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Priority-Oriented Adaptive GTS Allocation in IEEE 802.15.4 WSNs

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ABSTRACT: The IEEE 802.15.4 standard is known to be widely utilized in Wireless Sensor Networks (WSNs) for their time sensitive applications. However, the default contention-based MAC operations suffer from delays, resource wastage, etc. with heterogeneous dynamic traffic. Though some Guaranteed Time Slots (GTS) are offered, they make little to no use of adaptable allocation GTS strategies to improve the real-time operation of the network. This paper presents GTS Adaptive Priority-Based GTS Allocation Algorithm for the beacon enabled mode of IEEE 802.15.4. It allows better MAC-layer scheduling to improve differentiation and service facilitation for time-sensitive data. The performance of the algorithm was assessed through comparative analysis against the standard CSMA-CA operation in MATLAB simulations with the same topology and traffic distribution. Simulation results prove the predicted GTS allocation algorithm to significantly optimize the network performance across multiple performance metrics. The CSMA-CA algorithm provides data transmission rates of 29.9 and 40.0 (lower and upper bounds respectively). Proposed algorithm offers these same metrics at 92.6 and 94.3, respectively. The method proposed shows low packet loss irrespective of the communication range. On the contrary, CSMA-CA suffers from high packet loss under high traffic and poor channel conditions. With the results confirming that adaptive and priority-aware GTS allocation is a mechanism that improves throughput, reliability, and determinism at the MAC layer, it means that IEEE 802.15.4 networks can be utilized for real-time and high-throughput applications in WSNs.

Keywords: IEEE 802.15.4, Wireless Sensor Networks, Guaranteed Time Slot, Adaptive Algorithm, Priority-Based Scheduling, CSMA-CA, Data Throughput, Low Latency

1. INTRODUCTION

Wireless Sensor Networks (WSNs) enable automated sensing, monitoring, and data exchange in domains such as healthcare, environmental observation, and industrial automation. As a result, WSNs have become a key component of contemporary communication systems. For short-range and low-data-rate wireless communication, the IEEE 802.15.4 standard has received significant attention due to its support for low-complexity and energy-constrained devices, rather than an inherent requirement of low power operation [1,2]. The standard serves as the physical and MAC-layer foundation for several upper-layer protocols, including ZigBee and 6LoWPAN, and has played a crucial role in the development of the Internet of Things (IoT) ecosystem. There remain inefficiencies in MAC-layer scheduling, as well as efficiency, scalability (high node density), and adaptability (dynamic changes in traffic patterns). These issues persist despite the widespread implementation of the 802.15.4 standard. The standard includes latency sensitive traffic [3,4], that has contention free access and time bounded channel access, through mechanisms known as Guaranteed Time Slots (GTS). While allocating GTS can lower contention during the contention free periods, GTS approaches are static and do not avoid collisions in the frame structure, resulting in unavailable resources, increased access delays, and channel unavailability. Additonally, in Wireless Sensor Networks (WSNs), the traffic demands are more heterogeneous, and therefore the inequalities of channel access opportunities among nodes are more apparent [5].

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Consequently, a significant body of research has focused on adaptive GTS-based frameworks that incorporate traffic awareness, prioritization, and scheduling intelligence sometimes informed by cross-layer information to improve fairness, responsiveness, and overall network performance [6,7].

More recent studies also focus on developing AI-based methods including optimization techniques to address communication efficiency and energy management in WSNs· For example, bio-inspired algorithms and reinforcement learning techniques have been used to optimize routing, clustering, and power control, which improves a sensor network's life and flexibility in the sensor network's power control· Similarly, low-latency, reliable communication infrastructures with adaptive MAC scheduling are central to IoT applications in smart agriculture, healthcare monitoring, and environmental sensing [8]. These applications illustrate how next-generation IoT systems demand novel, flexible, and intelligent mechanisms at the MAC layer· The proposed method attempts to bridge the gap caused by traditional systems designed for static environments, and to provide real-time service in adaptive dynamic wireless systems by merging adaptive scheduling concepts with the deterministic access of guaranteed time slots [9].

2. RELATED WORK

The IEEE 802.15.4 standard constitutes the foundational MAC protocol for low-rate wireless sensor networks composed of resource-constrained devices.

Contention-based and contention-free channel access is achieved through the use of CSMA-CA and Guaranteed Time Slot (GTS) mechanisms. Early efforts, such as those of Khan et al., concentrated on the MAC structure and adaptive construction for GNSS-enabled WSNs and reported positive consequences on bandwidth and latency [1,2]. Subsequent studies targeted the coexistence of GTS layers and the macro performance of the IEEE 802.15.4 (and enhancements, such as IEEE 802.15.4e). In this area, Li et al. and Choudhury et al. concentrated on the scheduling and coexistence of GTS frameworks and beyond, pioneering adaptive scheduling frameworks centered on fairness and throughput with respect to time-sensitive traffic [6][10]. These studies provided a direct impetus for the time-sensitive research focus on dynamic, traffic-responsive allocation of GTS. In the case of DSME-based networks, for example, Kang et al. introduced a method for enhancing the responsiveness of scheduling through traffic-responsive determination of GTS intervals [3]. Meyer et al. focused on evaluating the impact of multiple packet transmissions within a single GTS on the optimization of throughput [11,12]. Moreover, in constrained communications networks, and primarily networks of higher density, the GTS allocation policies of the IEEE 802.15.4-DSME have been modified to enhance the scalability and reliability of such networks [7][13]. These studies show that large-scale sensor networks optimization through adaptive slot assignment is possible by controlling the level of contention, latency, and time wasted. Access control and the quality of service (QoS) have been studied in the case of time-sensitive applications of IEEE 802.15.4. For the industrial domain and in real-time communication applications, frameworks for equitable slot allocation and reduction of transmission times have been proposed for time GTS allocation that is fair and for the reduction of issued GTS allocations [14]. In the case of critical applications, such as in defense and homeland security, the inclusion of traffic differentiation and adaptive control of GTS has been shown to enhance the responsiveness and throughput of GTS [15]. But in the case of studies in dynamic slot assignment, most of the control models used are still dynamic and semi-dynamic, thus considerably limiting the models ability to respond to the rapidly changing traffic patterns [16].

This demonstrates that adaptive GTS strategies are needed where both allocation and slot time vary with dynamically changing traffic. In addition to the enhancements made to the MAC layer, the extension of network lifetime and the automation in the control of deployed municipal WSNs have been explored in a number of studies. Aside from simple heuristics, candidate solutions for the optimization of cluster-head selection and routing have been implemented using bio-inspired algorithms like grey wolf optimization, particle swarm optimization and genetic algorithms [17-21]. By using adaptive decision-making, these techniques prove to be effective [22]. However, they tend to be used above the MAC layer, thus, do not improve time-slot allocation more directly. More recent studies have implemented various machine learning techniques, including reinforcement learning, for the optimization of communication. There has been application of federated learning for the optimization of WSNs with IoT, and blockchain technology has been used for secure data collection. These techniques improve adaptability and security, but do not capture the full potential of the GTS mechanism in IEEE 802.15.4 networks, particularly the lack of a cooperation degree in the underlying network. Although there has been a plethora of studies on the optimization of the MAC layer, the energy-efficient routing of WSNs, and the intelligent scheduling, there are still a number of widely adopted solutions that have not addressed problems such as static slot allocation, low adaptability to variations in traffic, and inadequate prioritization of nodes [23].

Although prior studies have addressed frame structure improvements, fairness, and dynamic GTS mechanisms [1-3][7][13], they remain inadequate in handling heterogeneous traffic loads and urgent communication requirements. Similarly, AI- and optimization-based approaches often focus on clustering and routing rather than real-time MAC scheduling [17][20]. To address these limitations, this research proposes a novel Adaptive Priority-Based Guaranteed Time Slot Allocation algorithm.

3. METHODOLOGY

This paper will analyze the first proposed enhancement specifically targeting the reliability and efficiency of Wireless Sensor Networks (WSNs) adhering to the IEEE 802.15.4 standard. We will examine the Adaptive Priority-Based Guaranteed Time Slot (GTS) Allocation Algorithm. The proposed algorithm allocates GTS and makes modifications to the WSNs GTS in response to the MAC (Medium Access Control) layer performance, the priority and the traffic of the sensor nodes. The proposed algorithm is designed to work with the IEEE802.15.4 MAC beacon-enabled mode [24]. The architecture of the algorithm is based on analytical modeling of network traffic and queue dynamics. The primary focus of the proposed algorithm is adaptive GTS allocation, in response to the traffic flowing. A proposed solution is assessed using a comprehensive simulation environment designed on the MATLAB platform [25,26]. The performance of the adaptive GTS based scheduling mechanism is measured against the default CSMA-CA which is the standard protocol to ensure a fair and a protocol compliant comparison. The throughput, access delay, and efficiency of GTS utilization are the primary metrics in evaluating performance of GTS allocation [27].

3.1 ALGORITHM DESIGN

The Adaptive Priority-Based Guaranteed Time Slot (GTS) Allocation Mechanism aims to Enhancing IEEE 802·15·4-based Wireless Sensor Networks (WSNs) [28]. It focuses on the beacon-enabled mode of the standard where communication is organized in frame structure which comprise active and inactive periods· During the active periods, the algorithm dynamically adjusts time slot assignments during the Contention-Free Period (CFP) based on the transmission requests and priorities of the eligible active nodes. Every node describes their traffic patterns, including the size and rate of packets and the urgency, which enables the Personal Area Network (PAN) coordinator to assess the node’s transmission needs. For each node, the algorithm computes a priority index which determines the node’s weight based on application criticality and traffic volume· Nodes with relatively higher values are assigned GTSs that are longer and are positioned earlier in the frame structure, thereby guaranteeing timely and collision-free transmissions. Remaining low-priority nodes are assigned short, postponed slots to share, thereby ensuring fairness and neural network scheduling· Low-priority nodes share shorter, deferred slots to maintain fairness and prolonged utilization of bandwidth· The algorithm’s self-scheduling is based on predefined network-adaptive criteria like node density and the rate of data generation.

The designed framework incorporates feedback-based slot reassignment to improve throughput, decrease packet loss, and enhance latency performance compared to the standard Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) protocol. This feedback-based slot reassignment showcases the adaptability and scalability characteristics necessary for the seamless integration and dependable real-time communication across different high-demand and low-demand Wireless Sensor Networks (WSNs) settings· To assess the performance of the adaptive GTS allocation method, a model was developed to explain how the traffic load, transmission rate, and slot utilization interrelate· Let N denote the active sensor nodes in the network, each creating data packets of size LP bits at a frequency of R packets per second.

The proposed mathematical model provides a baseline for analyzing the performance of an intelligent scalable MAC layer scheduling algorithm design for IEEE 802·15·4 based wireless sensor networks, guiding its actual implementation in detail parameters selection.

3.2 SIMULATION SETUP AND IMPLEMENTATION FRAMEWORK

To assess the effectiveness of the proposed Adaptive Priority-Based Guaranteed Time Slot (APG) allocation algorithm, a dedicated simulation framework was implemented using MATLAB R2023a. The primary objective of this simulation is to evaluate the performance of the APG scheme in comparison with the conventional Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) protocol under the same network conditions.

The simulation model emulates the operation of a wireless sensor network (WSN) compliant with the IEEE 802.15.4 standard in beacon-enabled mode. Realistic parameters of transmission and network behavior modeling are used to the establish the most probable deployment scenarios. Discrete modeling of communication systems and events (without proprietary wireless toolboxes) is best carried out in MATLAB. Therefore, the focus is directed to GTS (Guaranteed Time Slots) functions within the core MAC (Medium Access Control) layer, GTS allocation, packet transmission, collision, and acknowledgment functions. The network is designed as a star topology, with one central PAN (Personal Area Network) coordinator and ten sensor nodes distributed in a uniform circular formation around the central node. To ensure fairness in GTS (Guaranteed Time Slot) communication, as well as in the functions of CSMA-CA (Carrier Sense Multiple Access with Collision Avoidance), all nodes in the simulation opened all the roles to ensure that all the nodes had equal opportunities to directly participate in all the functions. All of the given simulation parameters are aligned with the given standard of the IEEE 802.15.4 and the constraining conditions of a wireless sensor network, which are given in Table 1.

Table 1 **List of key parameters**

Parameter	Value	Description
Number of nodes	10	Total number of end devices in the network
Simulation iterations	10,000	Number of repeated runs for statistical convergence
GTS length	4 symbols	Duration of each guaranteed time slot
CSMA contention slots	4	Number of backoff slots during contention access
GTS priority levels	1–3	Node priority, where 3 is the highest
Data rate	250 kbps	IEEE 802·15·4 nominal PHY rate
Packet size	120 bytes	Average packet payload size
Channel frequency	2·4 GHz	Operating frequency band
Topology type	Star	One PAN coordinator and multiple end devices
Simulation tool	MATLAB R2023a	Custom script implementation

During the initialization phase, all simulation parameters, including the number of nodes, slot duration, contention window size, and iteration limits, were configured according to IEEE 802·15·4 specifications· Nodes were randomly distributed within a defined transmission range around the PAN coordinator to emulate realistic wireless network deployment scenarios·

In the GTS prioritization and scheduling phase, each node was assigned a priority level (P_i) based on the simulated data generation rate and traffic volume· The coordinator then applied an adaptive scheduling model to calculate the GTS duration (D_i) for each node using the demand function D_i=f(L_i,R_i,P_i), where L_i denotes the packet size and R_i the data rate· In the transmission and channel access phase, nodes assigned GTS transmitted their data in contention-free slots, while other nodes used the CSMA-CA protocol to compete for access during the contention time period (CAP)· All collision and retransmission events were recorded to assess protocol reliability and channel performance· During the performance monitoring phase, key performance metrics such as total packets received, throughput per node, packet loss rate (PLR), and average latency were measured for each iteration· The data visualization and analysis phase involved processing the collected data using MATLAB's plotting and analysis tools to generate performance comparison graphs highlighting the differences in throughput, packet loss, and latency between the adaptive GTS and CSMA-CA protocols under varying traffic loads and inter-node distances· Each simulation scenario was run repeatedly under identical conditions to ensure statistical consistency·

Mean and variance analysis was performed to verify the stability and reliability of the results· To ensure the rigorousness of the experiment, I controlled the random seed initialization to allow for natural stochastic variability in node locations and communication behavior while maintaining repeatability· Throughout the simulation process, I followed the IEEE 802·15·4-2015 standard, which guarantees methodological correctness and the possibility of generalizing the results·

4. RESULTS AND DISCUSSION

The Adaptive Priority-Based Algorithm was tested alongside the classical CSMA/CA Algorithm on the 802.15.4 based MAC Layer using MATLAB R2023. The simulations ran fairly relatively to each other since the MAC and Physical Layer parameters were the same on the 802.15.4-2015 Standard. The simulation configured bottom-up wireless sensor networks (WSNs) in transmitter-on mode. All sensor nodes were configured to communicate with the Personal Area Network (PAN) Coordinator on a 2.4 GHz shared channel. The bottom layer of the configured WSN contained 10 sensor nodes in a circular formation with the PAN coordinator at the center. The nodes of the simulation were configured to operate under the same parameters with the only exception being the communication mode that was selected. The communication mode was alternated between GTS-based access and balanced CSMA-CA operation. The simulation console was used to monitor and control the simulation. The WSN configuration was designed to be as realistic as possible. The design of the simulation focused on the selected key parameters and the positions configured to Table 2. The WSN configuration was simulated a total of 10,000 times to achieve convergence and to minimize the effect of randomness.

The main parameters are presented in Table 2, and the parameter values comply with the IEEE 802.15.4-2015 standard, which describes the interplay of the physical and MAC layers in the best possible way. The simulation scenarios were designed to replicate real-world conditions in a WSN as closely as possible and involved beacon-enabled scenarios, and random node distributions with mixed (i.e., both contention and contention-free) access. Each scenario was run 10,000 times with identical conditions to ensure a sufficient level of statistical confidence. The extensive repetition of the stochastic processes minimized the effects of random initialization and the averaged performance metrics of the system (throughput, packet loss ratio, and latency) meaningfully captured the steady-state performance of the system.

Table 2 Simulation parameters for IEEE 802·15·4-based performance evaluation·

Parameter	Value	Description
Number of Nodes	10	Total end devices in the network
Iterations	10,000	Simulation repetitions for convergence
GTS Length	4 symbols	Duration of each guaranteed time slot
CSMA-CA Slots	4	Number of contention slots
GTS Priority	Random (1–3)	3 = highest priority, 1 = lowest

The results in Figure 1 show that in every testing case, the suggested GTS-focused algorithm has throughput that is much higher than the CSMA-CA Protocol. The main contributor to this is GTS's lossless pre-determined transmission bursts. The CSMA-CA method suffers from issues of lost packets as well as wasted lost time waiting for packets to be lost and time spent on retransmission. The CSMA-CA method is based on randomized channel questioning, waits an arbitrary time, and suffers delay. The A GTS adaptive scheduler is designed to sidestep these by employing node prioritization and transmission time slot allocation into tiers for each time slot. A Reduction in data segmentation minimizes access contention and enhances the utilization of the channel in a steady state. In GTS advantageous throughput is between 92,632 and 94,288 bps vs CSMA-CA 29,940 to 39,973 bps which gives us a 230% throughput enhancement utilization. This is clearly indicative of how much bandwidth is being utilized in the IEEE 802.15.4 networks. Additionally, high-priority nodes do not experience backoff delays, and therefore, due to deterministic slot assignment, also suffer less latency.

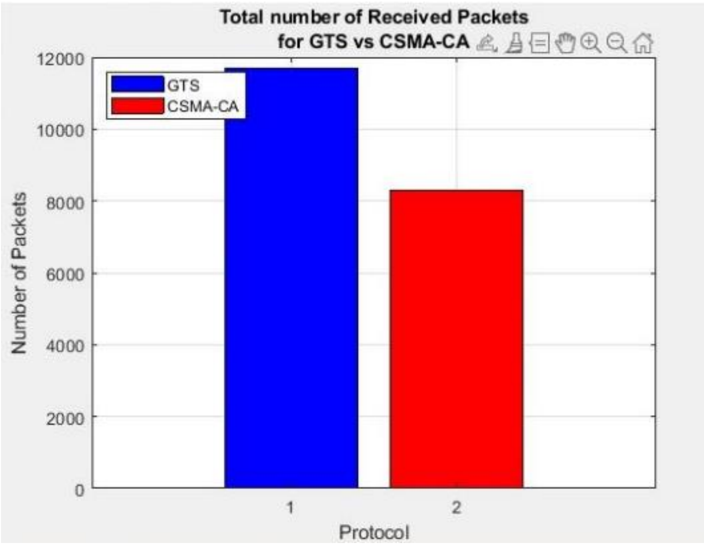

FIGURE 1 Total number of received packets for GTS and CSMA-CA

The datasets shown on Figure 2 detail the quantities of packets received and acknowledged by each node for both access methods. Figure 2 demonstrates that under Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) protocol, GTS-assigned nodes (even nodes) always receive and acknowledge more packets than the odd nodes. This is a more fundamental merit of absence of contention. GTS (without going into detail) implies that a node can only transmit during its allocated time slots. Thus, there is no contention, no lost packets, and GTS nodes simply have more packets delivered. GTS nodes achieve more consistent stable throughput across simulations because CSMA-CA nodes are suffering from lost packets due to the random access back off collisions. As a result of all these challenges, nodes assigned under CSMA-CA will be subjected to longer transmission delays and will deliver packets even less than they are expected to. It can be said that GTS is not even close to the same number of lost at the received packets which indicates more fairness. When there are guaranteed CF periods that do not overlap, a sign of the adaptability of the scheduling is the scheduling of nodes to these periods.

Nodes are assigned GTS based on a combination of node ranking and windowed traffic demand. The even spread of GTS (Guaranteed Time Slot) durations indicates that the scheduler is managing to avoid GTS starvation, which is the issue GTS starvation most for schedulers allocating resources in a set manner or using prioritization. In cases of varied traffic, GTS bias or allocation tends to lead to GTS starvation and the sub-optimal use of available bandwidth. In comparison, the results from the simulations seem to indicate that the suggested adaptable model for dynamic allocation of slots successfully responds to changing conditions. The dynamic adjustment of allocation and feedback intervals appears to optimize the use of contention-free periods (CFP) along with the contention access period (CAP), while the algorithm actively maintains access equity amongst all nodes. The adaptive mechanism provides high and low degrees of traffic reliability on GTS as well as predictable Quality of Service (QoS) assurance.

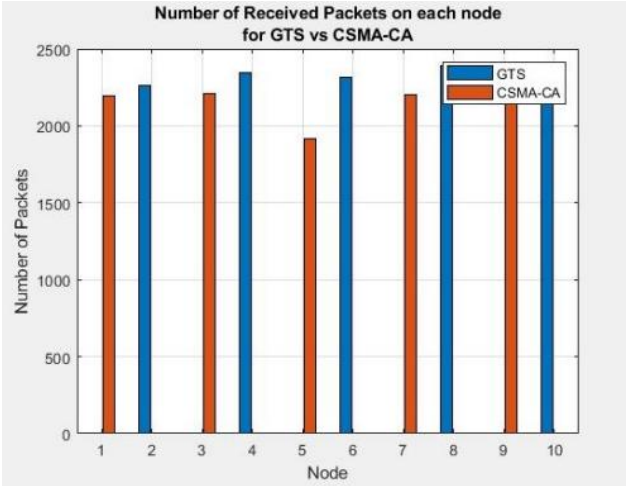

FIGURE 2 Number of received packets per node for GTS and CSMA-CA

Figure 3 shows per node data rates achieved and CSMA-CA rates achieved for the Adaptive Priority Based Guaranteed Time Slot GTS mechanism. Results achieved by the adaptive GTS node and CSMA-CA are the most efficient for transmission. Adaptive GTS nodes achieved values between 92,632 and 94,288 bps, whereas CSMA-CA nodes achieved rates of 29,940 and 39,973 bps. Adaptive scheduling is over 200% more efficient. GTS improves the performance and stability of the channel, as evidenced by the data. Performance improvements result from GTS channel access. GTS channel access is contention free and guarantee nodes scheduled time slots. They are scheduled ahead of time, which allows data to be transferred continuously and without interruption. In contrast, CSMA-CA is random, and there are backoff transmission delays. This is more problematic because of the delays. In high traffic situations, it decreases the flow of information and the data throughput. An Adaptive GTS scheduler mitigates the problem by dynamically assigning time slots based on the values of P_i and R_i. This is why it is so effective in reducing idleness and significantly reducing the chances of retransmission caused by collision or contention.

The almost same data streams among the GTS-enabled (even-numbered) nodes strengthens the consistency and fairness of the adaptive slot allocation strategy. Each nodes' assigned priority and the traffic demand determine the throughput, allowing high-priority nodes to receive sufficient bandwidth while low-priority nodes ensure fair access to the bandwidth. Moreover, the exclusion of exponential backoff delays and waiting time due to contention, results in more deterministic time-slot assignment, reducing latency, and supporting consistent and efficient operation of the network.

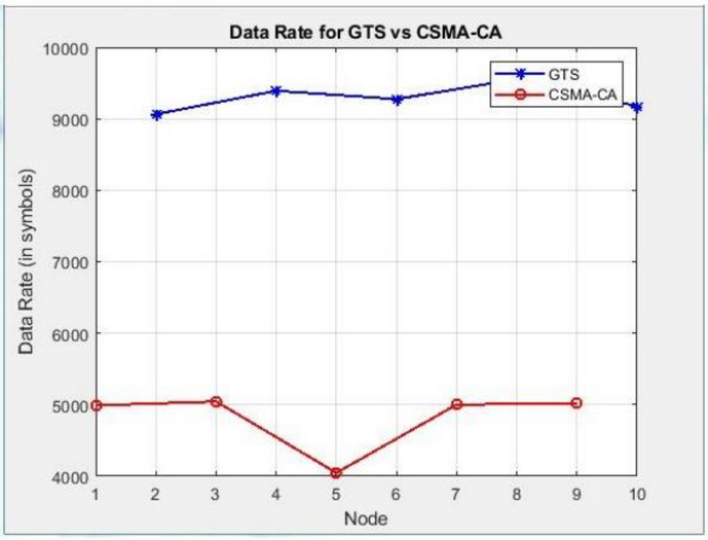

FIGURE 3 Data rate comparison between GTS and CSMA-CA protocols

The results from all the experiments indicate that the most pronounced effects of CSMA-CA's poor performance occur at the greatest distances from the coordinator. As the nodes distance themselves from the coordinator, the PLRs of the nodes at and beyond the 80-meter mark reach 100%, indicating that virtually none of the packets are being received. Certainly, the major causes of the high distance degradation and collisions include signal loss, longer range distance SNR and collision loss, and aggregated distance multiple access collisions. Contention for the channel on CSMA-CA occurs through a method to access the channel that includes a random back-off mechanism. The distance to which collision sensing occurs also varies randomly, resulting in many collisions. Ultimately there are numerous conditions of the channel that provide poor outcomes for access collisions that increase loss from the controller. All these conditions negatively impact network performance while increasing packet loss. In contrast, the GTS model, at all distances tested, loses packets at a lower rate than all other models. With the CSMA-CA protocol, the adaptive GTS algorithm has managed to improve the packet loss ratio to 30%, which indicates that other CSMA-CA packets are lost at 80 meters. This is better than the other systems because GTS access systems have lower contention and greater channel coverage. The network loss is also higher, since there are less allocated time slots at the intermediate channel access nodes. Additionally, the adaptive scheduling mechanism in GTS systems is designed to in real time adjust the time slots to streamline them based on the prioritize level of the nodes and the traffic. This gives high-prioritized nodes packet delivery, even in channels that suffer from distance degradation. There are some anomalies in both graphs, such as some cases of zero/negative packet loss, but these are from the inherent stochastic nature of the random distance and environmental modeling in MATLAB. Such variations arise naturally from random seed initialization and are statistically insignificant relative to the overall performance trend. Most importantly, the consistently lower and more stable packet loss curve achieved by the GTS-based approach, compared with CSMA-CA, confirms the robustness and effectiveness of the proposed adaptive mechanism in mitigating packet loss as transmission distance increases.

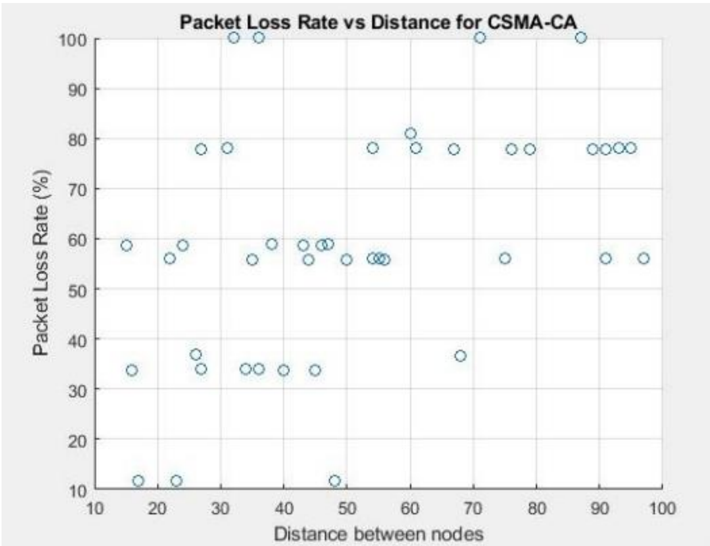

FIGURE 4 Packet loss percentage of CSMA-CA vs· node distance

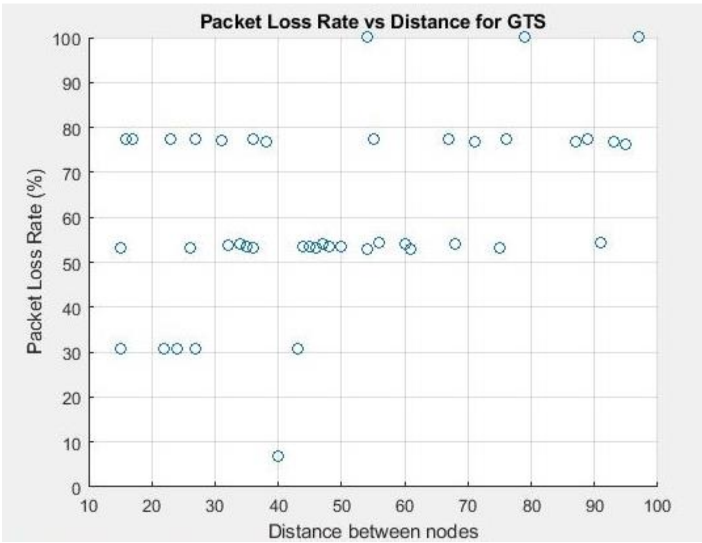

FIGURE 5 Packet loss percentage of GTS vs· node distance

The performance of the adaptive GTS model remains consistent, unlike CSMA-CA, which experiences severe performance penalties over longer distances due to contested and sharply dropped packets· The contention-free design guarantees each node a protected access window, thus ensuring stable performance despite increased cascading losses· Also, unlike the other designs, the proposed algorithm features a priority-driven adaptive scheduling that dynamically alters time slot assignment, which prevents excessive delay and buffer overflows in high-traffic nodes·

The results presented in Figures 3 through 5 illustrate that the proposed adaptive GTS mechanism improves throughput and reliability and predictability and fairness in the communication of IEEE 802·15·4-based wireless sensor networks· The algorithm's performance in terms of low packet loss and high, stable data rates, even at the extreme ranges of communication, confirms the algorithm's relevance to real-time and mission-critical applications in the IoT and WSN domains· In these applications, the need for deterministic energy-efficient and scalable communication is paramount· Within these contexts, the findings reinforce the proposition that adaptive GTS scheduling improves the underpinnings of adaptive GTS wireless communication in networks· It provides a basis for more intelligent, self-optimizing wireless networks·

The performance trends, paired with descriptive analysis, also lend further credence to the theoretical access characteristics with respect to contention and contention-free MAC protocols. With the distance in communication and load, losses in packets and reduced throughput in CSMA-CA are more likely because of the backoff, collisions, and the retransmission storms which resulted in wasted bandwidth because the channel was idle for long periods of time. The adaptive GTS mechanism, unlike the above, correlates with the MAC access theory in that it eliminates contention and delays by providing exclusive time slots which improves predictability of throughput. The adaptive GTS algorithm records an increase in average throughput of more than 200%, which corresponds to better channel utilization, and also less retransmission congestion. The GTS nodes also recorded less congestion in terms of throughput which was a sign of stable scheduling and suggests the variance was lower which best fulfills the QoS for real time systems. The 10,000 iterations per scenario, although there were no formal hypothesis tests or confidence intervals, resulted in a form of convergence, thus the average reported values are representative of the state of the network in steady state.

Undoubtedly, the loss of packets proportional to distance is consistent with our theorized expectations. In CSMA-CA, the longer the distance, the greater the potential errors in sensing and collisions, which result in the loss of packets over a given distance. In contrast, the GTS-based mechanism limits packet loss because, with access prediction, there is no dependence of zone contention to distance with respect to channel loss. Although there are lower-layer losses contributing to non-zero packet losses, the controlled growth of loss with the adaptive scheduling is commendable.

Overall, these findings indicate that the performance improvements achieved by the adaptive GTS algorithm are not incidental but are a direct consequence of its design principles. The results validate that adaptive, priority-driven, contention-free scheduling significantly enhances throughput determinism, reduces performance variability, and improves reliability compared to contention-based access—properties that are theoretically expected and practically essential for latency-sensitive IEEE 802.15.4 WSN applications.

5. CONCLUSIONS

The work reported has validated the role of the MAC layer adaptive and priority aware GTS scheduling as a means to improve the performance of IEEE 802.15.4 based LR-WPANs for time-sensitive and heterogeneous traffic. This work addressed the phenomenon of static GTS assignment, as well as the unpredictability of the CSMA-CA contention. The main contribution of this work is the design and development of the Adaptive Priority Based GTS Allocation Algorithm, which seeks to satisfy the demand for contention-free bandwidth and the traffic priority of a given node. The simulations based on the proposed adaptive GTS algorithm(s) were able to increase the MAC layer effective data rates from the 30-40 kbps rates which were attributed to the CSMA-CA to over 92 kbps which is attributed to the adaptive GTS scheduling. Additionally, the proposed algorithm improved the reliability and fairness of packet delivery and service to nodes with varying traffic and node requirements, avoiding the starvation and poor channel utilization. The notable benefits of GTS adaptiveness support the assertion that GTS mechanisms should be employed for service class applications with strict latency and throughput requirements. The study shows the promise of adaptive scheduling at the IEEE 802.15.4 MAC layer with the ability to help the WSNs to be used for real-time and mission-critical applications in industries such as automation, environmental monitoring, and healthcare sensing. These applications will also help improve the potential of WSNs for these uses. The proposed solution aligned with current IEEE 802.15.4 implementations and provides deterministic, contention free access service without any physical layer modifications. The proposed solution's algorithm, however, requires further development and validation on hardware test beds and large-scale implementations to assess scalability and energy efficiency. Additionally, considering the use of predictive and learning-based mechanisms, including reinforcement learning, can enhance the optimal allocation of time slots, especially during periods of high traffic. Extending the proposed framework to the IEEE 802.15.4e modes, especially the DSME and TSCH modes, offers potential in improving the precision and reliability of synchronization as well as the QoS support for next generation IoT and cyber-physical systems.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest

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