Q-Learning-Driven Enhancement of Slotted ALOHA in IEEE 802.15.4 WSNs

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***Abstract*— Given the proliferation of connected devices and the prioritization of real-time data acquisition across various scenarios, enhancing the energy efficiency within Wireless Sensor Networks (WSNs) is of paramount importance. This work has focused on the IEEE 802.15.4 standard and addresses existing medium access control protocols such as CSMA or Slotted ALOHA and proposes refinements in the Slotted ALOHA protocol through incorporating techniques like Binary Exponential Backoff (BEB) and Q-learning. These enhancements have demonstrated to be promising in terms of average delay reduction, energy efficiency and bolstered network throughput. As it facilitates more efficient energy management it constitutes a robust alternative to conventional CSMA in WSN MAC sub-layer protocols.**

Keywords*— *Wireless Sensor Networks, IEEE 802.15.4, Slotted ALOHA, Q-ALOHA, Binary Exponential Backoff, Medium Access Control Protocols, Latency, Energy Efficiency.

I. Introduction

In an epoch where the Internet of Things (IoT) is continuously redrawing the technological boundaries, one witnesses a transformative synergy of devices interacting within various aspects of daily life [1]. This evolution is not confined to theoretical horizons. In fact, it has prospered into a realistic reality covering a sophisticated network of devices, perpetually engaged in data collection and exchange, fuelling a cascade of innovations and practical applications [2]. Wireless Sensor Networks (WSNs) stand at the forefront of this technological innovation, playing a paramount role in facilitating real-time data acquisition across a multitude of machine-type scenarios. This spans from urban landscapes to convoluted industrial infrastructures [3]. Such networks support various applications, such as health monitoring and the realization of smart cities [4].

Forecasts propel the anticipation that by the year 2030, the global framework will be intricately interlinked with approximately 29 billion IoT devices. A significant faction of these devices will be seamlessly integrated into WSNs, playing quintessential roles in a multitude of critical applications [5]. Given their deployment in remote and hard-to-reach locations where maintenance, particularly battery replacement, is challenging, energy efficiency is pivotal in the sustainable operation and management of these networks [6].

Centrally situated in this framework are the Medium Access Control (MAC) protocols. Specifically, the IEEE 802.15.4 standard has been a vanguard, incorporating the CSMA protocol and underlining an exigency for low data rate communications coupled with a pronounced emphasis on energy efficiency [7], [8]. This study embarks on a meticulous examination and critical appraisal of alternatives to the CSMA protocol, spotlighting the Slotted ALOHA protocol. Noted for its operational simplicity and robust demeanour, Slotted ALOHA folds up as a promising contender to augment the realms of efficiency and performance in WSNs [9], [10].

Thus, the purpose of this research is to delve deeply into the Slotted ALOHA protocol, evaluating its practicability and adaptive prowess in the dynamic milieu of WSNs. The inquiry's focal point transcends the rudimentary assessment of Slotted ALOHA, venturing into an exploration of innovative enhancements and optimizations. This encompasses the combination of advanced strategies, such as Binary Exponential Backoff (BEB) and reinforcement learning (RL) paradigms, like Q-learning, aimed at amplifying the protocol's competencies. Such a nuanced approach is poised to significantly bolster the robustness and expansive applicability of WSN-based applications.

The remainder of this paper is organized as follows. Section II addresses the methodologies. Section III presents the simulation environment in detail, while Section IV presents results and discusses the lessons learned. Finally, conclusions are drawn in Section V, where suggestions for further work are also discussed.

II. Methodologies

In this section, we apply theoretical approaches and mathematical formulations for each protocol selected for our analysis. An extensive simulation exercise was conducted across various scenarios, aiming to dissect and understand the behaviour of each evaluated protocol. This methodological process allows for a detailed evaluation, fostering a comprehensive discussion on the observed outcomes and protocol performances.

A. Slotted ALOHA in WSNs

The Slotted ALOHA is a MAC protocol commonly used in WSNs, where time is divided into discrete intervals known as slots. Each node in the network transmits its data within a designated time slot. The probability of successful transmission for a node in each slot is represented by $P_s = G \cdot e^{-G}$, where G is the average transmission rate of the nodes. While Slotted ALOHA offers simplicity and efficiency in data transmission, its use in high-traffic environments may result in frequent collisions and underutilization of the communication channel. In such scenarios, more advanced alternatives, such as enhanced medium access protocols, are necessary to optimize performance. Additionally, below we describe other protocols that combine or hybridize with Slotted Aloha for IEEE 802.15.4 wireless sensor networks.

B. Slotted ALOHA with BEB

The integration of BEB into the Slotted ALOHA protocol is as a robust strategy that clearly enhances its functionality and performance within high-density environments. It orchestrates the timing of retransmissions following a collision, thereby cultivating an environment conducive to efficient data transmission [11]. Mathematically, the backoff window $W(i)$ subsequent to the i^{th} collision is articulated as:

$$W(i) = min(2^i * W_0, W_{max}) \quad (1)$$

Here, W_0 signifies the initial backoff window, and W_{max} represents the maximum allowable window. This technique's quintessence lies in its capacity to substantively diminish collision frequencies and reinforce channel efficiency. Consequently, this fosters a dynamic adaptability to network conditions, an essential enhancement for WSNs, ensuring equitable transmission opportunities across network nodes. Incorporating BEB seamlessly aligns with the energy conservation objectives, pivotal in the domain of WSNs, whilst showing that the Slotted ALOHA-BEB is a resilient, adaptable and auspicious way to enhance network communication reliability and efficiency [12]. Key benefits encompass:

Collision Reduction - By incorporating BEB's adaptive waiting mechanism, collisions are further mitigated due to the strategic spacing of retransmission attempts. The retransmissions are meticulously spaced, granting each node a clearer transmission window, thus fostering a more harmonious and less collision-prone communication environment.

Enhanced Channel Efficiency - An inherent by product of reduced collisions is the elevation of the channel's overall throughput and efficiency. This optimized channel performance paves the way for higher successful packet delivery rates, signifying a more fluid and effective communication process.

Dynamic Adaptability - The adaptability of Slotted ALOHA-BEB is notably dynamic, capable of intelligently acclimatizing to variable network conditions, exhibiting a robust resilience and a swift responsiveness to changing network statuses and demands.

Energy Efficiency - The protocol shows a conscientiousness towards energy consumption. Reduced collisions and the deliberate spacing of retransmissions signify fewer wasted energy resources, a critical conservation aspect in the realm of Wireless Sensor Networks (WSNs).

Fair Access - BEB provides a sense of fairness in transmission opportunities among the nodes. Its randomized backoff approach assures that no single node can monopolize the transmission channels, promoting a more balanced and equitable network operation.

By delving deeper into the optimized Slotted ALOHA-BEB protocol, we uncover a method laden with potential for augmenting the protocol resilience and performance.

C. Slotted ALOHA with Q-learning

The application of Q-learning to Slotted ALOHA protocols in WSNs, named as Q-ALOHA, is a harmonious amalgamation of RL techniques with traditional Medium Access Control (MAC) protocols [13]. This fusion aims to harness the decision-making processes, optimizing operations like data transmission timing, route selection, and energy management within the dynamic landscapes of WSNs [14]. Details are as follows:

Q-Learning Application in WSNs - Q-learning operates as a model-free RL algorithm, crucial for making optimized decisions in different scenarios within the WSNs. For instance, in a dynamic channel allocation setting, a sensor node might deploy Q-learning to discern the most opportune channel for data transmission, basing its decision on variables such as channel quality, prevailing interference, and other pertinent parameters [13].

Q-ALOHA: A Symbiotic Integration - In the Q-ALOHA protocol, Q-learning intertwines with the operational mechanics of the Slotted ALOHA. Here, nodes continually refine their transmission strategies by learning from past actions and their subsequent rewards or penalties [15]. This integrative approach aims to bolster the protocol's resilience and adaptability amidst fluctuating traffic conditions, guiding nodes to make well-informed transmission decisions to enhance overall network performance.

Mathematical Framework - The mathematical foundation of Q-ALOHA [16] pivots around key variables: the state s, representing the outcome of the last transmission attempt; the action a, embodying the decision to transmit or postpone transmission; and the reward R, assigned based on the outcome of the action taken. Nodes update their transmission strategies by adhering to the Q-learning update rule:

$$Q(s,a) \leftarrow Q(s,a) + \alpha[R + \gamma \max_a Q(s',a) - Q(s,a)] \quad (2)$$

where α denotes the learning rate, and γ symbolizes the discount factor. This mathematical confluence aims to hone a policy $\pi*$ to maximize the expected returns.

Performance Expectations - The incorporation of Q-learning within the Slotted ALOHA protocol is anticipated to offer a commendable improvement in network performance metrics such as transmission success rates and energy efficiency. In environments marred by dynamic traffic variations, Q-ALOHA stands poised to exhibit superior adaptability and operational efficiency, minimizing collisions, and optimizing channel utilization compared to Slotted ALOHA (baseline).

After a thorough examination of the operational mechanics and mathematical framework of Slotted ALOHA, as well as exploring strategies for its enhancement through Binary Exponential Backoff (BEB) and Q-learning, we have embarked on the implementation phase. Essential parameters and variables have been defined, enabling us to conduct practical simulations and analyzes of the enhanced protocol's performance [14].

III. Simulation Environment

In this section, we delineate the WSN characteristics and parameters instrumental in configuring the simulation environment, ensuring an authentic and rigorous evaluation of the protocol's performance and enhancements. The simulation environment is crafted with a focus on replicating realistic conditions as closely as possible, permitting a profound exploration and assessment of the protocol within operational contexts akin to real-world scenarios. Details are as follows:

Network topology - For our analysis, a peer-to-peer (P2P) network topology has been selected. In a P2P network, two nodes communicate directly with each other without the need for a centralized coordinator or any other intermediaries [17]. This choice of network topology is instrumental in our study, as it allows for a focused examination of the direct interactions between transmitting and receiving nodes, thus enabling us to analyze and assess the protocol's behaviour and performance characteristics in a streamlined communication environment.

Parameters and variables - Key parameters and variables have been precisely defined to guide the simulation process, establishing a robust foundation for our simulation analysis, pivotal to our study. Refer to Table I for a detailed list of chosen parameters.

TABLE I. DEFINED PARAMETERS AND VALUES FOR PROTOCOL ANALYSIS IN IEEE 802.15.4 WSNS

Parameters	***Values***
Data Transmission Rate	250 kb/s
Data Reception Rate	250 kb/s
Transmission Energy	50 mJ
Reception Energy	50 mJ
Data Packet Size	1044 bits
Number of Slots	1000 slots

In this study, the performance of the protocol is critically assessed using specific evaluation metrics. These metrics are indispensable for a nuanced understanding of the protocol's operational effectiveness and efficiency in the network. The key metrics utilized in this analysis include:

Accumulated Packet Delivery Ratio - The Accumulated Packet Delivery Ratio (APDR) is an important metric that signifies the proportion of data packets successfully received by the destination in relation to the total data packets transmitted [18]. A higher APDR indicates enhanced network reliability and efficacy, reflecting the protocol's robustness in ensuring data packet delivery even in challenging network conditions.

Latency - Latency represents the time interval that a data packet takes to traverse from the source node to the destination node. It is a crucial metric that provides insights into the network's responsiveness and the protocol's capability to facilitate timely data transmission. Lower latency values are desirable as they denote a more agile and responsive network communication facilitated by the protocol [18].

By considering these metrics, we aim to conduct a comprehensive and objective evaluation of the protocol, thereby gaining profound insights into its operational strengths and potential areas of improvement.

IV. SIMULATION OF SLOTTED ALOHA IN WSNS

In this section, we explore theoretical approaches and mathematical formulations for each protocol selected for our analysis. An extensive simulation exercise was conducted in MATLAB aiming to dissect and understand the behaviour of the Slotted ALOHA protocol in WSNs, considering a specific number of repetitions m in the simulations.

We defined the initial parameters according to the real operation of WSNs, created a structure in the code to store the output data of the output variables and the number of users (in this case, network devices) to calculate the average over the specified simulation repetitions, m. With this information, we were able to plot the results for better analysis, and finally, we calculated the confidence interval.

Figure I presents the throughput results obtained for different events. We have analyzed the desired output metrics versus the number of network devices, with $m = 20$. One observes that, as the number of devices grows, throughput tends to decrease due to increased competition for access to the communication channel.

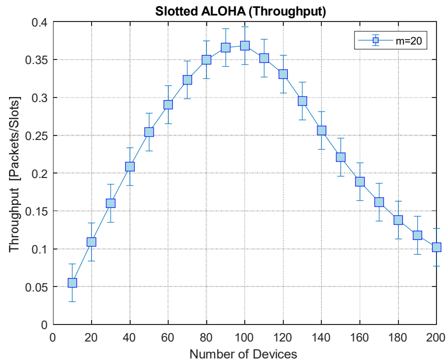

FIGURE I THROUGHPUT VS. NUMBER OF NETWORK DEVICES

Figure II shows the evolution of the offered traffic with the number of network devices, considering m=20. As more devices are added, offered traffic increases, which can lead to an increase in the number collisions. Figure III shows the average delay as a function of the number of devices in the network for m=20. As the number of devices grows, the average delay tends to increase, indicating that the network may experience higher latency, as more devices compete for the communication channel. Figure IV shows how the packet collision probability varies with the increasing number of devices in the network, considering m=20. The collision probability increases as more devices contend for the channel.

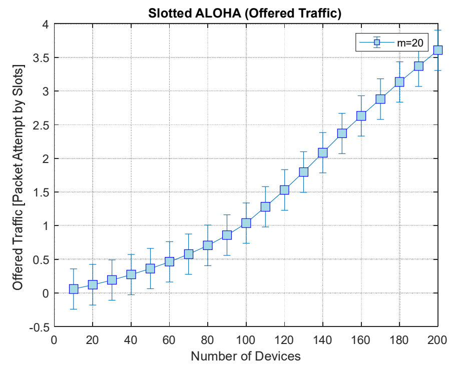

FIGURE II OFFERED TRAFFIC VS. NUMBER OF NETWORK DEVICES

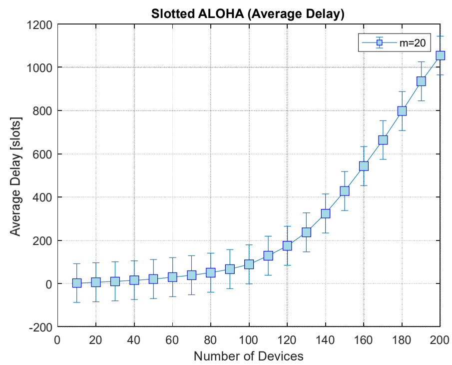

FIGURE III AVERAGE DELAY VS. NUMBER OF NETWORK DEVICES

Figure V shows the variation of the packet throughput as a function of the offered traffic, with *m*=20. We can observe how the throughput responds to an increase in offered traffic. Throughput may saturate at a certain point, indicating the network's maximum capacity. Figure VI presents the average delay versus packet throughput for *m*=20. The chart helps to understand how average delay is affected by network performance in terms of throughput. Figure VII shows the variation of the average delay with the offered traffic, for *m*=20. An increase in offered traffic can lead to greater congestion, thus, an increase in the average delay. Figure VIII explores how packet throughput is related to collision probability, with *m*=20. Collision probability can significantly impact on packet throughput.

By performing these simulations, we have been able to understand the multi-parameter behaviour of Slotted ALOHA (with *m*=20). We observed that the throughput of Slotted ALOHA tends to increase with the probability of collision. Then it decreases to 0, after reaching its peak.

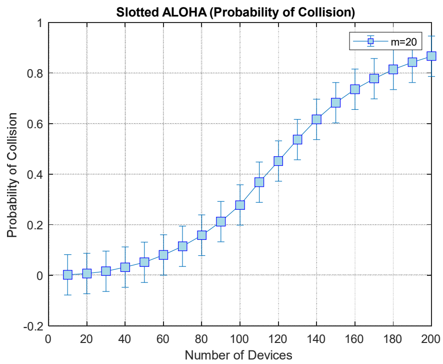

FIGURE IV PACKET COLLISION PROBABILITY VS. NUMBER OF NETWORK DEVICES

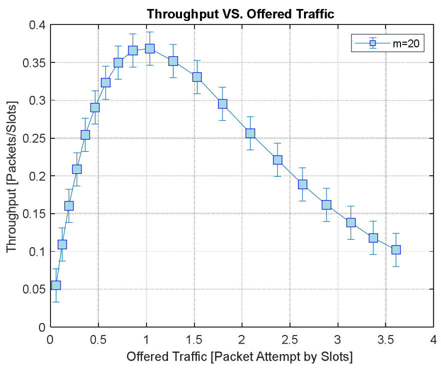

FIGURE V PACKET THROUGHPUT VS. OFFERED TRAFFIC (*M*=20)

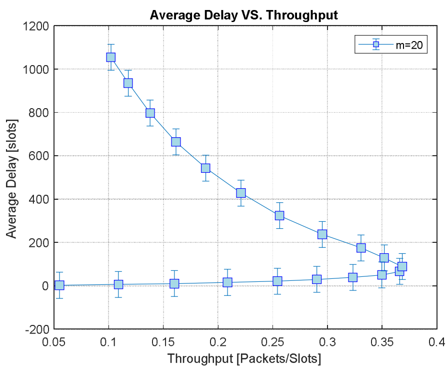

FIGURE VI AVERAGE DELAY VS. PACKET THROUGHPUT (*M*=20)

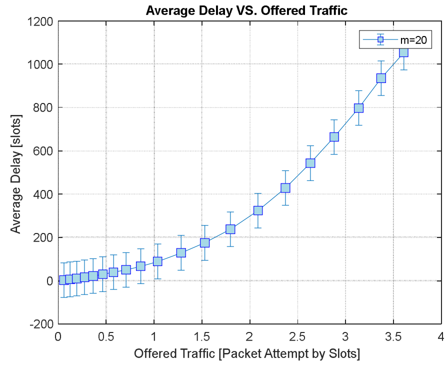

FIGURE VII AVERAGE DELAY VS. OFFERED TRAFFIC (*M*=20)

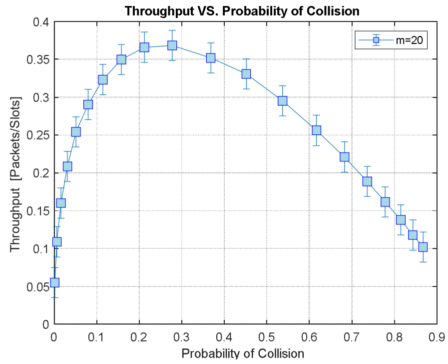

FIGURE VIII PACKET THROUGHPUT VS. COLLISION PROBABILITY (*M*=20)

We have also noticed that, as the number of devices in the network increases the offered traffic increases, leading to higher delay and collision probability. On the other hand, we have compared several graphs to analyze the network protocol's performance. Initially, we have observed the link between throughput and offered traffic, with throughput peaking when $G = 1$. A packet throughput efficiency of 37 packets per slot is achieved. Next, we have analyzed the relationship between average delay and packet throughput. We have observed that, as the packet throughput increases, the average delay tends to increase. Then, we have observed that the average delay increases as the offered traffic increases. Finally, we have analyzed the throughput versus collision probability. It became evident that the Slotted ALOHA protocol exhibits high success efficiency at a low collision probability, but it decreases as the collision probability increases. With this comprehensive study conducted to analyze the behaviour of Slotted ALOHA, we are ready to delve into scenario 2 and analyze the behavior of the CSMA, Slotted ALOHA, Slotted ALOHA-BEB, and Q-ALOHA protocols for different IEEE 802.15.4-based WSN scenarios.

A. Scenario 1

In Scenario 1 of our investigation, we concentrated on the analysis of accumulated packet delivery, a pivotal metric to assess the performance and efficiency of protocols in WSNs. Following meticulous initial parameter configuration and MATLAB code implementation, we embarked on the analysis of this specific scenario, from which the subsequent results were obtained, as shown in Figure IX. Efficient packet delivery holds paramount significance in WSNs, where energy conservation is a crucial priority. Any subsequent packet retransmissions due to collisions or other communication discrepancies can culminate in excessive and unwarranted energy consumption.

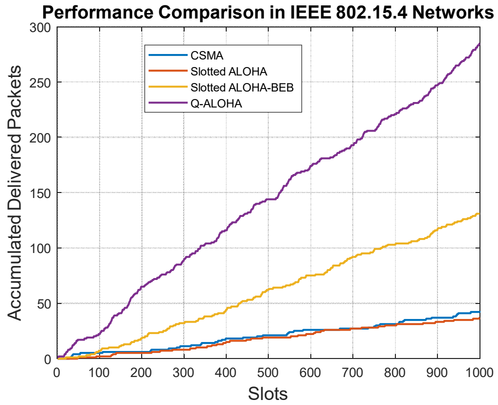

FIGURE IX ACCUMULATED PACKET DELIVERY

Thus, ensuring a reliable and efficient packet transmission is imperative to guarantee the accurate communication of sensor data to the base station or other pertinent nodes, thereby facilitating appropriate monitoring and analysis of the observed systems or environments.

In this scenario, the cumulative analysis enabled us to discern the prevailing trends of successful packet delivery over time, fostering a robust evaluation of the efficacy of specific protocols or systems in securing consistent and reliable packet deliveries. This analytical approach provided invaluable insights, instrumental for the comparative performance assessment of various protocols or systems over a period, underscoring the essentiality of Scenario 1's implementation, and the underlying analysis in our research.

In this scenario, we evaluated the implementation of four distinct medium access protocols for WSNs based on the IEEE 802.15.4 standard: Q-ALOHA, Slotted ALOHA-BEB, CSMA, and Slotted ALOHA. Notably, Q-ALOHA, integrating RL techniques, exhibited superior performance, delivering approximately 240 accumulated packets over the slots. This proficiency is explained by the protocol's dynamic learning ability aimed at optimizing transmission probabilities to enhance packet delivery. Such inherent adaptability in Q-learning facilitates nodes in fine-tuning their transmission decisions based on historical experiences, thereby optimizing channel efficiency.

Contrastingly, Slotted ALOHA-BEB, employing the Binary Exponential Backoff (BEB) mechanism, delivered commendable performance, outpacing CSMA and the conventional Slotted ALOHA by delivering approximately 130 packets. The BEB mechanism crucially enables nodes to dynamically adjust their backoff intervals post-collision, promoting a more proficient channel utilization compared to the basic Slotted ALOHA, which lacks this adaptive mechanism.

On the other hand, CSMA, despite being a prevalently employed protocol, demonstrated subpar performance in this specific setting (approximately 38 packets), overshadowed by Q-ALOHA and Slotted ALOHA-BEB. Such performance disparities can be attributed to various factors, including network node density and channel configurations. Slotted ALOHA, in its rudimentary form, exhibited the least effectiveness, elucidating the protocol's constraints in the absence of supplementary adjustment or learning mechanisms.

Based on the observed results, one has learned that incorporating learning or adaptive mechanisms, such as Q-learning or BEB, significantly enhances the performance of medium access protocols in wireless sensor networks. Specifically, Q-ALOHA, with its dynamic learning capability, emerged as particularly promising, outperforming the evaluated protocols. In contrast, traditional protocols like CSMA and Slotted ALOHA displayed certain limitations in this context, highlighting the need for their evolution and adaptation to meet the augmented demand and increasing node densities of wireless networks, delivering approximately 31 packets.

B. Scenario 2

In scenario 2, we conducted a comparative study focusing on the average latency in various protocols such as CSMA, Slotted ALOHA, Slotted ALOHA-BEB, and Q-ALOHA, as shown in Figure X. As previously mentioned, latency in Wireless Sensor Networks (WSNs) based on the IEEE 802.15.4 standard plays a crucial role. Elevated latency in networks may not be suitable for real-time applications such as system controls, gaming, or VoIP applications. Moreover, devices prone to frequent collisions and subsequent retransmissions, tend to consume more energy. So, protocols that efficiently minimize latency indirectly contribute to enhancing the battery lifespan of the network devices. This highlights the significance of analyzing latency to evaluate the energy efficiency of WSN protocols, ensuring they are optimized for practical, real-world application and usage.

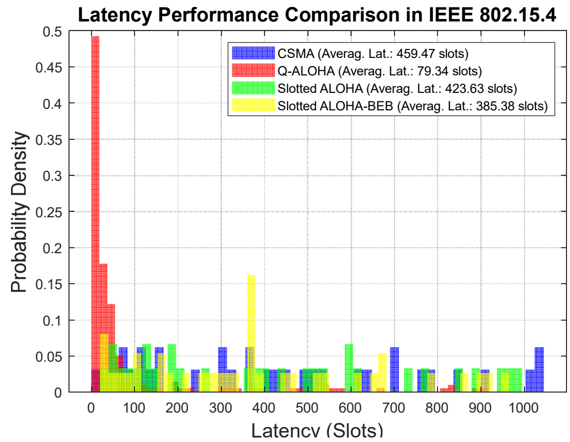

FIGURE X LATENCY PERFORMANCE COMPARISON

In this scenario, we evaluated the performance of four distinct protocols—Q-ALOHA, Slotted ALOHA-BEB, CSMA, and Slotted ALOHA—focusing primarily on their average latency. Q-ALOHA emerged as the most efficient protocol, boasting the lowest average latency of 79.34 slots, as shown in Table II. The protocol's proficiency is credited to its RL approach, enabling nodes to adaptively adjust their MAC schemes, thus optimizing transmission decisions, minimizing collisions, and consequently, reducing latency.

TABLE II. PERFORMANCE COMPARISON BETWEEN THE SCENARIOS

MAC protocol	*Delivered accumulated packets*	*Average latency*
Slotted ALOHA	31 packets	459.47 slots
CSMA	38 packets	423.63 slots
Slotted ALOHA-BEB	130 packets	385.38 slots
Q-ALOHA	240 packets	79.34 slots

Following Q-ALOHA, Slotted ALOHA-BEB exhibited a notable performance with an average latency of 385.38 slots, demonstrating its enhanced efficiency over the remaining protocols. The implementation of the Binary Exponential Backoff (BEB) in this protocol significantly spaces out retransmissions following collisions, reducing the likelihood of subsequent collisions.

The CSMA protocol, with an average latency of 459.47 slots, has shown to be less efficient in comparison to both Q-ALOHA and Slotted ALOHA-BEB. The protocol's design to detect the medium before transmission is challenging in environments characterized by significant node density and traffic, culminating in considerably increasing number of collision occurrences and resultant increased latency. Lastly, the Slotted ALOHA protocol, albeit straightforward in its application, exhibited a latency closely mirroring that of CSMA, with a record of an average of 423.63 slots (38 packets). The absence of additional mechanisms such as BEB or RL renders the protocol susceptible to increased collisions, particularly in congested network settings. Among the evaluated protocols, Q-ALOHA demonstrated to be the most proficient, underpinned by its real-time adaptive capabilities through RL, enhancing transmission decision-making, and optimizing latency. Despite exhibiting a reduced efficiency relative to Q-ALOHA, the Slotted ALOHA-BEB protocol illustrated that the integration of additional mechanisms like exponential backoff could significantly bolster the performance of traditional Slotted ALOHA.

V. Conclusions

This study concentrated on exploiting various medium access protocols to optimize performance and energy efficiency in wireless sensor networks based on the IEEE 802.15.4 standard. The selection of an appropriate protocol is paramount for maximizing network longevity and ensuring efficient node communication. Our research unveiled that Q-ALOHA, integrating reinforcement learning techniques such as Q-learning, displayed notable superiority in terms of latency and cumulative packet delivery compared to traditional protocols like CSMA and Slotted ALOHA, as well as its variant, the Slotted ALOHA-BEB. The effectiveness of Q-ALOHA is mainly explained by the nodes' ability to dynamically adapt to fluctuating network conditions, minimize collisions, and optimize transmission times. Furthermore, it was observed that the incorporation of Binary Exponential Backoff (BEB) in Slotted ALOHA enhanced its performance, even though it did not match Q-ALOHA's efficiency. CSMA exhibits diminished efficiency in high-node-density environments, underscoring the pressing need for more adaptable and resilient protocols. These findings not only contribute to the advancement of wireless sensor network technology but also highlight the significance of continued exploration and innovation in protocol design and implementation.

VI. Acknowledgment

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