A Group-Based Access Coordination Scheme for Low-Latency and High-Throughput IoT over IEEE 802.11ah

Seung-ha Jee[1], Yu-ran Jeon[1], Il-Gu Lee*[1,2]
[1]Dept. of Convergence Security Engineering
Sungshin Women's University
[1,2]Dept. of Future Convergence Technology Engineering
Sungshin Women's University
Seoul, Korea
e-mail: {shjee2001, cseyrj}@gmail.com, iglee@sungshin.ac.kr
*Corresponding author

***Abstract*—As network infrastructure expands, the Internet of Things (IoT) demands extensive coverage, substantial throughput capacity, and real-time performance. The 802.11ah standard's raw mechanism was proposed to enhance efficiency in high-density environments. However, its implementation in latency-sensitive IoT network environments is constrained by inherent limitations. In this paper, we propose the Secure Restricted Access Window Based Group Coordination (SRAW-GC) technique, which prioritizes the processing of latency-sensitive traffic while aggregating high-throughput traffic for transmission, addressing both throughput and latency requirements. Experimental findings indicate that SRAW-GC improves performance metrics by 29.86% in throughput, 19.3% in latency, and 48.23% in energy consumption compared to conventional mechanisms. The proposed technique can ensure better availability in IoT network environments than the conventional RAW technique.**

Keywords- IoT (Internet of Things) Network; IEEE 802.11ah; Network Efficiency.

I. INTRODUCTION

The proliferation of Internet of Things (IoT) devices, along with the rapid increase in network traffic among these devices, has led to the development of technologies to address the diverse security and performance needs of IoT networks. Specifically, IoT networks require wide coverage, high throughput, and real-time performance. Therefore, developing wireless communication technologies that meet these performance criteria is crucial for advancing IoT technology [1]. The types of traffic exchanged between devices in IoT networks vary based on the purpose of transmission and network conditions. Each type of traffic has distinct requirements, such as latency, throughput, and reliability. To efficiently manage the vast amount of diverse traffic, it is essential to understand the characteristics of each traffic type and apply appropriate transmission and processing methods [2].

IoT communication technologies can be broadly divided into two categories: Wireless Personal Area Network (WPAN) technologies and Low-Power Wide Area Network (LPWAN) technologies. WPANs, exemplified by ZigBee and Bluetooth Low Energy (BLE), facilitate medium-level data transmission rates over short distances. In contrast, LPWANs, such as Long Range (LoRa), enable long-distance transmission at low data rates. Consequently, WPAN and LPWAN exhibit distinct advantages and disadvantages regarding throughput and coverage [3]. IEEE 802.11ah, also known as Wi-Fi HaLow, is a technique designed to overcome the limitations of conventional IoT communication technologies. It is gaining attention for its potential to enhance throughput, coverage, and power efficiency in IoT networks. IEEE 802.11ah provides a long-range, low-power, low-speed alternative to traditional Wi-Fi, supporting approximately 8,000 nodes per AP (Access Point) within a 1-2 km service radius. Unlike other IoT connectivity technologies, it does not require the implementation of separate controllers, hubs, or gateways, ensuring cost effectiveness and substantial scalability.

IEEE 802.11ah incorporates several pivotal features within the MAC layer, offering functionalities such as fast authentication and association, Restricted Access Window (RAW), Traffic Indication Map (TIM) segmentation, and Target Wake Time (TWT). Among these technologies, the RAW technique is noteworthy for providing a distributed channel access method that can enhance the efficiency of densely packed, energy-constrained Stations (STAs) and can be flexibly applied to varying network conditions. However, the conventional RAW technique groups STAs based on their required throughput levels and allocates time slots to ensure high network throughput, which limits its applicability in real-time IoT environments that require latency-sensitive traffic [4]. Consequently, this study proposes the Secure Restricted Access Window Based Group Coordination (SRAW-GC) technique, which considers both traffic throughput and latency requirements, prioritizes the processing of latency-sensitive traffic, and aggregates traffic requiring high throughput for transmission.

The contributions of this study are as follows:

- An SRAW-GC mechanism is proposed to address latency and throughput requirements. This mechanism utilizes a grouping approach to organize traffic and allocate time slots based on the characteristics of each group.
- The proposed SRAW-GC mechanism prioritizes time slots for latency-sensitive traffic while aggregating traffic that requires high throughput for transmission. Its efficacy is demonstrated by improvements in both network latency and throughput.

- An evaluation of the proposed SRAW-GC across various network environments shows a performance enhancement of 29.86% in throughput, 19.3% in latency, and 48.23% in energy consumption compared to the conventional RAW scheme.

The structure of this paper is as follows: Section 2 analyzes previous studies related to technologies introduced in 802.11ah, and Section 3 proposes the SRAW-GC technique to address the limitations of the RAW technique in 802.11ah. Section 4 evaluates and verifies the performance of the proposed SRAW-GC technique, while Section 5 concludes the paper.

II. RELATED WORK

The IEEE 802.11ah standard introduces technologies such as TIM segmentation, TWT, and RAW to enable efficient channel access for resource-constrained STAs in dense IoT networks. TIM segmentation is a power-saving technique that divides TIM information in beacons into groups, allowing STAs to activate only during their corresponding groups, thereby improving energy efficiency. TWT is a reservation-based communication technique that facilitates the negotiation of activation timings between STAs and APs, enabling communication during designated time slots while preserving power-saving mode during other periods, thus significantly enhancing power efficiency. The RAW technique groups STAs to access the channel only during specified time slots, reducing network collisions and improving scalability. Table 1 summarizes existing studies relevant to TIM segmentation, TWT, and RAW technologies in 802.11ah.

TABLE I. COMPARISON OF PREVIOUS STUDIES

Feature	Ref.	Contribution	Limitation
TIM segmentation	[5]	· The proposed network architecture enhances scalability by incorporating control loops and monitoring sensors into the network infrastructure.	· It has been demonstrated that if the beacon cycle is not optimized, there will be an increase in throughput and energy consumption.
	[6]	· The proposal entails the implementation of a link-layer mechanism, comprising downlink TIM and uplink RAW groups, to mitigate energy consumption.	· It is challenging to verify performance on real-time networks because link latency is not taken into account.
TWT	[7]	· The proposed methodology involves implementing a multifaceted approach, integrating the utilization of RAW and TWT, to enhance network energy efficiency.	· It has been demonstrated that there is an increase in latency when using RAW and TWT in conjunction with one another.
	[8]	· The proposal entails the implementation of a novel channel access methodology for STAs within a network environment characterized by the coexistence of RAW STA and TWT STA configurations.	· TWT transmission is contingent upon the availability of empty RAW slots, a factor that compromises energy efficiency and engenders augmented latency.
RAW	[9]	· The proposal entails implementing a RAW mechanism to identify concealed terminals and organize STAs into designated groups.	· It has been demonstrated that an increase in network latency is associated with a failure to consider traffic latency requirements.
	[10]	· The proposal entails the implementation of a machine learning-based mechanism within the RAW framework to facilitate the process of grouping and the subsequent control of channel access.	· The method of determining channel access depends on the number of collisions between STAs.

Seferagić et al. [5] propose a network that hosts a control loop to regulate its dynamic status. Additionally, the network includes monitoring sensors that periodically transmit measurement results. The purpose of this system is to enhance the scalability of IEEE 802.11ah. The proposed method utilizes a control loop to dynamically adjust the beacon interval, ensuring compliance with latency requirements. However, it is important to note a limitation inherent to this approach: optimization of the beacon cycle is necessary since throughput and energy consumption increase with the beacon cycle. Bel et al. [6] propose a link-layer mechanism consisting of downlink TIM and uplink RAW groups to reduce energy consumption. The study demonstrated that energy efficiency can be enhanced to prolong the battery life of sensor nodes. However, it does not consider delays in uplink and downlink communications, complicating the verification of performance in real-time networks.

Santi et al. [7] call for research to enhance network energy efficiency by utilizing RAW and TWT technologies. Energy consumption calculations under various conditions demonstrate that the proposed method significantly improves energy efficiency. However, it is important to note the limitation of this method: a substantial increase in latency, which makes it difficult to apply in real-time networks. Santi et al. [8] analyze energy consumption rates in scenarios where RAW STAs and TWT STAs coexist, proposing a channel access method for STAs designed to enhance energy efficiency. The implementation of the IEEE 802.11ah TWT technique in an NS-3 environment has demonstrated the degradation of energy efficiency for TWT STAs caused by RAW STAs. Furthermore, a scheduling method has been proposed that allows TWT STAs to reserve empty RAW slots. However, this method raises concerns regarding energy consumption and latency when RAW slots are occupied, complicating TWT transmission. Similarly, the TIM technique has been observed to have increased beacon overhead. Additionally, TWT has the limitation of being challenged to apply in dynamically changing networks due to its reservation-based approach, which requires real-time performance.

Mondal et al. [9] proposed the HTAG (Hidden Terminal Aware Grouping) technique to address the hidden terminal problem that arises when employing the RAW technique in IEEE 802.11ah-based high-density IoT networks. The system detects hidden terminal devices through the Neighbor Detection Table (NDT) and engages in the grouping of these hidden nodes. However, this method has a limitation: it does not consider traffic delay requirements, which leads to increased network delays. Mahesh et al. [10] propose a machine learning mechanism to group STAs and control channel access for each STA group. After calculating the collision count for each RAW group using an unsupervised learning model, the AP adjusts the beacon interval based on this information and broadcasts it to the STAs. However, this method bases the channel access determination solely on the collision count between STAs, complicating the fulfillment of the network's real-time requirements, as ensuring smooth channel access for low-latency traffic is challenging. The conventional RAW technique groups STAs solely based on network throughput when managing traffic. However, low latency is essential in IoT environments with densely packed and interconnected sensors. This necessitates a mechanism that considers both latency and throughput when grouping traffic.

III. PROPOSED SCHEME

This section delineates the methodologies of SRAW-GC for facilitating efficient data transmission in dense network environments with IoT STAs. As illustrated in Figure 1, high-throughput STAs are grouped within the same Basic Service Set (BSS), and each STA transmits data to the AP.

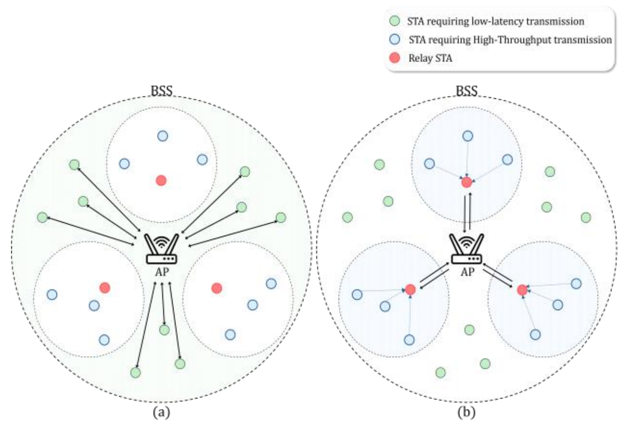

Figure 1. This is how STAs that require low latency and STAs that require high bandwidth transmit data to AP. (a) shows how low-latency STA communicates with AP, and (b) shows how high-bandwidth STA communicates with AP.

SRAW-GC has developed a methodology for classifying STAs at the application level. These STAs are divided into two distinct categories: those requiring low-latency transmission and those requiring high-throughput transmission. STAs that require low-latency transmit their data, known as MAC Protocol Data Unit (MPDU), to the AP individually. In contrast, STAs that require high throughput prioritize the transmission of MPDU to the Relay STA. The selection of relay STAs is determined by the Modulation and Coding Scheme (MCS) index, which provides a comprehensive assessment of the channel quality between the AP and the STAs. The selected Relay STA receives MPDUs from nearby STAs requiring high throughput and aggregates the data using the Aggregated MAC Protocol Data Unit (A-MPDU) method. Low-latency STAs generate data irregularly and require low-latency transmission rather than high throughput. Consequently, aggregating data and transmitting it in batches, as high-throughput STAs do, does not satisfy their low-latency transmission requirements. Instead, it is more efficient for them to transmit data immediately as the need arises. High-throughput transmission requires a throughput that exceeds the transmission delay rate. The A-MPDU method, as outlined in the extant 802.11n specification for high throughput, meets these requirements by allowing data to be transmitted in batches.

As illustrated in Figure 2, the operation methods for low-latency and high-throughput slots are sub-slots within the RAW slot.

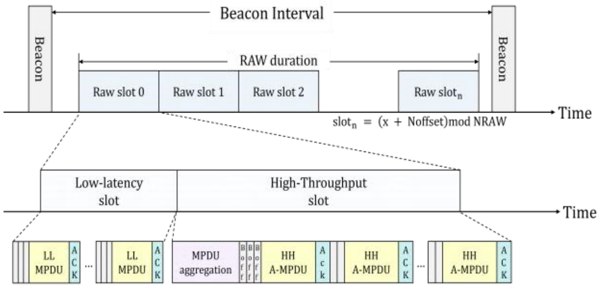

Figure 2. SRAW-GC technique showing a RAW slot divided into a low-latency sub-slot for individual transmissions and a high-throughput sub-slot for aggregated A-MPDU transmissions.

The SRAW-GC technique has been designed to be compatible with the 802.11ah RAW technique, and STAs are assigned to the n_{th} RAW slot according to (1) to access the channel:

$$slot_n = (x + N_{offset}) mod\ NRAW \tag{1}$$

In (1), $slot_n$ is the index number of the RAW slot allocated to the STA, and x represents either the AID position index or the AID of the STA. N_{offset} is the offset value expressed with the lower two bytes of the FCS field in the SIG beacon frame. $NRAW$ is the total number of slots in RAW.

The RAW slot is divided into two sub-slots: a low-latency sub-slot and a high-throughput sub-slot. In the low-latency sub-slot, STAs requiring low-latency transmission compete for channel access with the AP to transmit MPDU data. After this, the STA anticipates the designated back-off time and transmits its MPDU to the AP. It has been shown that since the low-latency sub-slot is prioritized within the RAW slot, STAs needing low-latency transmission can effectively address transmission delays caused by high-throughput STAs with long channel occupancy times. This situation is analogous to the existing RAW mechanism. Once the low-latency sub-slot concludes, a transition to the high-throughput sub-slot occurs. In this slot, the AP first selects relay STAs within the BSS. These designated relay STAs receive MPDUs from high-throughput STAs nearby and aggregate the data using the A-MPDU method. The aggregated data is then transmitted to the AP through channel competition among the relay STAs. The improved transmission efficiency observed in this scenario can be attributed to the superior channel quality and status maintained by the relay STAs with the AP, compared to situations where individual STAs transmit data directly to the AP. Furthermore, since only relay STAs are responsible for transmitting data to the AP, the probability of competition and subsequent collisions is significantly reduced, thereby enhancing the efficiency of high-throughput transmission.

IV. EVALUATION AND ANALYSIS

A. Evaluation Environment

This section delineates the experimental environment for evaluating the performance of the proposed SRAW-GC technique. The conventional model selected the 802.11ah RAW mechanism for performance comparison with that of SRAW-GC [9][10].

The experiment aimed to assess the performance of both the proposed and conventional models in a network environment based on the 802.11ah standard. The experiment was conducted in a Python 3.12 environment. The simulation environment was set up with one AP and 2,000 STAs within a single BSS. Performance evaluations were conducted for each scenario, considering the number of STAs, the ratio of low-latency STAs to high-throughput STAs, and the collision probability among STAs. The evaluation metrics used included throughput, latency, and energy consumption. The variables employed in the equations are detailed in Table 2, and throughput was calculated according to (2):

TABLE II. VARIABLES IN FORMULAS

Parameter	Meaning
D_i	Data successfully transmitted by i_{th} STA (byte)
T_{RAW}	Total RAW duration (ms)
P_{base}	0.1 W (basic transmission power)
P_{idle}	0.02 W (idle power)
$T_{active,n}$	Active transmission time of nth STA (ms)
$T_{idle,n}$	Idle time of nth STA (ms)
$E_{STA}(n)$	Energy consumption of node i (joules)
E_{total}	Sum of energy consumed by all N nodes plus energy consumed by the access point (joules)

$$Throughput(kbps) = \frac{\sum_{i=1}^{n} D_i(bytes) \times 8}{T_{RAW}(ms)} \tag{2}$$

To express throughput in kbps, the number of bytes successfully transmitted was multiplied by 8 to convert the unit to bits. This equation represents the successful transmission of data to the AP during the total RAW duration, T_{RAW}. Latency was determined via (3):

$$Latency(ms) = T_{Data\ transmission} + (T_{backoff} \times N_{backoff}) \tag{3}$$

Latency is calculated as the sum of data transmission time and back-off time. Subsequently, energy consumption could be predicted using (4):

$$E_{total}(J) = \sum_{n=1}^{N} E_{STA}(n) \tag{4}$$

The total energy consumption of BSS is defined as the sum of the energy consumption of all STAs and APs, as shown in Equation (4). The energy consumption of each STA can be calculated according to (5):

$$E_{STA}(J) = P_{base} \times \left(T_{active,n}/1000\right) + P_{idle} \times \left(T_{idle,n}/1000\right) \quad (5)$$

Within the same BSS, throughput, latency, and energy consumption were evaluated for each number of STAs, the ratio of low-latency STAs to high-throughput STAs, and the collision ratio. The simulation was repeated a total of 10,000 times.

B. Evaluation Results and Analysis

As illustrated in Figure 3, a comparative analysis was conducted to assess the throughput, latency, and energy consumption of SRAW-GC and conventional models in relation to the number of STAs.

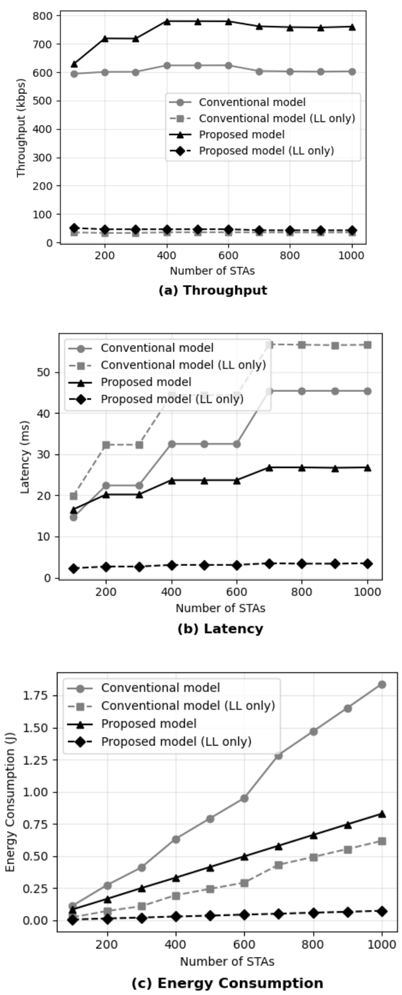

Figure 3. Performance evaluation results for (a) throughput, (b) latency, and (c) energy consumption according to the number of STAs.

As illustrated in Figure 3, the performance of the proposed model was compared to that of the conventional model in a network scenario where the ratio of STAs requiring low-latency transmission to those requiring high-throughput transmission is set at 1:1, and the collision probability is set at 0.3. A thorough analysis revealed that while throughput increased for both models as the number of STAs grew, they reached similar throughput levels starting from 400 STAs. This phenomenon can be attributed to the gradual increase in the number of STAs allocated to each RAW slot, which reduces the amount of data successfully transmitted within the slot. Consequently, both models achieved maximum throughput at 600 STAs, with the proposed model reaching 779.7 kbps and the conventional model achieving 624.4 kbps. When comparing the throughput of low-latency STAs alone, the proposed model achieved 46.3 kbps. In comparison, the conventional model attained 35.5 kbps at 600 STAs, indicating a 30.3% improvement in throughput for the proposed model. As the number of STAs increased, the average latency increased for both models. The conventional model exhibited an increase in latency from 14.7 ms (milliseconds) to 45.4 ms as the number of STAs increased from 100 to 1,000, while the proposed model demonstrated an increase from 16.6 ms to 26.8 ms. At 100 STAs, the proposed model had a latency that was 1.9 ms higher; however, as the latency of the conventional model increased sharply, the proposed model improved latency by up to 41.1% when the number of STAs reached 900. When examining the latency of low-latency STAs specifically, the proposed model showed a significant enhancement. This improvement results from the proposed model allocating sub-slots to prioritize the transmission of low-latency STAs within the RAW slot. In contrast, high-throughput STAs and low-latency STAs coexist within the conventional model, leading to competition within the same RAW slot. This competition increases latency for low-latency STAs due to the long channel occupancy times of high-throughput STAs.

As illustrated in Figure 4, an increase in the ratio of low-latency STAs led to a decline in throughput for both the proposed and conventional models. This phenomenon occurs because the data size transmitted by low-latency STAs is smaller than that of high-throughput STAs, resulting in an overall decrease in throughput. The proposed model demonstrated superior performance for both all STAs and low-latency STAs. In the initial phases, when the proportion of low-latency STAs was minimal, the proposed model exhibited higher latency compared to the conventional model. This can be attributed to the allocation of a minimum low-latency sub-slot within the RAW slot by the proposed model, which prioritizes the transmission of low-latency STAs. Consequently, even in the absence of low-latency STAs to transmit, high-throughput STAs must wait. However, as the proportion of low-latency STAs increased to an 8:1 ratio with high-throughput STAs, the latency of the proposed model exhibited a 62.2% improvement compared to the conventional model. This finding substantiates the efficacy of the proposed mechanism in reducing latency in network environments characterized by a high density of low-latency STAs.

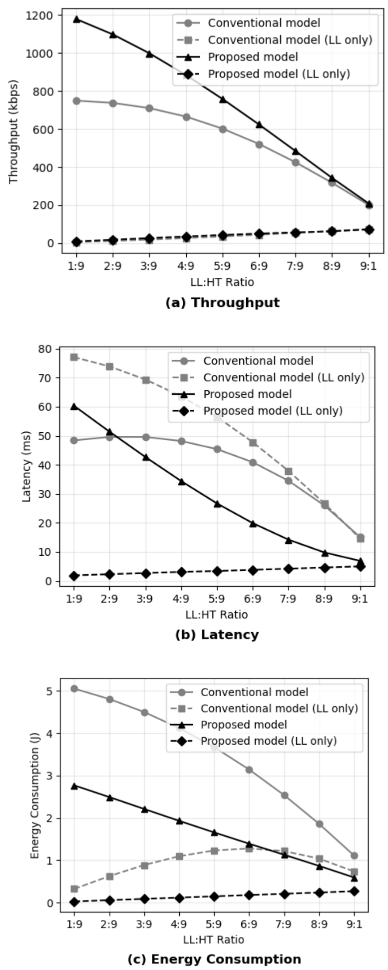

Figure 4. Performance evaluation results for (a) throughput, (b) latency, and (c) energy consumption based on the ratio of low-latency STAs to high-throughput STAs.

A comparison of the latency exhibited by low-latency STAs reveals that the proposed model exhibited an average reduction of 93.4% in latency compared to the conventional model. As the proportion of low-latency STAs increased, both models exhibited a decline in energy consumption. It has been demonstrated that low-latency STAs maintain an active state for a shorter period than high-throughput STAs due to their shorter channel occupancy time, resulting in a reduced energy consumption rate. Nevertheless, the proposed model demonstrated a notable enhancement in energy efficiency, achieving an average savings of 51.2% compared to the conventional model. Figure 5 compares the throughput, latency, and energy consumption of SRAW-GC and the conventional model based on collision probability in an environment with 2,000 STAs. Figure 5 compares the throughput, latency, and energy consumption of SRAW-GC and the conventional model based on collision probability in an environment with 2,000 STAs.

As illustrated in Figure 5, an increase in collision probability led to a decline in throughput for both the proposed and conventional models.

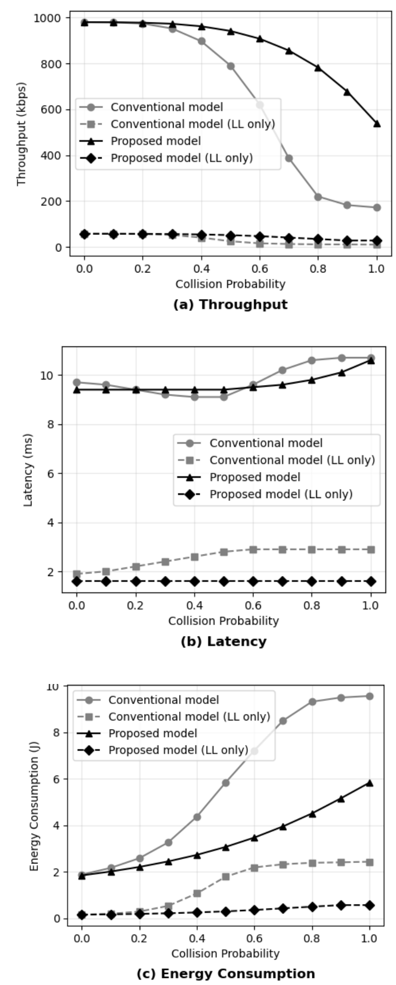

Figure 5. Performance evaluation results for (a) throughput, (b) latency, and (c) energy con-sumption based on collision probability.

The conventional model showed a sharp decrease in throughput, dropping from 980.1 kbps to 172.2 kbps (82.43%). In contrast, the proposed model exhibited a more modest reduction, from 980.1 kbps to 540.8 kbps (44.82%), demonstrating its effectiveness in maintaining throughput performance. The proposed technique employs the A-MPDU mechanism to transmit aggregated data from relay STAs with optimal channel conditions and transmission efficiency to the AP among high-throughput STAs. This allows the proposed model to sustain a higher throughput than the conventional technique. As the collision probability increased, the latency of both models also rose; however, the proposed model maintained a lower latency. This is due to the classification of traffic into low-latency and high-throughput slots by dividing the RWA slot, which mitigates collisions within the slot compared to the conventional RAW technique. Conversely, the conventional model competes for channel occupancy across all traffic within the same RAW slot, resulting in increased latency for STAs with low-latency requirements. A comparison of the proposed and conventional models in terms of latency for low-latency STAs shows that the conventional model suffers from increased latency as the collision probability increases. In contrast, the proposed model maintained lower latency. This can be attributed to the fact that, even in scenarios with collisions, the competition among low-latency STAs mitigates the latency caused by high-throughput STAs, ensuring system availability and contrasting with the outcomes observed in the conventional method. As the collision probability increased, the retransmission mechanism was triggered, resulting in elevated energy consumption for both models. However, the proposed model demonstrated reduced energy consumption compared to the conventional model. Notably, when the collision probability was set at 0.8, the proposed model showed a significant reduction in energy consumption of 51.62%, underscoring its effectiveness in energy-efficient operations.

V. Conclusion and Future Work

As the proliferation of IoT devices continues to accelerate, the demand for efficient processing of the substantial volume of IoT traffic associated with wireless networks is increasing. While prior studies have focused on enhancing wide coverage and high throughput, it is crucial to recognize the need for advancements in real-time and low-latency data transmission within mission-critical IoT networks. Consequently, the RAW technique of 802.11ah has been proposed as a solution to improve latency. However, this technique groups STAs based on the required throughput level of the traffic and allocates time slots to ensure high network throughput, which limits its applicability to real-time IoT environments that require latency-sensitive traffic. This study proposes an A-MPDU grouping technique based on IEEE 802.11ah RAW to achieve low latency and high throughput. According to the experimental results, SRAW-GC enhances throughput by 29.86%, reduces latency by 19.3%, and decreases energy consumption by 48.23% compared to the conventional model. Furthermore, for STAs with low-latency requirements, the proposed SRAW-GC approach demonstrates improvements of 29.53% in throughput and 74.66% in latency compared to the conventional method. Consequently, the SRAW-GC technique can ensure better availability in IoT network environments than the conventional RAW technique. Future research will determine the optimal values for the low-latency sub-slot and the high-throughput sub-slot within the RAW framework.

Acknowledgment

This work was supported by the Ministry of Trade, Industry and Energy (MOTIE) under the Training Industrial Security Specialists for High-Tech Industry program (RS-2024-00415520), supervised by the Korea Institute for Advancement of Technology (KIAT); the Ministry of Science and ICT (MSIT) under the ICT Challenge and Advanced Network of HRD (ICAN) program (IITP-2022-RS-2022-00156310); and the Information Security Core Technology Development program (RS-2024-00437252), supervised by the Institute of Information & Communication Technology Planning & Evaluation (IITP).

References

[1] Q. V. Khanh, N. V. Hoai, L. D. Manh, A. N. Le, and G. Jeon, “Wireless communication technologies for IoT in 5G: Vision, applications, and challenges,” *Wireless Communications and Mobile Computing*, vol. 2022, Article ID 3229294, 2022.

[2] L. H. Shen, C. H. Wu, W. C. Su, and K. T. Feng, “Analysis and implementation for traffic-aware channel assignment and contention scheme in LoRa-based IoT networks,” *IEEE Internet of Things Journal*, vol. 8, no. 14, pp. 11368–11383, 2021.

[3] L. Tian, S. Santi, A. Seferagić, J. Lan, and J. Famaey, “Wi-Fi HaLow for the Internet of Things: An up-to-date survey on IEEE 802.11ah research,” *Journal of Network and Computer Applications*, vol. 182, p. 103036, 2021.

[4] Wi-Fi Alliance*, “Wi-Fi CERTIFIED™ for WMM™—Support for multimedia applications with quality of service in Wi-Fi® networks,”* Austin, TX, USA: Wi-Fi Alliance, 2004.

[5] A. Seferagić, I. Moerman, E. De Poorter, and J. Hoebeke, “Evaluating the suitability of IEEE 802.11ah for low-latency time-critical control loops,” *IEEE Internet of Things Journal*, vol. 6, no. 5, pp. 7839–7848, 2019.

[6] A. Bel, T. Adame, and B. Bellalta, “An energy consumption model for IEEE 802.11ah WLANs,” *Ad Hoc Networks*, vol. 72, pp. 14–26, 2018.

[7] S. Santi, L. Tian, E. Khorov, and J. Famaey, “Accurate energy modeling and characterization of IEEE 802.11ah RAW and TWT,” *Sensors*, vol. 19, no. 11, p. 2614, 2019.

[8] S. Santi, L. Tian, and J. Famaey, “Evaluation of the co-existence of RAW and TWT stations in IEEE 802.11ah using ns-3,” in *Proc. 2019 Workshop on Next-Generation Wireless with ns-3 (WNS3)*, 2019.

[9] M. A. Mondal and M. I. Hussain, “Station grouping mechanism using machine learning approach for IEEE 802.11ah,” *Ad Hoc Networks*, vol. 149, p. 103238, 2023.

[10] M. Mahesh and V. P. Harigovindan, “Hidden terminal aware grouping scheme for IEEE 802.11ah based dense IoT networks,” *Computer Communications*, vol. 191, pp. 161–172, 2022