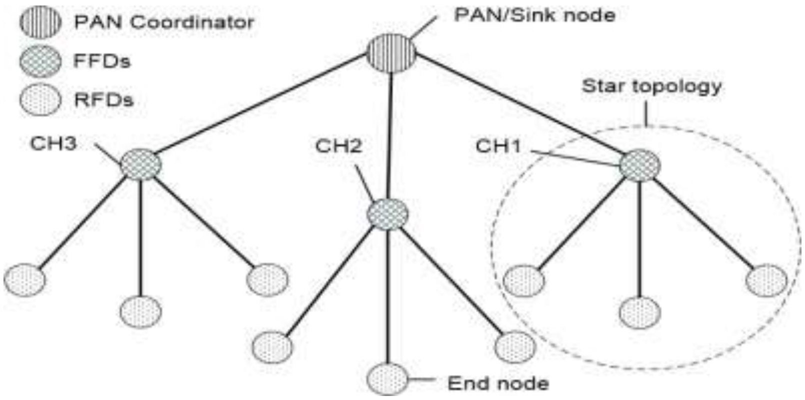


Figure 1. Network topologies of IEEE 802.15.4

2. Overview of IEEE 802.15.4

IEEE 802.15.4 is a defined protocol, Low-Rate Wireless Personal Area Networks (LR-WPANs), whose applications are focused on low data rates, low power usage, and low-cost communication systems. IEEE 802.15.4 is unlike other wireless technologies, like Wi-Fi and Bluetooth, in that it is much more energy efficient, making it especially appropriate to sensor-based, sensor-savvy settings [5], [6]. The specification specifies two base protocol layers: the Physical (PHY) layer, which controls radio transmission and reception, and the Medium Access Control (MAC) layer, which controls access to the protocol channel, channel synchronization, frame transmission, and acknowledgment protocols. The standard allows both beacon-enabled and non-beacon-enabled operation modes, where in the former case, PAN coordinators and cluster heads periodically broadcast beacon frames to coordinate the nodes and define the structure of the super frame, which consists of an active period, which is divided into a Contention Access Period (CAP) and optional Contention-Free Period (CFP). The Beacon Order (BO) and Super frame Order (SO) govern the duty cycle, although fixed settings of the two parameters can cause latency and throughput impairment during dynamic traffic performance [7]. In addition, IEEE 802.15.4 supports cluster tree topologies, with the PAN coordinator being the root node in the cluster, cluster heads (Full Function Devices, FFDs) transmitting data between the end node based on Reduced Function Devices (RFDs), and communication flowing to the sink. This hierarchical model is commonly used in smart houses, medical surveillance, and industrial robots due to its scalability and structured model of communication [8, 9]. However, the rigidity of fixed super frame parameters underscores the necessity for adaptive MAC-layer mechanisms capable of accommodating dynamic traffic demands.

3. Related Work

There have been long research studies in enhancing the performance of the IEEE 802.15.4-based networks in terms of delay, throughput, energy efficiency, and the network lifetime. Early research mainly concentrated on star topologies, but more recent research concentrates on cluster tree topologies to facilitate the use of large-scale and heterogeneous WSN deployments [10, 11]. There are a number of strategies that dynamically tune the Super frame Order according to the length of the queue or the intensity of the traffic, or the remaining energy to optimize network performance [11, 12]. In other words, researchers focus on improving their quality of service through maximizing the Contention Access Period (CAP) and the Guaranteed Time Slot (GTS) allocation that will minimize the transmission delay on time-sensitive data [13]. The CSMA/CA mechanisms, such as adaptive backoff mechanisms, have also been suggested to be improved in order to reduce the number of collisions and retransmissions [14]. Association schemes and energy-aware clustering have proved to be useful in enhancing scalability and increasing network lifetime [15], [16]. Artificial intelligence and techniques based on learning, including reinforcement learning and metaheuristic optimization, have also been investigated more recently to increase the energy efficiency and scheduling in WSNs [17, 18]. But these techniques tend to impose computational load that is inappropriate to the computational capabilities of low-capability hardware. Although such developments have taken place, a paucity of studies has been done on the dynamic super frame adaptation in non-homogeneous IEEE 802.15.4 cluster tree networks that consist of both FFDs and RFDs.

4. Simulation Results and Analysis

The simulation of the proposed system is assessed on the Network Simulator 2 (NS2), where the simulated environment is made of multiple clusters, whereby each cluster has a number of sensor nodes and a cluster head. The active and passive phases of work, as well as synchronization between nodes, are implemented by the periodic delivery of beacon frames. Two simulation scenarios are considered: a situation where a fixed Beacon Order (BO) is used in different Super frame Order (SO) values. Key metrics are used to do performance evaluation, such as network throughput, end-to-end delay, and packet delivery ratio (PDR). Findings indicate that the latency and packet-loss of static SO configurations are higher when the traffic is high, compared to the proposed Dynamic MAC-layer Configuration Technique (DMCT) algorithm, which dynamically tunes the SO parameter to meet the best throughput, low latency, and high ratio of packet delivery compared to the default IEEE 802.15.4 protocol. Moreover, the dynamic quality of the DMCT algorithm itself leads to better network stability under a variety of traffic conditions.

5. PROPOSED ALGORITHM

5.1 Delay Mitigation in Cluster Tree. The scheme is designed as an algorithm intended to use a tree-based topology in accordance with IEEE 802.15.4 specifications. The subsequent sections of this paper elaborate on the key components and operational details of the proposed approach. The algorithm operates by following a structured sequence of steps, which are described in detail in the following discussion. The suggested algorithm is executed through the following steps. Initially, the expected duration is calculated using the nodes' traffic flows and their respective data transmission rates. These parameters are mathematically formulated and evaluated using Equations (5), (6), and (7), respectively.

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

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

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

The expected order of super-frame, referred to as ExpSDCHn, equation (5), calculates the expected order of super-frame given that the number of active nodes in communication is known as TXdev, the amount of packet transmission of each node as Devpkt, and the size of each packet is known as Suspect. Eq. (6) determines the duration of transmission of one packet between a source and a destination. The transmission delay of a single packet, including ACK transmission, is computed internally. (7), (Ramjet & Shin, 2023). The proposed algorithm further introduces performance metrics, including throughput and received ratio, which are detailed in the following sections based on Eq. (8).

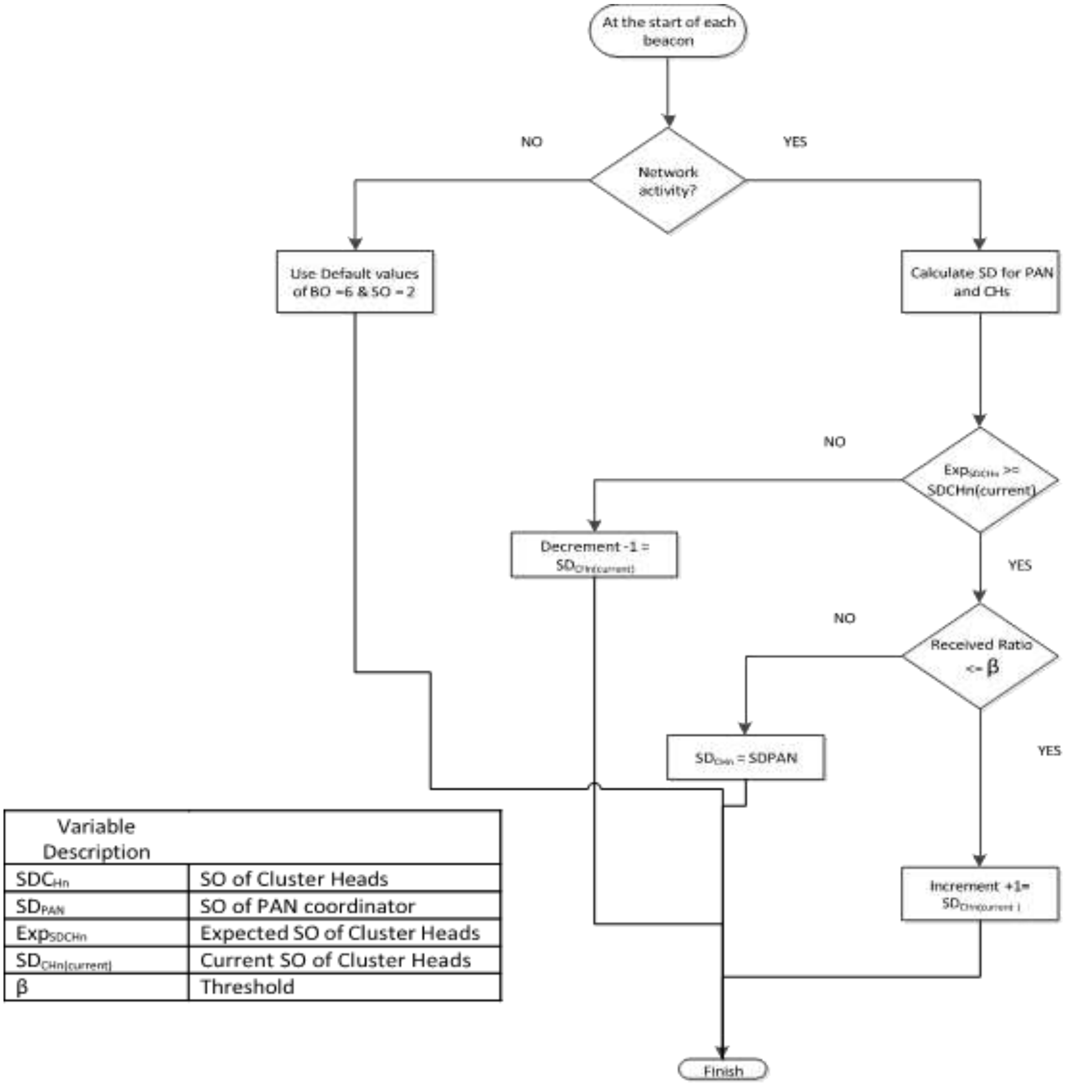
$$Thr_{network} = \frac{(R_{pkts} * Size_{pkt} * 8)}{1000} \quad (8)$$

Equation (8) defines the network throughput, Thrnetwork, in terms of the aggregate number of packets R_{pktsR}_Rpkts, packet size $Size_{pkt}$ (bits), and a simulation time of 1000 s.

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

\

Equation (9) is employed to estimate the received ratio (RR) at each cluster head as well as at the PAN coordinator. In this formulation, RpktsR_{pkts}Rpkts denotes the cumulative count of packets successfully received at the corresponding cluster head or PAN coordinator. The term CHnpktsCHn_{pkts} CHnpkts denotes the entire amount of source nodes within a given cluster, while TotpktsTot_{pkts}Totpkts refers to the aggregate number of packets generated across all clusters figure 2.



Variable Description	
SDC_{Hn}	SO of Cluster Heads
SD_{PAN}	SO of PAN coordinator
Exp_{SDCHn}	Expected SO of Cluster Heads
$SD_{CHn(current)}$	Current SO of Cluster Heads
β	Threshold

Figure .2 Dataflow

The received ratio is computed at the end of each Beacon Interval (BI), as described in the previous section, and is subsequently compared with SOcurSO_{cur}SOcur, which represents the current Superframe Order of the coordinators. If the calculated received ratio is greater than SOcurSO_{cur}SOcur, it is further evaluated against a predefined threshold. When the received ratio exceeds this threshold, the beacon is transmitted in its original form. This demonstrates that the network meets the required performance criteria. Otherwise, the Superframe Order is incremented by one in order to enhance throughput and to lessen the end-to-end delay. On the other hand, when the ratio obtained is less than SOcurSO cur SOcur, the Superframe Order is reduced by one. The network will use the default parameter values in cases where the network activity cannot be detected.

6. SIMULATION RESULTS AND ANALYSIS

6.1 Simulation Setup

The proposed algorithm is tested with the help of the Network Simulator 2 (NS2) and compared with the IEEE 802.15.4 standard. The measures of performance on which the evaluation is done are three major performance parameters, such as the delivery ratio of packets, network throughput, and end-to-end latency.

6.2 Network Topology and Communication Protocol

The network architecture consists of two different clusters having a Personal Area Network (PAN) coordinator at the central location of the geometric center, acting as the main coordinating body between the clusters. The operational protocol is a hierarchical beacon-based communication structure. When starting every super frame, the PAN coordinator starts network synchronization by sending beacon frames, which are received by the assigned cluster heads. When each cluster head receives the beacon of the PAN coordinator, they all then transmit their own beacon frames to their member nodes within their cluster domain. These beacon frames carry with them important timing information, which outlines the super frame structure, i.e., specifying active and inactive periods. Depending on the time information, the individual nodes automatically plan their duty cycles in the best way to minimize power consumption. In the active phase, nodes are involved in data reception and data transmission in the Contention Access Period (CAP), where they use a contention access scheme called CSMA-CA. On the other hand, in the inactive phase, nodes enter into the low-power sleep status, hence realizing a large amount of energy savings and the general lifetime of network operation. This beacon-based hierarchy architecture provides temporal synchronous operation throughout the network and also provides energy-efficient operation of the architecture through coordinated sleep schedules.

6.3Network Configuration

The hierarchical network architecture is set up in the simulation environment and was composed of a single (1) PAN coordinator, five (5) cluster heads, and five (5) transmitting nodes. These network entities are geographically separated over a specific radius of coverage of 50 meters and are all combined to create a cluster tree topology, as shown in Figure 3. As a measure to make the simulation results as accurate and realistic as possible, the energy consumption model, as applied to ATMEGA motes, has been put in place and applied to all the end devices in the network.

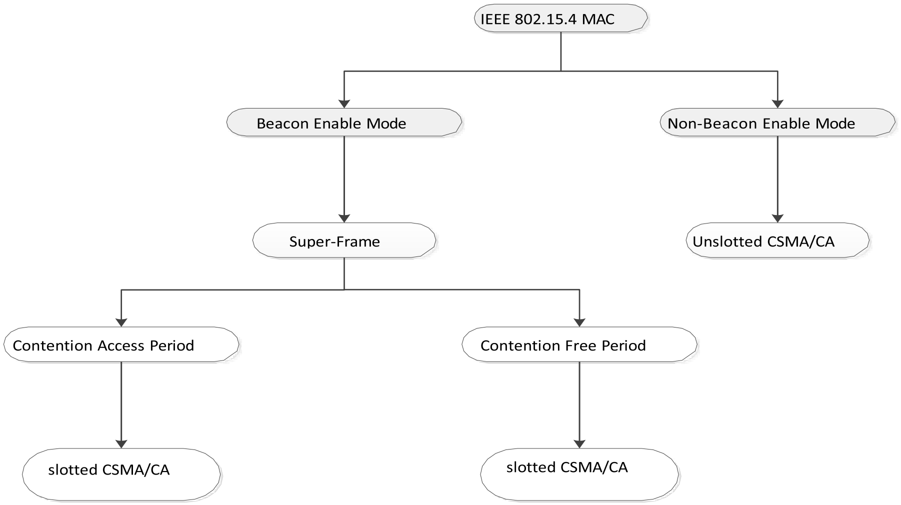


Figure 3. Operational Modes of IEEE 802.15.4

This power model truly represents the power consumption patterns at the transmission, receiving, and sleep modes. All the parameters of a simulation, such as network structure, physical layer, MAC layer, and energy model parameters, are thoroughly specified in Table 1.

TABLE 1 SIMULATION PARAMETERS

Parameter	**Value**
Number of PAN Coordinators	1
Number of Cluster Heads	5
Number of Transmitting Nodes	5
Coverage Area	50 meters
Energy Model	ATMEL mote
Data Rate per End Device	20 kbps
Total Network Capacity	100 kbps

6.4 Simulation Scenarios

The effects of a fixed Super frame Order (SO) and a fixed static Beacon Order (BO) on the network performance of a cluster-tree topology are studied in the simulation study. Two different situations were used to carry out this assessment.

Scenario 1: BO at the PAN coordinator is fixed to 6, whereas SO will be between 2 and 6. The cluster head coordinators are kept at the constant values of BO = 3 and SO = 2.

Scenario 2: BO at the PAN coordinator is constant, and SO takes values of 2-6. The cluster head coordinators work using constant values of BO = 4 and SO = 3.

On the way to statistical stability, every experiment was conducted 10 times, and the average results were noted.

6.5 Performance Evaluation

The output of the proposed system would be measured regarding four main performance measures, which are network throughput, network lifetime, packet drop rate, and communication latency.

6.6 Network Throughput

Fig. 5 shows the total throughput at the PAN coordinator, which assumes a total network capacity of 100 kbps, and each end device has a data rate of 20 kbps. In order to avoid node disassociation with respect to synchronization, BO is held at 6, at which the higher values of BO have been noted to result in node disconnection. The parameter used is Super frame Order (SO), which is not less than 2 to 6, to examine the performance of the network in terms of communication with super frame duration. The findings prove that the configuration that has BO = 6, SO = 6 has the highest throughput of 54.72 kbps of the overall capacity of 100 kbps. This high performance is realized due to the longer Super frame Duration (SD) that gives more time to the transmission of data. The findings prove that the configuration that has BO = 6, SO = 6 has the highest throughput of 54.72 kbps of the overall capacity of 100 kbps. This high performance is realized due to the longer Super frame Duration (SD) that gives more time to the transmission of data figure 3.

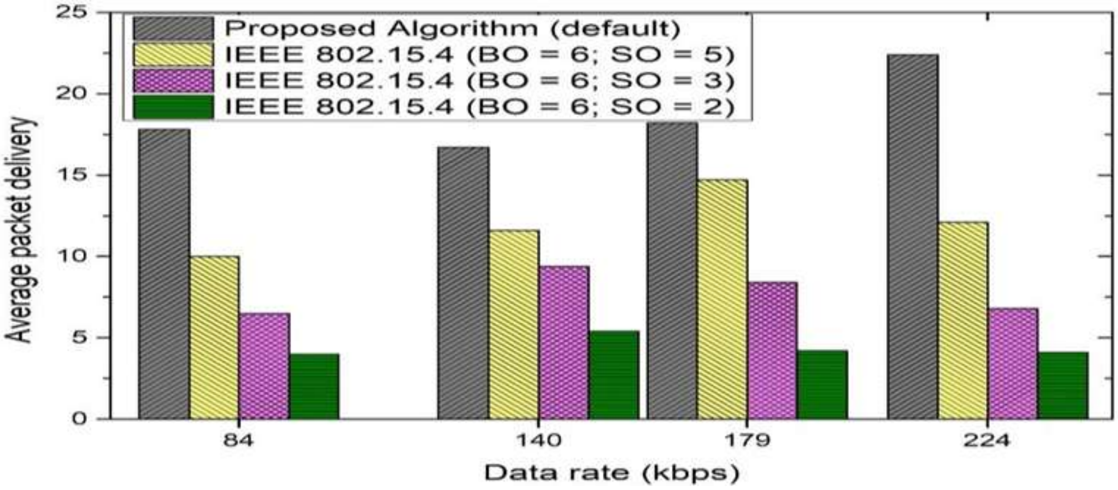


Figure 4. Packet delivery ratio

6.7 Network Lifetime

The network lifetime will be measured on the energy consumption analysis of the end devices and the PAN coordinator. The energy measurements will be completed, and detailed results will be provided.

6.7 Packet Delivery Ratio (PDR)

A ratio between the received and the sent packets is calculated to compute the packet delivery ratio. The findings are arrived at after doing the simulations in the packet transmission.

6.8 End-to-End Delay

To determine the network latency, end-to-end delay will be measured, which is the duration of time that has elapsed from when the packet is produced by the source node until it is received by the destination node. Reporting of the results will be made after latency measurements have been made figure 5.

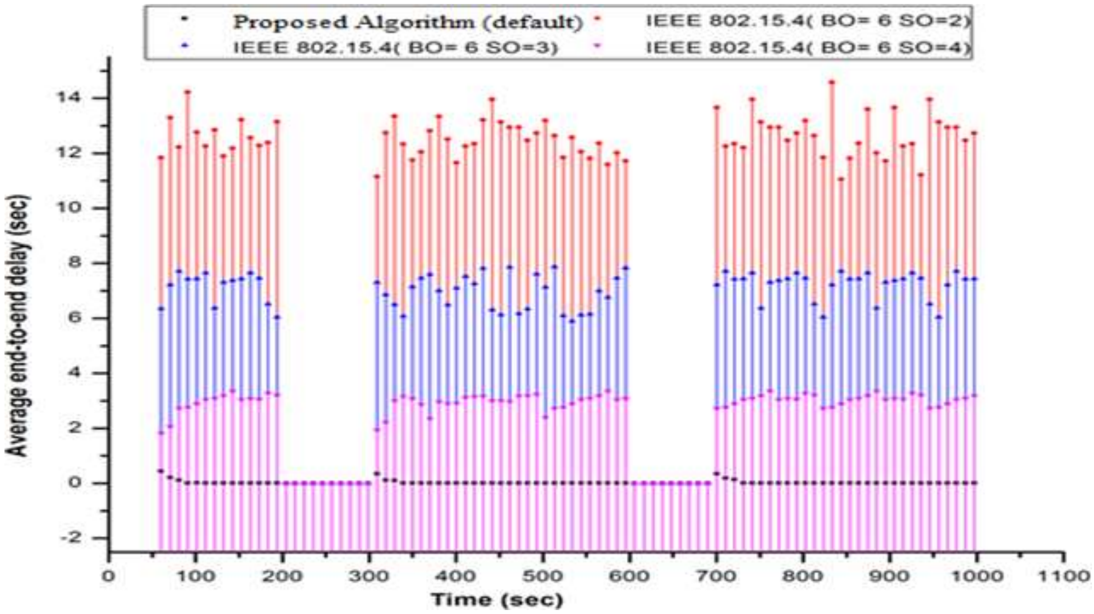


Figure 5. End-to-End Delay Comparison between IEEE 802.15.4 and the Proposed Algorithm

6.9 Discussion

The results of the simulation suggest that the choice of BO and SO parameters has a heavy influence on network performance on IEEE 802.15.4 cluster tree networks. The best configuration (BO = 6, SO = 6) is the best performer in terms of throughput as it utilizes the highest active transmission time and ensures network synchronization. Nonetheless, trade-offs among throughput, energy consumption, and latency have to be taken into consideration depending on the application requirements.

Table 2. Simulation parameter

Parameter	**Description**
Simulation Duration	100 seconds
Communication Range	50 meters
Operating Frequency	2.4 GHz
Beacon Order at PAN (BO_PAN)	6
Super frame Order at PAN (SO_PAN)	2–6
Beacon Order at Cluster Heads (BO_CH)	6
Super frame Order at Cluster Heads (SO_CH)	2–6
Traffic Pattern	Constant Bit Rate (CBR)
Interface Queue Length	50 packets
Packet Size	60 bytes
Number of PAN Coordinators	1
Number of Cluster Heads (Coordinators)	5
Number of Transmitting Nodes	5
Data Rate per Node	20 kbps
Energy Consumption Model	ATMEL Mote Model [12]
Simulation Duration	100 seconds

Figure 6 depicts the throughput of the PAN coordinator of the network with a total capacity of 100 kbps (20 kbps per end device). The Beacon Order (BO) is set at 6 in this analysis to eliminate the problem of synchronization, since an increase in the Beacon Order (BO) value has been observed to elicit the problem of node disassociation. In turn, the value of BO is held to be 6 during the experiment. Conversely, the Super frame Order (SO) is adjusted with a variety of 2 to 5 to determine its effect on the network performance. According to the results, the throughput is maximum at the configuration of BO = 6 and SO =6 due to the much longer Super frame Duration (SD) that achieves 54.72 kbps out of 100 kbps.

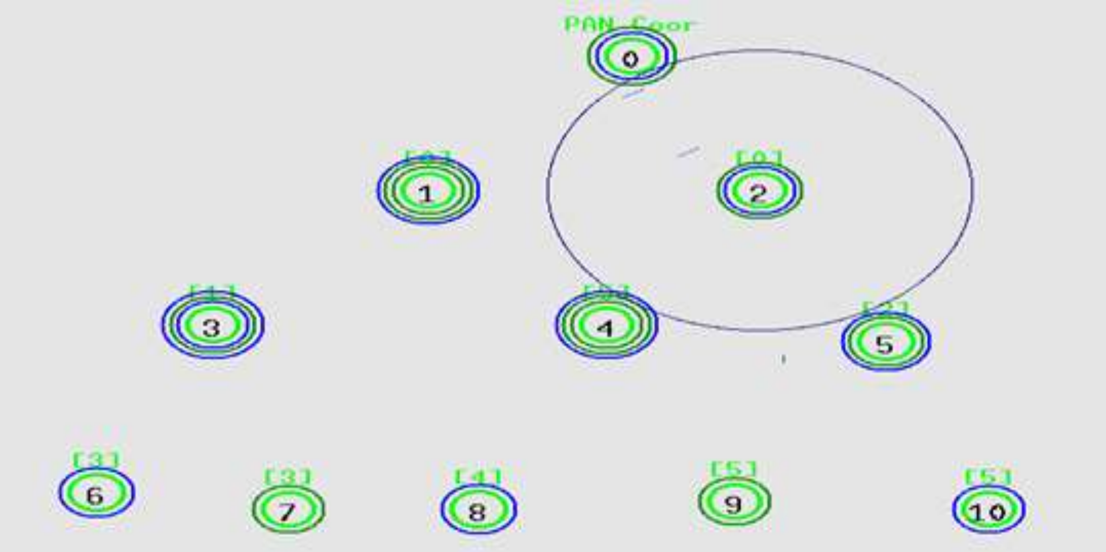


Figure 6. Fixed network environment

6.10 Throughput

Figure 7 illustrates the throughput measured at the PAN coordinator for the entire network capacity of 100 kbps (20 kbps per end device). To mitigate synchronization issues, the Beacon Order (BO) is maintained at 6, as higher BO values can result in node disassociation. The Super frame Order (SO) varies from 2 to 5 to evaluate its effect on network performance. As shown in the figure, the configuration with BO = 6 and SO = 6 achieves the highest throughput, delivering 54.72 kbps out of the available 100 kbps, due to the extended Super frame Duration (SD).

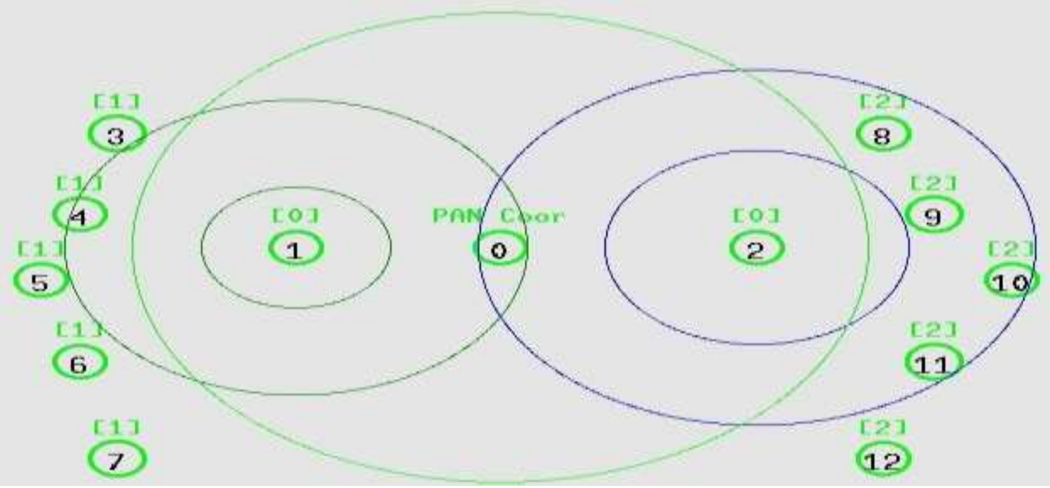


Figure 7. Network Simulation Scenario

6.11 End-to-End Delay

Figure 8 illustrates the throughput of the PAN coordinator at the rate of 100kbps in total (20kbps per end device). Synchronization problems in this figure have made the value of BO constant at 6. The increased values of BO lead to the dissociation of nodes; hence, to prevent this scenario, BO is fixed to 6. SO, on the other hand, varied between 2 and 5 to monitor the network performance. It is apparent in the figure that the throughput at BO=6, SO=6 is the optimal because the SD duration offers 54.72kbps out of 100kpbs

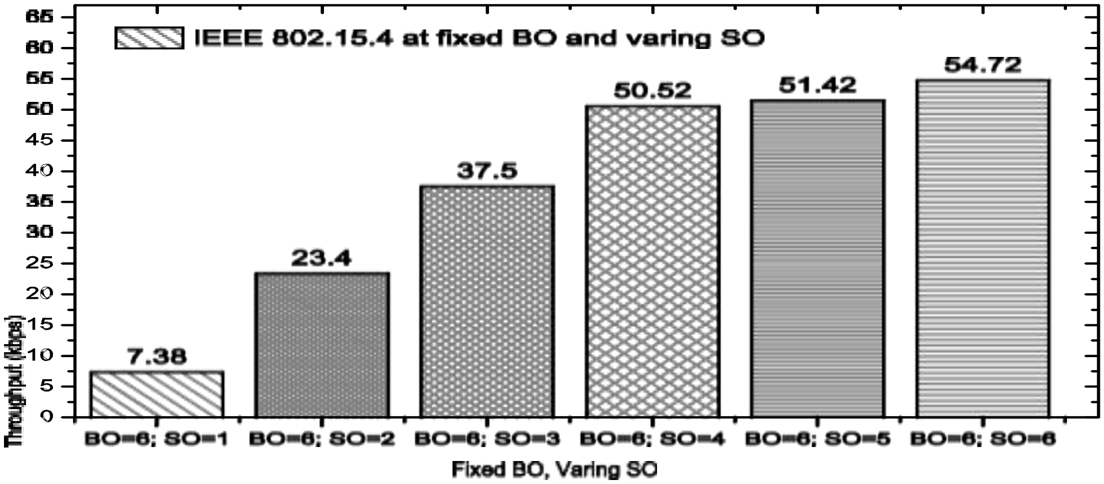


Figure 8. Average Network Throughput with Fixed Beacon Order (BO) and Super frame Order (SO).

6.12 Packet Receive Ratio

The Packet Delivery Ratio (PDR) quantitatively represents the relationship between the total number of packets transmitted by the source nodes and those successfully received at the PAN coordinator. Figure 9 illustrates the average PDR observed at the PAN coordinator. The performance of the IEEE 802.15.4 standard protocol with a fixed Beacon Order (BO) of 6 and Super frame Order (SO) values of 2, 3, 4, and 5 is compared with that of the proposed algorithm, in which the SO parameter is dynamically adjusted. The results indicate that the proposed algorithm outperforms the standard protocol. A summary of the packet delivery performance across various data rates for both the standard and proposed algorithms is provided in Table 2.

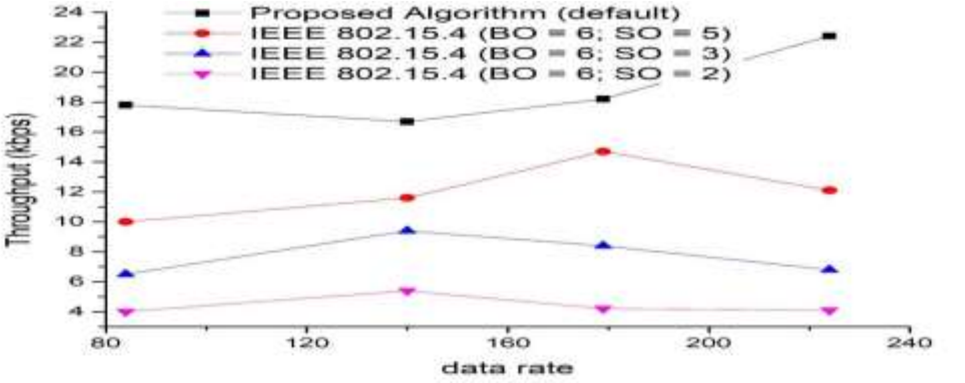


Figure 9. Comparison of Throughput between the Proposed Algorithm and IEEE 802.15.4 Standard

Table 2. Simulation parameter

Parameter	**Configured Value**
Simulation duration	1000 seconds
Operating frequency band	2.4 GHz
Supported data rates	28, 56, 84, 112, 140, and 224 kbps
Interface queue (IFQ) size	50 packets
Traffic model	Constant Bit Rate (CBR)
Payload size	70 bytes
Communication range	15 meters
Number of clusters	2
Active source nodes	10
Total number of nodes	13
Transmission current	12.3 mA
Reception current	14 mA
Beacon Order (BO)	6
Super frame Order (SO)	2, 3, 4, and 5
Sleep current consumption	0.2 µA
Idle current consumption	0.5 mA

7. Conclusion and Future Work

This paper presents a dynamic super frame adjustment mechanism for IEEE 802.15.4-based Wireless Sensor Networks employing a cluster-tree topology. The proposed design enables the adaptive modification of the Super frame Order (SO) based on real-time traffic conditions and network performance requirements, while maintaining compliance with the IEEE 802.15.4 MAC standard. The proposed solution preserves interoperability and simplicity of deployment in existing WSN infrastructures by not altering the underlying protocol structure in any way. The functionality of the suggested Delay Mitigation in Cluster Tree (DMCT) algorithm was confirmed with the help of broad simulations. The results of the performance evaluation indicate that the adaptive SO mechanism is much better than the standard static super frame configuration. Specifically, the algorithm suggested will result in a visible decrease in end-to-end packet transmission delay, as well as an increased throughput and a higher ratio of the packets delivered. Such enhancements can be explained by the capabilities of the algorithm to enhance or shrink the active task of the super frame based on the demand of the traffic and, thus, relieve the network overload under high-load conditions and save energy when the network is not busy. Additionally, the adaptive nature of the suggested algorithm positively affects the overall network efficiency by ensuring a trade-off between the latency and the energy consumption is balanced. The decentralization aspect of the adjusting process enables the cluster heads to respond locally to the local traffic changes, which is particularly useful in large-scale and heterogeneous WSN configurations. This means that the proposed scheme enhances the scalability and reliability of the network without adding extra overhead and computation resources to sensor nodes with resource constraints. Although these advances have been made, there is still room to optimize more. In future research, efforts will be directed toward the coordinated and dynamic adjustment of both Beacon Order (BO) and Super frame Order (SO). It is anticipated that such a two-parameter adaptation strategy will offer more detailed control over the duty cycle, and thus allow better control of synchronization overhead, energy consumption, and delay. Also, future studies will examine how the suggested approach can perform in the conditions of large-scale deployments with highly dynamic traffic, mobility, and diverse application demands. Incorporation of the learning or predictive features to predict traffic variations can also improve flexibility and resiliency in Wireless Sensor Networks of the next generation.

References

1. Zhang, S., & Liu, X. (2025). Enhancing wireless sensor network functionality using reinforcement learning and metaheuristic energy-efficient strategies. *Scientific Reports, 15*(1), 30758.
2. Wen, K., & Zhao, H. (2025). Scheduling algorithms for power-constrained wireless sensor networks considering service priority and delay constraints. *IET Science, Measurement & Technology, 19*(1), e70008.
3. Li, S., Yuan, Y., & Pan, G. (2024). SS-MAC protocol for IEEE 802.15.4-based cluster tree WSNs. *Electronics, 13*(13), 2520.
4. Du, W., Navarro, D., & Mieyeville, F. (2015). Performance evaluation of IEEE 802.15.4 sensor networks in industrial environments. *International Journal of Communication Systems, 28*(10), 1657–1674. https://doi.org/10.1002/dac.2756
5. Oveisi, S., Gholamrezaie, F., Qajari, N., Moein, M. S., & Goodarzi, M. (2024). Artificial intelligence-based systems: Evaluation, standards, and methodologies. *Advances in Standards & Applied Sciences, 2*(2), 4–29.
6. Adu-Manu, K. S., Engmann, F., Sarfo-Kantanka, G., Baiden, G. E., & Dulemordzi, B. A. (2022). Wireless sensor network protocols and security challenges for environmental monitoring: A survey. *Journal of Sensors, 2022*(1), 1628537.
7. Latif, U., Farhad, A., & Zafar, N. A. (2016). Smart duty cycle adaptation for low-rate wireless personal area networks. In *2016 19th International Multi-Topic Conference (INMIC)* (pp. 1–6). IEEE. https://doi.org/10.1109/INMIC.2016.7840117
8. Siddik, M. A., Hasi, M., Nitu, J. A., Sarker, S., Sultana, N., & Ali, E. (2022). Modified IEEE 802.15.6 MAC scheme for enhancing wireless body area network performance in e-health applications. *arXiv preprint arXiv:2209.00247*.
9. Salles, N., Krommenacker, N., Lecuire, V., & Cedex, F.-V. (2008). Performance study of IEEE 802.15.4 in industrial maintenance applications. *Proceedings, 4–9*.
10. Bhatti, M. N., Kumar, P., Parveen, R., Sherbaz, M., & Sheikh, U. (2023). Improving lifetime and real-time support in IEEE 802.15.4-based wireless personal area networks. *Mehran University Research Journal of Engineering & Technology, 42*(2), 133–141.
11. Dadhich, K., & Kataria, D. (2022, December). Impact of channel slot time on IEEE 802.15.6-based medical body area network performance. In *International Conference on Advanced Network Technologies and Intelligent Computing* (pp. 376–385). Cham: Springer Nature Switzerland.
12. Kim, J. W., Kim, J., & Lee, J. (2023). Efficient cluster tree topology operation and routing for IEEE 802.15. 4-based smart grid networks. *Sensors*, *23*(13), 5950.
13. Li, S., Yuan, Y., & Pan, G. (2024). An Efficient SS-MAC Protocol for IEEE 802.15. 4-Based WSNs of Cluster Tree Topology. *Electronics*, *13*(13), 2520.
14. Akbar, M. S., Hussain, Z., Sheng, M., & Shankaran, R. (2022). Wireless body area sensor networks: Survey of MAC and routing protocols for patient monitoring under IEEE 802.15. 4 and IEEE 802.15. 6. *Sensors*, *22*(21), 8279.
15. Anand, S., Choudhury, N., Ojha, T., Hazarika, A., & Dave, J. (2024, December). Improving Network Efficiency in Clustered Tree Topology through PSO Optimization in IEEE 802.15. 4-DSME-based IoT Networks. In *2024 IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS)* (pp. 1-6). IEEE.
16. Alawadhi, A., Almogahed, A., Ahmad, R. B., Barraood, S. O., Al-Jamili, O., & Adawy, M. I. (2024, August). Improving Packet Delivery Ratio through Duty Cycle Control in Heterogeneous Visible Light Communication. In *2024 4th International Conference on Emerging Smart Technologies and Applications (eSmarTA)* (pp. 1-5). IEEE.

17. Alawadhi, Abdulwadood, Abdullah Almogahed, Bushra Abdullah Shtayt, Samera Obaid Barraood, Mohammad Ibrahim Adawy, and Omar Al-Jamili. "The Role of Blockchain Integration in Edge Computing for 6G IoT: Challenges and Applications." In *2024 7th International Conference on Internet Applications, Protocols, and Services (NETAPPS)*, pp. 1-6. IEEE, 2024.
18. Reddy, K. S., Choudhury, N., Hazarika, A., & Ojha, T. (2025, March). DyHSARW: A Dynamic GTS Scheduling Mechanism for Large IEEE 802.15. 4 DSME-Based IoT Networks. In *2025 IEEE Wireless Communications and Networking Conference (WCNC)* (pp. 1-6). IEEE.
19. Raja, G. B. (2024). Green Communication Technologies and Protocols. In *Artificial Intelligence Techniques for Sustainable Development* (pp. 86-113). CRC Press.
20. Meyer, F. (2023). *Adaptive multi-hop networks for industrial applications with dynamically changing traffic* (Doctoral dissertation).