RAW Optimization of IEEE 802.11ah Networks

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***Abstract*—IEEE 802.11ah (also known as WiFi Halow) is a new WiFi standard for sub-1 GHz communications intended to address key challenges of the Internet of Things. IEEE 802 working group introduces IEEE 802.11ah to overcome the disadvantages of various previously introduced protocols (more data rate and very less transmission range, and more transmission range and very less data rate) by providing much data rate and transmission range of up to 1 km and has the capacity of 8192 devices connecting simultaneously with only one access point. The IEEE 802.11ah standard was released to support Machine-to-Machine (M2M) Communication between a large number of sensor devices that are rapidly increasing with the Internet of Things (IoT). IEEE 802.11ah protocol introduces the RAW Mechanisms in the MAC layer to avoid channel contention, especially when there is a large number of stations trying to access the channel simultaneously, thereby increasing scalability in dense deployments. In this paper, we analyze the network performance in terms of throughput through the proper allocation of nodes. This article investigates the impact of the number of stations and the number of groups on network performance, specifically throughput, in wireless networks. The article examines how varying the number of stations and groups affects the network's performance and identifies the optimal values for these parameters that can maximize the network's throughput.**

***Index Terms*—IoT, IEEE 802.11ah, Restricted Access Window (RAW)**[1]

I. Introduction

The tremendous growth of sensor devices in the Internet of Things (IoT) in recent years is attributable to a much more distinct vision of a smarter future [1]. Over the years, we have also observed good effects of IoT on human lives, including economic, political, and social life. The Internet of Things (IoT) adds a contemporary dimension to the field of information and communication technology by making it simple for us to connect at any time, anywhere, and for any purpose. Emerging applications demand innovative connectivity options and novel data-sharing strategies among diverse networks and devices, which results in the development of a new idea of the internet [2].

Future IoT applications will allow for the implementation of innovative concepts like smart metering, smart cities, and smart/e-health, which are essential to the realization of the smart world vision. An example of an IoT architecture is shown in Fig. 1. However, due to the unique requirements that each of these applications has, such as different data rates, low power consumption, low implementation costs, a sizable number of supported devices, and the capacity to cover a range of distances, a very large number of communicating devices and stations connecting to the IoT network are necessary [3]. Many aspects of our lives will change as a result of the widespread adoption of the Internet of Things paradigm, though it is still unclear what technological development will be responsible for this shift. Wi-Fi appeared to be on the sidelines as a result of the numerous competitors that emerged throughout time.

RFID, Low-Power Wide Area Network (LPWAN), and Wireless Personal Area Network (WPAN) (similar to Bluetooth and ZigBee) are a few technologies for wireless networking that have been suggested because of their high throughput, simple association, and ease of implementation. However, because of their less coverage range, low data rates, and limited device connectivity, these technologies are viewed as inappropriate for use in large networks [4].

In an effort to address these issues with wireless technologies, the IEEE 802 LAN/MAN Standards Committee (LMSC) established the IEEE 802.11ah (also called WiFi Halow) Task group [5]. The latest IEEE 802.11ah standard fills this gap to a certain extent by combining the advantages of Wi-Fi and low-power sensor network communication technologies. The advent of unlicensed sub-GHz frequency bands (863-868 MHz in Europe, 902-928 MHz in North America, and 755-787 MHz in China) has allowed IEEE 802.11ah to link up to 8192 low-power devices at distances of up to 1 km at speeds ranging from 150 kbps to 78 Mbps [6].

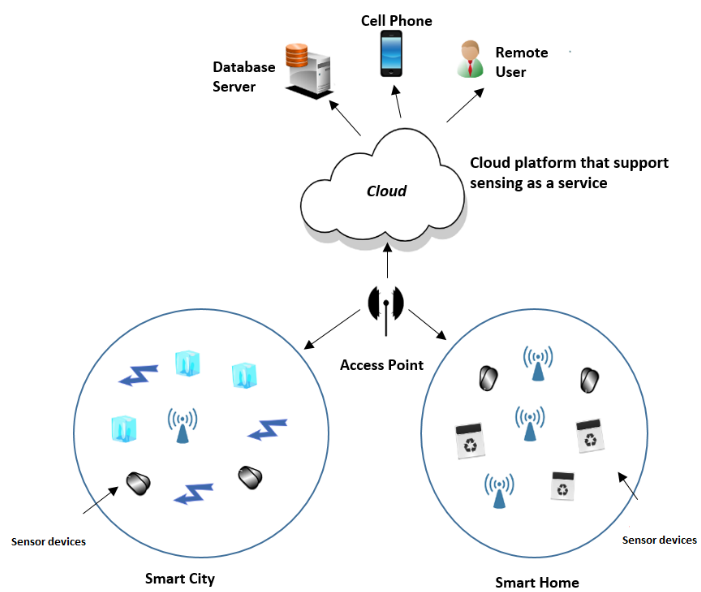

Fig. 1: An example of IoT Architecture

The main focus of IEEE 802.11ah's Media Access Control (MAC) layer is on improving the efficiency of dense deployments of various energy-constrained devices. As a result, several novel

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MAC techniques are described, including the short MAC header, the Restricted Access Window (RAW), the Target Wake Time (TWT), and the Traffic Indication Map (TIM) [7].

The fundamental idea behind the RAW method is that the stations are split up into groups, and only those in their group can access the channel at the specified time periods for that group. Therefore, the likelihood of a collision is significantly reduced by limiting the number of stations that can access the channel simultaneously. The three parameters that can be adjusted for the hierarchical RAW mechanism but are not included in the standard are the number of RAW slots, the size of each RAW slot, and the RAW duration. Based on the channel condition, these parameters must be taken into account efficiently and collectively in order to improve network performance [5]. However, the standard does not specify the grouping technique that is utilized to divide the stations into groups. A grouping approach should be used by an access point (AP) to decide the number of groups, the size of each group, and the distribution of stations. Furthermore, these properties may be dynamically changed by the AP. The goal is to find an optimal solution to the saturation problems of IoT networks by using the RAW mechanism of 802.11ah [1].

The organization of this paper is as follows. Section II discussed the background and literature review of IEEE 802.11ah. Section III describes the key features of IEEE 802.11ah. The RAW mechanism, along with its architecture, is presented in Section IV. Section V gives the simulation results and discussions. And the paper is finally concluded with Section VI.

II. Background and Literature Review

The IEEE 802.11ah standard was primarily designed for dense IoT networks. It provides better coverage and high scalability for IoT devices. The standard uses unlicensed ISM frequencies below 1 GHz, with the exception of television-free spaces that depend on country regulations. For instance, the intended frequency ranges in Europe are 863-868 MHz, 902-928 MHz in the US, and 916.5-927.5 MHz in Japan. Additionally, China and South Korea have their own allocations. These characteristics make it a desirable standard for long-range Internet of Things applications, such as home automation, smart parking, sensor-based monitoring, etc.

In the last recent years, many researchers have studied IEEE 802.11ah and its RAW mechanism. The performance analysis of IEEE 802.11ah has been extensively studied in the literature given in the references below, which mainly studies the performance of the MAC Layer using the RAW mechanism. The authors of [8] investigate the effects of Restricted Access Window (RAW) grouping and Traffic Indication Map (TIM) segmentation on scalability, throughput, latency, and energy efficiency in the presence of bidirectional TCP/IP traffic by taking into account both large-scale reliable sensing traffic and high-throughput video streaming traffic. When the link layer introduces lengthy delays, they also investigate how TCP behaves in both scenarios. Badarla et al. in [9] proposed a specific mathematical model with the unsaturated traffic situation in order to determine the throughput and energy efficiency of the IEEE 802.11ah multi-rate IoT network under the RAW mechanism, taking into consideration that the STAs are operating at various distinct data rates.

Alvarado et al. [2] examine the RAW mechanisms by increasing the number of the RAW groups. We can see that an increase in the number of the RAW group decreases the number of packet losses as the RAW mechanism restricts access to the channel. In [4], Mahesh et al. developed a simple and straightforward analytical model based on Bianchi's model to assess the RAW mechanism's throughput and energy efficiency in IEEE 802.11ah. In a dense IoT network, the RAW mechanism performs better than the DCF. The effectiveness of the RAW mechanism has been evaluated for several MCSs. Sangeetha et al. [10] presented an analytical model for calculating the saturation and non-saturation throughput of an IEEE 802.11ah-based WLAN using the RAW mechanism. In order to comply with the requirements of the RAW-based MAC scheme, Bianchi's DTMC model was altered. An analytical model of the average frame delay was presented. ns-3 was also used to implement the RAW mechanism, and simulations were used for in-depth research. It was convinced that the RAW-based scheme is suitable for situations with a high network density and that throughput rises with the group count.

The representation of mathematical concepts suitable for IoT scenarios that are in accordance with the RAW mechanism has been developed by Khorov et al. in [11]. By finding the optimal RAW parameters, the network performance, which is in terms of throughput, packet loss ratio, and power consumption was optimized. The authors of [12] suggested an ideal traffic sensor grouping method. For the IEEE 802.11ah network, the authors of [11] suggested an ideal traffic sensor grouping method. To achieve max-min fairness among the groups while achieving sub-optimal energy efficiency, they created a heuristic traffic sensor mapping technique. Tian et al. in [13] presented a novel training methodology for the SUMO model of IEEE 802.11ah heterogeneous networks. The model can precisely predict the packet receiving rate under a specific RAW configuration in IEEE 802.11ah heterogeneous networks, where stations have various packet sizes and MCSs depending on their distance to the AP. Second, the model may be trained with a limited amount of sample data points since the training approach is well-designed to choose the input and output parameters of the model accurately. Available research regarding optimization techniques on the MAC layer are summarized in TABLE I

III. Key Features of IEEE 802.11ah

A. PHY Layer

The IEEE 802.11ah PHY layer gets its features from IEEE 802.11ac and adapts them to frequencies below 1 GHz. This channel has bandwidths from 1 to 16 MHz, and only 1 and 2 MHz support is mandatory [16]. Compared to conventional Wi-Fi technologies that operate at frequencies in the 2.4 GHz and 5 GHz bands, 802.11ah can communicate over larger distances (up to 1 km) and with substantially less power usage. Despite the fact that the standard allows for bandwidths up to 16 MHz, not all regional regulations are in favor of such a wide band[2].

At the physical layer, the standard makes use of the orthogonal frequency division multiplexing (OFDM) approach. To exploit the trade-off between range, performance, and energy efficiency, IEEE 802.11ah uses different Modulation and Coding Schemes (MCS), Number of Space Streams (NSS), and Guard Interval (GI) durations. Binary Common Coding (BCC), which is required, and an optional LDPC (Low-Density Parity Check) are supported encoding techniques. The data rates and corresponding MCS for GI and NSS at 1 and 2 MHz, respectively, are listed in TABLE II [21]. In order to extend the coverage range, MCS10 is introduced in a 1 MHz channel with BPSK modulation[9].

TABLE I: Existing research works

Sl no.	References	Traffic	MAC Features	Objective	Validation Tools
1	Tian et. al [8]	Uplink	RAW	Throughput	ns-3
2	Raeesi et. al [14]	Uplink	RAW	Throughput and Energy	analytical
3	Charania et. al [3]	Uplink	TIM and RAW	Latency and Energy	MatLab
4	Wang et. al [15]	Uplink	RAW	Energy	Matlab
5	Ogawa et. al [16]	Saturated, Homogeneous	RAW	Throughput and Energy	Matlab
6	Zheng et. al [1]	Saturated, Homogeneous	RAW	Throughput	ns -3
7	Dong et. al [17]	Static, Heterogeneous	RAW	Contention	Analytical
8	Park et. al [18]	Uplink	RAW	Throughput	Analytical and Unknown Simulation
9	Bankov et. al [19]	Uplink/ Downlink	RAW	Energy and Throughput	Analytical and Unknown Simulation
10	Kim and Chang [20]	Uplink/ Downlink	TIM and RAW	Energy	Matlab

TABLE II: 802.11ah MCSs for 1,2 MHz, NSS=1 , GI = 8μs

MCS Index	Modulation	Coding Rate	Data Rate(Kbps) 1MHz	2MHz
0	BPSK	1/2	300	650
1	QPSK	1/2	600	1300
2	QPSK	3/4	900	1950
3	16-QAM	1/2	1200	2600
4	16-QAM	3/4	1800	3900
5	64-QAM	2/3	2400	5200
6	64-QAM	3/4	2700	5850
7	64-QAM	5/6	3000	6500
8	256 QAM	3/4	3600	7800
9	256QAM	5/6	4000	Not Valid
10	BPSK	1/2 with 2x repetition	150	Not Valid

B. MAC Layer

The IEEE 802.11ah MAC layer adds several new features in addition to those inherited from IEEE 802.11ac, such as Traffic Indication Map (TIM) segmentation, hierarchical Association IDentifiers (AID), Target Wake Time (TWT), and Restricted Access Window (RAW), all of which help to meets the strict requirements of sensor networks. A hierarchical AID structure is newly established in IEEE 802.11ah to simplify operations and enhance scalability with many connected stations. It consists of 13 bits, and the number of stations it can express is up to $2^{13} - 1$(=8191). The hierarchical AID structure is a four-level structure that consists of page ID(2 bits), block index(5 bits), sub-block index(3 bits), and STA position index in sub-block(3 bits). The 802.11ah standard specifies a new backward-compatible format for reduced header data, management, and new control frames to minimize the MAC header. In 802.11ah, the new and old MAC headers are supported[20].

Other 802.11 standards need beacons to activate the Power-Saving (PS) of the stations for the channel, which is the bottleneck of the entire power management system because the stations must wake up and listen to each and every beacon. IEEE 802.11ah uses a TIM segmentation technique to partition the data transmitted on the TIM into several segments and send the individual TIM segments. When transmitting to stations with pending data for TIM segments, an AP utilizes a Delivery Traffic Indication Map (DTIM) beacon. Numerous TIM beacons transmitting TIM segment data are present between two successive DTIM beacons[7]. To sustain a prolonged power-saving state, only the stations that are a part of that TIM segment need to wake up to listen to their own corresponding beacon. TWT can be employed on stations that only transmit data once to further reduce power consumption. When TWT stations need to wake up to exchange frames, they can negotiate a timeslot with the access points (AP). As a result, they can remain in the power-saving mode for a very long time after their TWT duration[21].

In dense IoT networks, STAs compete for channel access in a high-contention process. As a result, the network's performance will be degraded. As a result, a group-based restricted access window (RAW) mechanism is included in the IEEE 802.11ah standard. In this case, a specific group of STAs is only allowed medium access during the allotted time[9]. A detailed description of the RAW mechanism is given in the next section of this paper.

IV. Restricted Access Window

The Restricted Access Window or RAW mechanisms of the IEEE 802.11ah protocol is the main focus of this paper. The RAW mechanism's primary goal is to reduce collisions and throughput improvement in dense IoT networks where hundreds or even thousands of related stations require access to the channel[2]. It divides the stations into groups to reduce the number of stations that can use the channel simultaneously and allows only those stations belonging to specific groups to access the channel at certain times[13]. Fig. 2 shows the RAW grouping mechanism.

Each interval of the airtime is allotted to a different RAW group. The AP node transmits a RAW Parameter Set (RPS), including information about the group stations and the interval's beginning and ending duration[13]. One or more RAW periods might be present during a beacon interval. In addition, each RAW slot can consist of multiple slots with group positions evenly distributed between them. The duration and number of time slots in each RAW slot are also included in the RPS. Any station may use the channel outside of the RAW ranges[9].

Unlike earlier IEEE 802.11 technologies, each station uses two back-off modes to manage EDCA (Enhanced Distributed Channel Access) connectivity within a designated RAW slot. The first back-off function mode is employed outside of RAW slots, whereas the second is employed within RAW slots. In the initial regression mode, the station halts its back-off at the start of each RAW and restarts again at the end of RAW. In the second return mode, stations start with the original return mode at the beginning of their RAW time period and leave the return mode at the end of their RAW time period[8].

Since IEEE 802.11ah assigns RAW-based channel operation to STAs to lower the contention level, in contrast to legacy 802.11 WLAN protocols, it is crucial to develop analytical models to evaluate IEEE 802.11ah-based WLAN performance based on the RAW-based channel operating system[22].

V. Results and Discussions

Our findings using the ns-3 [23] implementation of the IEEE 802.11ah standard are presented in this section. The effects of various network-related characteristics on RAW performance are

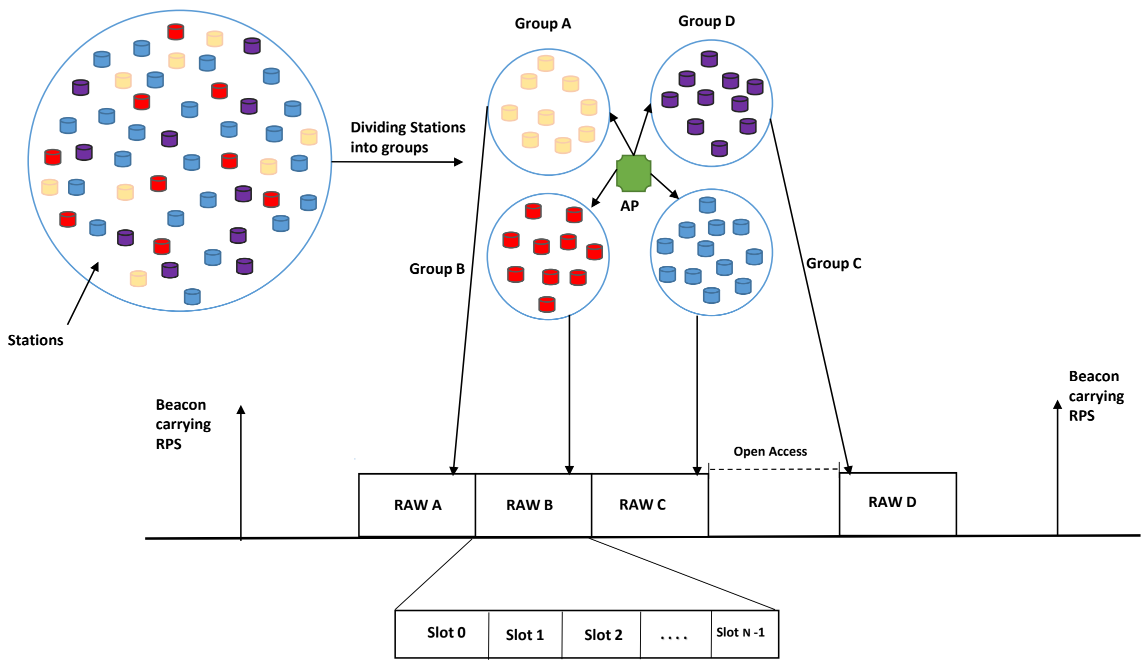

Fig. 2: RAW mechanism of IEEE 802.11ah

evaluated, and an experimental setup is given. We analyze an IoT network scenario where numerous battery-powered sensors periodically send data (through an AP) at regular intervals.

RAW performance is evaluated in terms of throughput. Based on the packets an AP successfully receives each second, throughput is computed. We evaluated the throughput of the network using the RAW mechanism by changing the number of stations, the number of groups, and the number of stations per group. The default RAW parameters used in this experiment are given in TABLE III.

TABLE III: Simulation parameters used in our study

Parameters	Value
Bandwidth	2 MHz
Data rate	650 Kbps
Traffic types	UDP
Modulation and coding scheme	MCS0
Initial backoff window	64
Backoff time	$(W_{min}/2)$ x Slot time
SIFS, DIFS	16 μ s , SIFS+2 x Slot time
CW_{min}, CW_{max}	15, 1023
Simulation area	1000 x 1000 m^2 (Flat-grid)
Beacon interval	100 ms.
No. of stations	1000 (Max.)
Simulator	ns-3

In Fig. 3, we assume the number of stations to be 400, 500, and 600. Altering the number of RAW groups, we monitor the performance of the network in terms of its throughput. As the number of the RAW group increases, we can see an increase in the throughput of the network and as the grouping of stations reaches 7 and 8 groups we can see a maximum increase in the throughput after which it gradually decreases. This is due to the fact that with less number of groups, there can still be collisions among stations in the same groups, since the number of stations in each group is still maximum, whereas for 7 and 8 groups there is an even distribution of stations which further results in less collision among the stations trying to access the channel, and with further increase in the number of groups we can see that the throughput gradually decreases instead of increasing since there will be an increase in the round trip time among the stations.

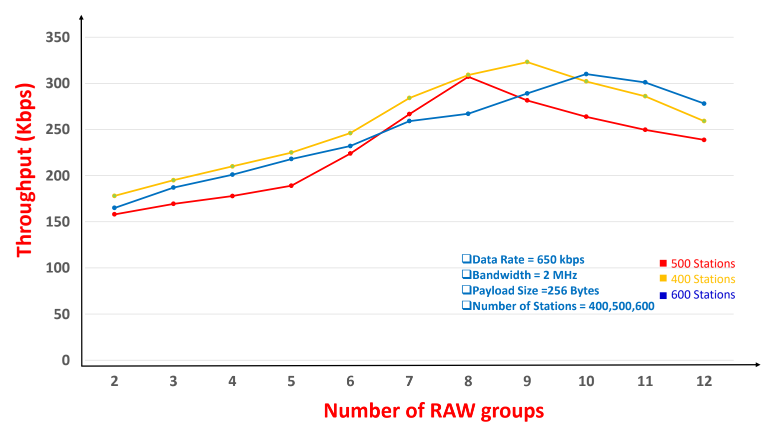

Fig. 3: *Throughput vs Number of RAW groups for various number of stations*

In Fig. 4, we observe the throughput of the network with respect to the number of stations for different numbers of RAW groups (in this case we take 2, 4, 8). It can be seen that for a RAW group of 2, the maximum throughput can be obtained for 200 stations. Whereas for group 4 maximum throughput can be obtained for 300 and 400 stations and for RAW group 8, maximum throughputs can be obtained for 600 and 700 stations after which it gradually decreases.

This is because, for group 2 with an increase in the number of stations, the throughput of the network increases for 100 and 200 stations which are maximum because there is an even distribution of stations and therefore less channel contention among the stations, after which it gradually decreases due to the increase in the round trip time among the stations. And for group 4, stations

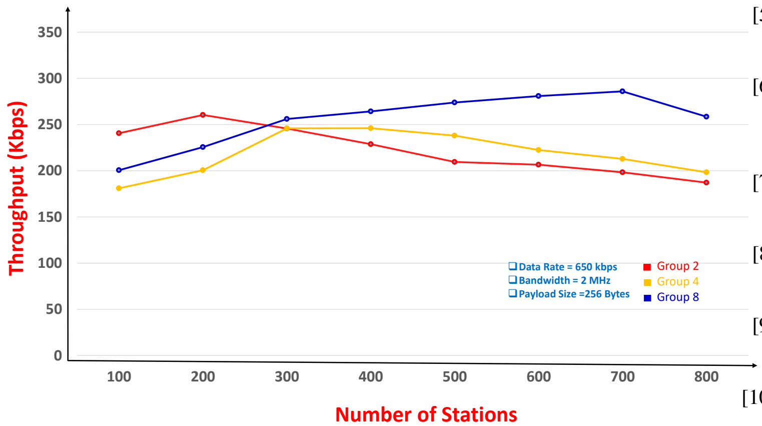

Fig. 4: *Throughput vs Number of Stations for various number of RAW groups*

300 and 400 have the maximum throughput and it also decreases for a higher number of stations with the channel contention and the round trip time as the reason. Also for group 8, we can see the same performance of the network but stations 600 and 800 have the maximum throughput with the channel contention and the round trip time as the reason for this network behavior.

VI. Conclusion

In this paper, we look into the efficiency of the new RAW mechanism that was recently introduced in the IEEE 802.11ah version of the standard. It can be seen that network performance in terms of throughput is affected by several factors, including the number of stations and the number of groups in the network. Varying these parameters can have a significant impact on the network's performance and can either improve or degrade the network's throughput. Optimizing the number of stations and groups requires appropriate consideration of the network's topology, channel condition, and traffic load. Through simulation and modeling, the optimal values for these parameters can be determined to maximize the network's throughput. Overall, the findings and results presented in this paper confirm and acknowledge IEEE 802.11ah's potential as one of the key enabling technologies for developing M2M deployments on a large-scale network that are low-cost and energy-efficient, as well as the future potential of IoT applications capable of supporting a large number of IoT devices. Checking the network performance using the RAW mechanism in terms of other network parameters, such as energy and latency, has been kept for future work.

References

[1] L. Zheng, M. Ni, L. Cai, J. Pan, C. Ghosh, and K. Doppler, "Performance analysis of group-synchronized DCF for dense IEEE 802.11 networks," *IEEE Transactions on Wireless Communications*, vol. 13, no. 11, pp. 6180–6192, 2014.

[2] E. R. Alvarado and I. Lavrinovica, "Improved Restricted Access Window Mechanism for IEEE 802.11ah Performance Optimization," in *2021 25th International Conference Electronics*, pp. 1–6, IEEE, 2021.

[3] N. F. Charania, M. K. Giluka, B. R. Tamma, and A. Franklin, "DEARF: Delay and Energy Aware RAW Formation Scheme to Support Delay Sensitive M2M Traffic in IEEE 802.11ah Networks," *arXiv preprint arXiv:1709.03723*, 2017.

[4] M. Mahesh and V. Harigovindan, "Throughput and energy efficiency analysis of the IEEE 802.11ah restricted access window mechanism," in *Smart and Innovative Trends in Next Generation Computing Technologies: Third International Conference, NGCT 2017, Dehradun, India, October 30-31, 2017, Revised Selected Papers, Part II 3*, pp. 227–237, Springer, 2018.

[5] W. Sun, M. Choi, and S. Choi, "IEEE 802.11ah: A long range 802.11 WLAN at sub 1 GHz," *Journal of ICT standardization*, vol. 1, no. 1, pp. 83–108, 2013.

[6] A. Šljivo, D. Kerkhove, L. Tian, J. Famaey, A. Munteanu, I. Moerman, J. Hoebeke, and E. De Poorter, "Performance Evaluation of IEEE 802.11ah Networks With High-Throughput Bidirectional Traffic," *Sensors*, vol. 18, no. 2, p. 325, 2018.

[7] Z. Liu and P. Lv, "RO-RAW: Run-Time Restricted Access Window Optimization in IEEE 802.11 ah Network with Extended Kalman Filter," *Wireless Communications and Mobile Computing*, vol. 2020, pp. 1–10, 2020.

[8] L. Tian, E. Khorov, S. Latré, and J. Famaey, "Real-Time Station Grouping under Dynamic Traffic for IEEE 802.11ah," *Sensors*, vol. 17, no. 7, p. 1559, 2017.

[9] S. P. Badarla and V. Harigovindan, "Restricted Access Window-Based Resource Allocation Scheme for Performance Enhancement of IEEE 802.11ah Multi-Rate IoT Networks," *IEEE Access*, vol. 9, pp. 136507–136519, 2021.

[10] U. Sangeetha and A. Babu, "Performance analysis of IEEE 802.11ah wireless local area network under the restricted access window-based mechanism," *International Journal of Communication Systems*, vol. 32, no. 4, 2019.

[11] E. Khorov, A. Krotov, A. Lyakhov, R. Yusupov, M. Condoluci, M. Dohler, and I. Akyildiz, "Enabling the Internet of Things With Wi-Fi Halow—Performance Evaluation of the Restricted Access Window," *IEEE Access*, vol. 7, pp. 127402–127415, 2019.

[12] C. Kai, J. Zhang, X. Zhang, and W. Huang, "Energy-Efficient Sensor Grouping for IEEE 802.11ah Networks With Max-Min Fairness Guarantees," *IEEE Access*, vol. 7, pp. 102284–102294, 2019.

[13] L. Tian, E. Lopez-Aguilera, E. Garcia-Villegas, M. T. Mehari, E. De Poorter, S. Latré, and J. Famaey, "Optimization-Oriented RAW Modeling of IEEE 802.11ah Heterogeneous Networks," *IEEE Internet of Things Journal*, vol. 6, no. 6, pp. 10597–10609, 2019.

[14] O. Raeesi, J. Pirskanen, A. Hazmi, T. Levanen, and M. Valkama, "Performance evaluation of IEEE 802.11ah and its restricted access window mechanism," in *2014 IEEE international conference on communications workshops (ICC)*, pp. 460–466, IEEE, 2014.

[15] Y. Wang, K. K. Chai, Y. Chen, J. Schormans, and J. Loo, "Energy-aware Restricted Access Window control with retransmission scheme for IEEE 802.11ah (Wi-Fi HaLow) based networks," in *2017 13th annual conference on wireless on-demand network systems and services (WONS)*, pp. 69–76, IEEE, 2017.

[16] K. Ogawa, M. Morikura, K. Yamamoto, and T. Sugihara, "IEEE 802.11ah Based M2M Networks Employing Virtual Grouping and Power Saving Methods," *IEICE Transactions on Communications*, vol. 96, no. 12, pp. 2976–2985, 2013.

[17] M. Dong, Z. Wu, X. Gao, and H. Zhao, "An efficient spatial group restricted access window scheme for IEEE 802.11ah networks," in *2016 sixth international conference on information science and technology (ICIST)*, pp. 168–173, IEEE, 2016.

[18] C. W. Park, D. Hwang, and T.-J. Lee, "Enhancement of IEEE 802.11ah MAC for M2M Communications," *IEEE Communications Letters*, vol. 18, no. 7, pp. 1151–1154, 2014.

[19] D. Bankov, E. Khorov, A. Kureev, and A. Lyakhov, "Improving Efficiency of Heterogeneous Wi-Fi Networks with Energy-Limited Devices," in *Internet of Things, Smart Spaces, and Next Generation Networks and Systems: 16th International Conference, NEW2AN 2016, and 9th Conference, ruSMART 2016, St. Petersburg, Russia, September 26-28, 2016, Proceedings 16*, pp. 181–192, Springer, 2016.

[20] T. Kim and J. M. Chang, "Enhanced Power Saving Mechanism for Large-Scale 802.11ah Wireless Sensor Networks," *IEEE Transactions on Green Communications and Networking*, vol. 1, no. 4, pp. 516–527, 2017.

[21] L. Tian, J. Famaey, and S. Latré, "Evaluation of the IEEE 802.11ah Restricted Access Window mechanism for dense IoT networks," in *2016 IEEE 17th international symposium on a world of wireless, mobile and multimedia networks (WoWMoM)*, pp. 1–9, IEEE, 2016.

[22] M. Mahesh, B. S. Pavan, and V. Harigovindan, "Data Rate-Based Grouping to Resolve Performance Anomaly of Multi-Rate IEEE 802.11ah IoT Networks," *IEEE Networking Letters*, vol. 2, no. 4, pp. 166–170, 2020.

[23] "What is ns-3." https://www.nsnam.org/overview/what-is-ns-3/. online.