International Journal of Academic Engineering Research (IJAER)
ISSN: 2643-9085
Vol. 9 Issue 1 January - 2025, Pages: 7-16

Performance and Energy Optimization for IEEE 802.11ah using Integrated Approaches

[1]Uduji Chikordi Joseph, [2]Anioke Chidera Linda

[1,2]Department of Electronic and Computer Engineering, University of Nigeria Nsukka, Enugu State, Nigeria

ABSTRACT: *IEEE 802.11ah, commonly known as Wi-Fi HaLow, is an emerging standard tailored for low-power, long-range Internet of Things (IoT) applications. While the adoption of the IEEE 802.11ah standard has enhanced IoT network performance, several challenges remain, such as the hidden node problem, channel contention and collisions, and high energy consumption caused by idle listening. These issues primarily arise from inefficient station grouping schemes and inadequate scheduling of the Target Wake Time (TWT). This work addresses these challenges by proposing an integrated approach that optimizes the performance and energy efficiency of IEEE 802.11ah networks. The proposed solution combines Target Wake Time (TWT), which schedules wake-up times for IoT devices to minimize idle listening, with Restricted Access Window (RAW), which coordinates transmission opportunities to reduce channel contention and collisions. The integration of the TWT and RAW mechanisms aims to optimize key network performance metrics such as throughput, delay, channel utilization, and energy efficiency. To validate the effectiveness of the proposed scheme, simulations were conducted using OMNeT++ 6.0, comparing the integrated TWT + RAW approach against a traditional RAW slot allocation mechanism based on a transitive grouping scheme. Results from the simulations revealed that the TWT + RAW approach significantly enhances network performance, achieving a 14.75% increase in network throughput, a substantial 20.5% reduction in network delay, and a 3% improvement in channel utilization. Additionally, the integrated approach demonstrated improved energy efficiency, attributed to reduced idle listening and more efficient energy usage.*

Keywords: Target wake time, Restricted access window, OMNet++ 6.0, Raw slot allocation, IoT, IEEE 802.11ah.

1. INTRODUCTION

The rapid increase in numbers of wireless technology and the increasing efficiency of small, embedded-systems has resulted in a technological convergence that is nowadays known as the Internet of Things (IoT) [1][2]. The Internet of Things (IoT) represents a significant evolution in modern technology, enabling everyday physical objects to be interconnected via the internet, allowing them to collect, share, and analyze data. IoT integrates a vast array of devices, from sensors, wearable's, and household appliances to complex industrial systems, transforming the way humans interact with their environment. By embedding communication capabilities in these objects, IoT enables real-time data exchange, remote monitoring, and automation, enhancing both convenience and efficiency across various domains, such as smart homes, healthcare, agriculture, and industrial processes. IEEE 802.11ah, a wireless networking standard, was designed to address the unique requirements of IoT applications by providing long-range communication, support for large-scale networks, and energy efficiency. Operating in the sub-1 GHz frequency band, IEEE 802.11ah can support communication over several kilometers with lower energy consumption compared to the traditional Wi-Fi standards [3]. IoT designs make it suitable for smart cities, industries and agriculture; including where large numbers of devices are required to communicate over long distances with limited energy resources.

A key feature proposed in the IEEE802.11ah standard is the Restricted Access Window (RAW). The RAW mechanism organizes devices into groups and assigns them specific time slots for medium access. RAW reduces contention and packet collisions leading to improved channel utilization, particularly in dense IoT environments [3]. RAW manages medium access in dense networks. RAW divides the network devices into groups, assigning specific time slots during which each group is allowed to access the communication medium [3]. This reduces contention for the medium, lowers packet collisions, and improves overall throughput and latency in the network [4]. In order to achieve optimal performance and energy efficiency, it is essential to integrate both mechanisms in a coordinated manner. Another mechanism introduced in the IEEE 802.11ah standard to enhance energy efficiency is the Target Wake Time (TWT). TWT is a power-saving mechanism that allows IoT devices to negotiate specific wake-up times with the access point (AP), enabling devices to remain in a low-power sleep state when communication is not required [5]. This allows devices to minimize energy consumption while ensuring they are awake and active only during pre-scheduled communication windows. TWT plays a crucial role in reducing energy consumption, especially in networks with battery-powered or resource-limited devices that need to operate for extended periods [5]. TWT reduces the likelihood of packet collisions and idle listening by coordinating wake-up times, thus conserving energy. While both TWT and RAW are effective mechanisms for improving energy efficiency and network performance, respectively, their individual application may not fully address the challenges of large-scale IoT networks. An integrated approach that combines TWT and RAW will provide synergistic benefits in dense IoT networks. This integrated solution will ensure that devices are awake only when they need to transmit or receive data, and that medium access is efficiently managed to prevent congestion. Such a coordinated approach is critical in large-scale IoT deployments, where the balance between energy efficiency and performance is a key determinant of network sustainability.

The network performance in dense IoT scenarios may be improved if devices are dynamically grouped on the basis of their traffic characteristics and transmission slot assignments [9]. An ANN-based optimization framework for the RAW mechanism in IEEE 802.11ah has been shown to provide a significant performance boost in a dense IoT network [11]. However, in [9] and [11], there is an increase in network delay if the selection of the slot size is done by considering the volume of traffic and the number of nodes in the network. Secondly, there is an increase in computational complexity in training and running the ANN-based optimization framework which consumes a lot of power. Several key challenges faced by IEEE 802.11ah network in an IoT environment such as increased registration time, hidden node problem and poor channel utilization were solved by the transitive grouping (TG) scheme [12]. Advanced algorithms for network sectorization and station grouping were integrated into the TG scheme to provide a comprehensive solution to the aforementioned key challenges. A solution for optimizing the IEEE 802.11ah referred to as the Model-Based RAW Optimization Algorithm (MoROA), was presented in [14]. MoROA uses a surrogate model to determine the optimal RAW configuration in real-time, for heterogeneous stations and dynamic traffic. MoROA addresses the limitations of static RAW configuration and homogenous station grouping. This offers a significant improvement in terms of throughput, latency & real-time optimization for heterogeneous IoT networks. However, the issue of energy efficiency was not discussed. Two novel mobility-aware clustering algorithms that successfully address critical issues in mobile WSNs, such as cluster stability, data loss, and energy efficiency were proposed in [13]. The proposed algorithms are the Mobility-aware Centralized Clustering Algorithm (MCCA) and the Mobility-aware Hybrid Clustering Algorithm (MHCA). The MCCA and MHCA algorithms significantly improve network lifetime & performance by mitigating the effects of node mobility. While the MCCA shows promise in stabilizing clusters, it introduces overhead and scalability concerns in large networks. A MIMO-based energy efficient unequal hybrid clustering (MIMO-HC) protocol for IoT applications in the 5G environment and beyond divides the network node hierarchically into unequal hybrid cluster to share energy consumption among the cluster head and to avoid hotspot issue that can be caused by overloading cluster heads closer to the central station [6]. This approach is not suitable for highly dense network since it is not flexible. The MIMO-HC protocol employs mixed topology (single hop topology and multi hop topology) which results in frequent data transmission and contention. The issue of energy efficiency in addition to device grouping was tackled by the application of the RAW and the target wake time (TWT) algorithm [16]. The authors evaluated the energy consumption in an IEEE 802.11ah network by the application of the RAW and TWT independently to determine which network feature best minimizes energy consumption. Traditionally, WSNs have relied on Low – Duty Cycling (LDC) protocol for energy conservation while effective, LDC protocol have limitation, such as ide listening and overhearing, making them unsuitable for ultra-low power and high-efficient application. However, [17] tackles the issue of energy efficiency by utilizing wake-up radio receivers (WuRx) to enhance energy savings in wireless sensor Network (WSNs).

The main contributions in this paper can be summarized as;

- Reduction of hidden node problem in the network using CVT-ME algorithm
- Reduction in contention and collision in the network using ETH grouping
- Reduction in network delay in order to minimize packet loss rate by scheduling Target wake time and ADA-TDMA algorithm for slot allocation
- Reducing energy consumption due to idle listening using Target wake time.
- Integration of TWT+RAW to optimize overall performance.

The rest of the paper is organized as follows: Section II discusses the research methods applied in the implementation of the TWT+RAW technique. Section III introduces the simulation tool employed and enumerates the simulation parameters used. The results of the simulation were discussed in section IV in terms of different performance metrics. Section V concludes the paper.

2. RESEARCH METHOD

The implementation of the Restricted Access Window (RAW) in this IoT network follows from the approach applied in [12] for the TG scheme. This method uses a multi-layered configuration approach, integrating both physical parameters and algorithmic controls to optimize network efficiency. The base configuration establishes RAW slots with a duration of 10 milliseconds each, and 10 slots per RAW period, as defined in table 1. The RAW architecture shown in figure 1 is organized hierarchically, consisting of one main Access Point (AP), several Relay Access Points (RAPs) distributed across multiple sectors, and groups of IoT stations under each RAP. By default, the network is configured with 5 sectors (`*numSectors*`), each containing 1 RAP (`*numRapsPerSector*`), and 10 stations per RAP (`*numStationsPerRap*`).

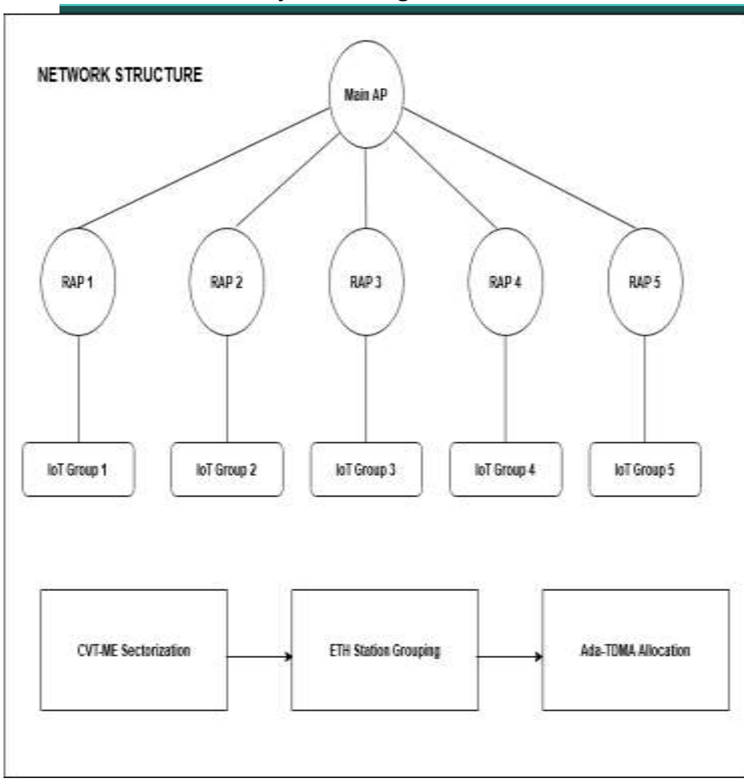

Figure 1: Restricted Access Window Architecture

The RAW algorithm implementation utilizes a three-phase approach as shown in figure 1. This approach includes the following stages:

2.1 CVT-ME Sectorization: The Centroidal Voronoi Tessellation with Modified Energy (CVT-ME) algorithm divides the network space into sectors. The CVT-ME setup creates Voronoi regions based on station density. It iteratively adjusts sector centers to minimize energy consumption and balances the number of stations per sector to prevent overloading. CVT-ME can be represented analytically by first determining the Voronoi tesselation from equation1 and then evaluating the centroid by applying equation 2.

Voronoi Tesselation:

$$V_i = \{x \in \mathbb{R}^2 \big| \parallel - C_i \parallel \leq \parallel x - C_j \parallel, \forall_j \neq i\} \quad (1)$$

where V_i − Voronoi cell for sector i

C_i − Center of Voronoi cell i

x − Position of a point in the network space

Centroid Calculation:

$$C_i = \frac{\sum x \epsilon V_i {}^{x.w(x)}}{\sum x \epsilon V_i {}^{w(x)}} \quad (2)$$

where $w(x)$ = Weight function representing energy demand or station density at point x

Energy Minimization:

$$minimum\ E = \sum_{i=1}^{N} \sum_{x \epsilon V_i} w(x) \parallel x - C_i \parallel^2 \quad (3)$$

where E – Total energy consumption
N – Total number of sectors

2.2. ETH Station Grouping: The Enhanced Traffic Handling (ETH) grouping algorithm organizes stations within each sector into two subgroups. It divides stations evenly, using a ceiling function to handle odd numbers, thus maintaining balanced group sizes and reducing channel access conflicts. The formula for group size is in equation 4

$$groupSize = \left\lceil \frac{numStations}{2} \right\rceil \quad (4)$$

where *numStations* = Total number of stations in the sector

Subgroup formation is expressed in equation 5:

Let S_i $be\ the\ set\ of\ stations\ in\ sector\ i, then$:

$$G_{i,1} = \{s_j \big| j \leq groupSize\}, G_{i,2} = \{s_j \big| j > groupSize\}$$
(5)

where $G_{i,1}$ − First subgroup

$G_{i,2}$ − Second subgroup

s_j − jth station in sector i

2.3. Ada-TDMA Slot Allocation: The Adaptive Time Division Multiple Access (Ada-TDMA) algorithm dynamically allocates RAW slots based on the size of each sector. The slot allocation ensures a minimum of 10 and a maximum of 100 slots per sector. Ada-TDMA is evaluated as shown in equation 6;

$$slots_i = max(10, min(100, numStation_i * k)) \quad (6)$$

where $slots_i$ − Number of allocated slots for section i

$numStation_i$ − Number of stations in sectior i

k − scaling factor (default: k = 10)

The adaptive slot calculation is expressed in equation 7

$$\Delta slots_i = slots_i \times \frac{numStation_{i,new}}{numStation_{i,old}} \quad (7)$$

where $\Delta slots_i$ − Adjusted slot allocation

International Journal of Academic Engineering Research (IJAER)
ISSN: 2643-9085
Vol. 9 Issue 1 January - 2025, Pages: 7-16

$numStation_{i,new}$ – New number of stations

$numStation_{i,old}$ – Previous number of stations

This adaptive mechanism adjusts slot allocation according to the number of stations in each sector. Energy efficiency is a critical consideration in the system. It tracks residual energy capacity and monitors power consumption. The device transmitter power settings, AP, RAPs and IoT stations are configured with the values in table 1. Performance monitoring is incorporated to ensure comprehensive analysis, including end-to-end delay recording, vector and scalar data collection for statistical analysis, and visualizations of transmissions and network topology. A custom network recorder is used for periodic measurements to provide insights into network performance.

Figure 2 presents the RAW sequence. Timing and synchronization are maintained through 100-millisecond beacon intervals for both AP and RAPs, with 90-byte beacons for efficient timing distribution. The system updates algorithm parameters at intervals of 1 second and varies packet transmission intervals between 20 and 200 milliseconds to prevent congestion. The RAW mechanism is seamlessly integrated with the MAC layer, operating in IEEE 802.11ah mode with customized contention window settings (`$cwMin = 8$` and `$cwMax = 20$`). It uses 120-bit MAC headers and a 250Mbps bitrate configuration. This design allows the RAW mechanism to dynamically adapt to changing network conditions while providing efficient channel access control. The modular approach also facilitates future enhancements to individual algorithmic components while preserving the overall structure of the RAW system.

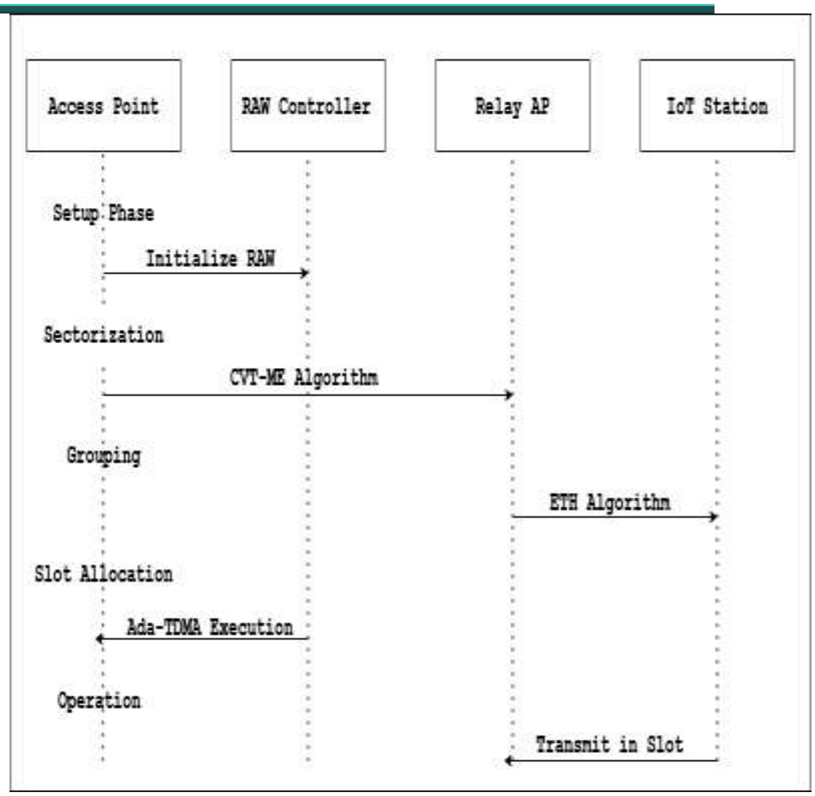

Figure 2: Restricted Access Window Sequence

B. Implementing TWT in the IEEE 802.11 MAC layer

The TWT enhancement includes several core components: configuration parameters, core mechanisms, integration with the RAW system, and performance considerations. The primary configuration parameters are `twtEnabled`, a Boolean flag to enable or disable TWT functionality; `twtInterval`, which defines the duration between wake periods; `twtDuration`, specifying the length of each wake period; and `twtOffset`, an initial delay before the first wake period.

The core mechanisms of the TWT implementation shown in figure 3 include an initialization phase, state management, and message handling. During the initialization phase, the MAC layer extends standard IEEE 802.11 functionalities, creating handlers for wake and sleep messages and scheduling the initial wake event based on the configured offset. The state management involves two primary states: Wake and Sleep. The implementation manages transitions between these states using message handlers and maintains timing synchronization through scheduled events. The message handling system processes three types of messages: wake-up triggers, sleep triggers, and standard MAC layer messages, ensuring smooth transitions between active and inactive periods.

The operational workflow for the TWT is presented in figure 4. It begins with the startup sequence, where the MAC layer components are initialized, TWT parameters are configured, and the initial wake event is scheduled. During regular operation, the system alternates between wake and sleep states, processes messages during wake periods, and maintains synchronization with network timing. In the shutdown process, scheduled events are cleaned up, the MAC layer reverts to standard operation if TWT is disabled, and operational statistics are collected and reported. This comprehensive implementation aims to enhance energy efficiency and reduce latency while maintaining reliable communication within the IEEE 802.11 MAC framework.

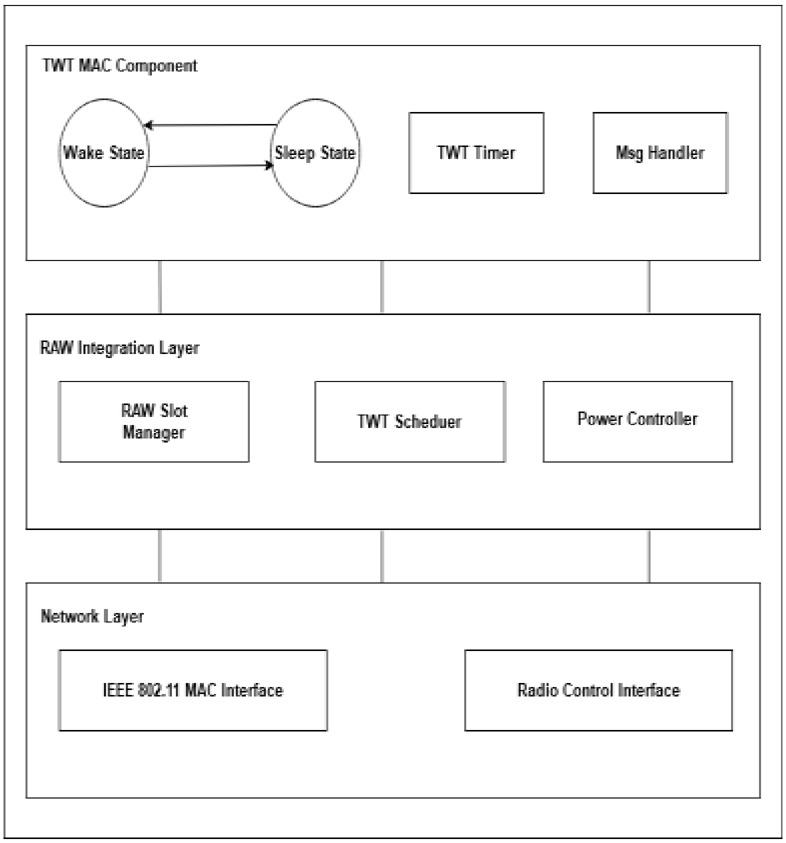

Figure 3: Target Wake Time (TWT) architecture

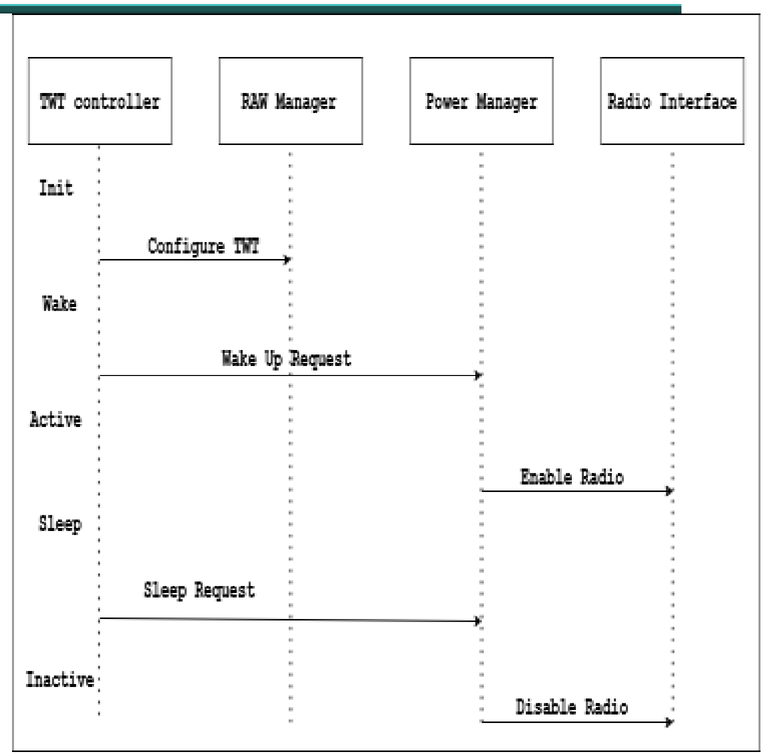

Figure 4 – Target Wake Time (TWT) Sequence

C. The integrated TWT+RAW

The integration between TWT and RAW (referred in this paper as TWT+RAW) is achieved through a coordination layer that manages the interaction between the two mechanisms. This integration ensures that devices wake up only during their assigned transmission opportunities, minimizing energy consumption while maintaining efficient communication. The Access Point (AP) coordinates the TWT schedules of devices with their assigned RAW slots. Devices are configured to wake up just before their RAW slot begins, ensuring they are ready to transmit or receive data during their allocated window. The twtOffset parameter is adjusted to align the TWT wake period with the start of the RAW slot. This synchronization ensures that devices are active only when they have a transmission opportunity, reducing unnecessary wake-ups and thereby conserving energy. The coordination layer also resolves potential conflicts where a device's TWT wake period might overlap with another device's RAW slot. If such conflicts arise, the AP can take corrective actions, such as adjusting the TWT schedule (by modifying twtInterval or twtOffset) to avoid overlapping or reassigning RAW slots to ensure fair access and minimize contention. During sleep periods, the radio is turned off or placed in a low-power state to save energy. The coordination layer ensures that devices transition to the active state only during their assigned RAW slots, minimizing unnecessary wake-ups. Precise timing is maintained by synchronizing TWT wake periods with the network's beacon intervals. The

International Journal of Academic Engineering Research (IJAER)
ISSN: 2643-9085
Vol. 9 Issue 1 January - 2025, Pages: 7-16

AP broadcasts timing information in beacon frames, allowing devices to adjust their TWT schedules dynamically based on network conditions.

3. SIMULATION

The proposed TWT+RAW scheme is simulated in OMNeT++ 6.0 environment. Figure 5 shows the simulation environment of the TWT+RAW approach in the IEEE 802.11ah.

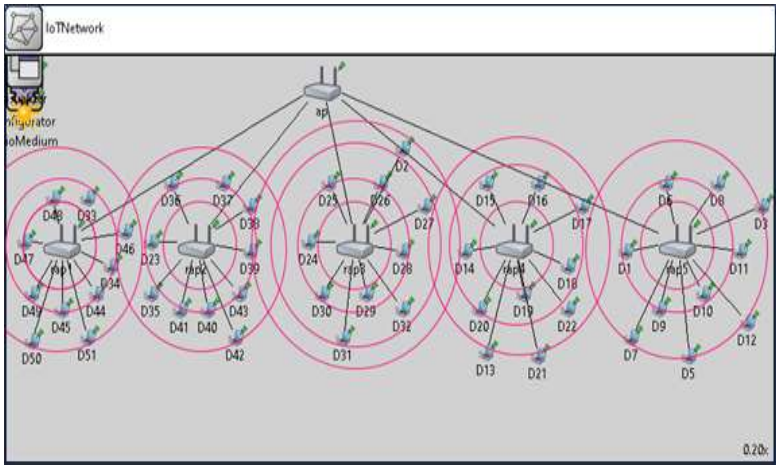

Figure 2: TWT+RAW simulation environment in OMNeT++ 6.0

Table 1: Summary of network/simulation parameters

PARAMETERS	**VALUES**
Network	IoT network
Simulation Time	100s
Number of AP	1
Number of sectors	5
Number of Stations per Sector	10
Simulation Area Dimension (X,Y,Z)	(3000m, 3000m, 1m)
Path Loss Model	Free Space Path Loss
Background Noise Power	-110 dBm
Traffic type	Constant Bit Rate
PHY Header length	6µs
MAC Header Lenth	15 bytes
AP, RAP, IoT Transmitter Power	45 dBm
AP, RAP, IoT Receiver Sensitivity	-85 dBm
Initial Energy Capacity	50J
Send interval	Uniform(20ms, 200ms)
Pending Queue Packet Capacity	8000
Header Bit Length	48 bits
Bit rate	54Mbps
MAC Protocol	IEEE 802.11ah
IEEE 802.11ah Operating mode	g(mixed)
TWT wake interval	100ms
RAW Slot Allocation	Ada-TDMA
Grouping Algorithm	ETH
Sectorization Algorithm	CVT-ME
RAW Slot duration	10ms
Beacon interval	100ms

3.1 Operational Workflow of the TWT+RAW

The operational workflow of the integrated TWT and RAW system begins with the initialization phase, where the AP configures TWT parameters (twtEnabled, twtInterval, twtDuration, twtOffset) for each device. Simultaneously, RAW slots are assigned to groups of devices based on traffic patterns and network density. This phase sets the foundation for coordinated wake and sleep schedules. Next, during the synchronization phase, the AP aligns the TWT wake periods of devices with their assigned RAW slots. Devices are configured to wake up just before their RAW slot begins, ensuring they are ready to communicate during their allocated window. The twtOffset parameter is fine-tuned to achieve this alignment, ensuring seamless transitions between sleep and active states.
In the operation phase, devices alternate between wake and sleep states. When a device wakes up, it communicates with the AP within its assigned RAW slot. Once the RAW slot ends, the device returns to sleep until the next scheduled wake period. This cycle ensures that devices remain energy-efficient while maintaining reliable communication. Finally, the system incorporates dynamic adjustments to adapt to changing network conditions. The AP continuously monitors the network and makes adjustments to TWT schedules or RAW slot assignments as needed. Devices update their TWT parameters based on beacon frames or direct messages from the AP. This adaptability ensures that the system remains efficient and responsive to evolving network demands.

4. RESULTS AND DISCUSSION

The results of the simulation on the integrated approach TWT+RAW schemes are evaluated on the basis of, throughput, channel utilization, energy efficiency, and network delay**.** Furthermore, the TWT+RAW scheme is compared with raw slot mechanism (Transitive grouping scheme). The comparison of the proposed TWT+RAW with raw slot mechanism (Transitive grouping scheme) is on the basis of throughput, network delay, channel utilization. The graphs present the relationships between the aforementioned metrics and the number of stations.

4.1 Effect of TWT+RAW on Network Throughput

Figure 3, shows graph of the network throughput obtained from the integrated mechanism approach (TWT+RAW). The graph shows the achieved throughput as the number of station increase from 10 to 50. As the number of station in the network increases, the throughput for the TWT+RAW scheme experience an exponential increase.

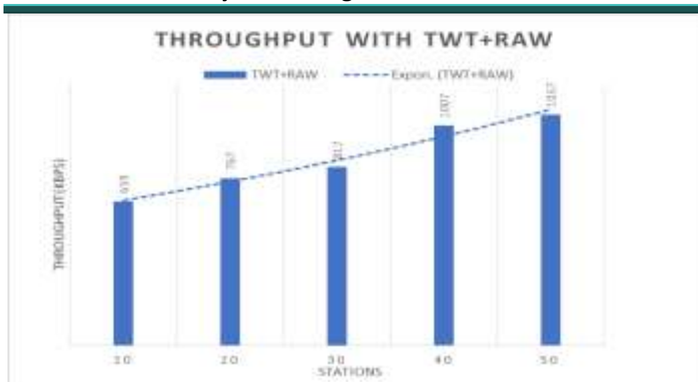

Figure 3: Effect of number of stations on Throughput for TWT+RAW Scheme

In Figure 4, the TWT+RAW scheme is validated with raw slot mechanism (Transitive grouping scheme). Throughput should be as high as possible, high throughput is crucial for high degree of network performance. The combination of TWT and RAW yields consistently higher throughput compared to the raw slot mechanism (Transitive grouping scheme). This is because TWT schedules devices to wake up only during their assigned RAW slots, thereby reducing idle listening, unnecessary transmissions, and collisions. The TWT mechanism ensures that devices only wake up when they need to transmit, which optimizes energy usage and reduces network congestion. Figure 4 show a more pronounced improvement:

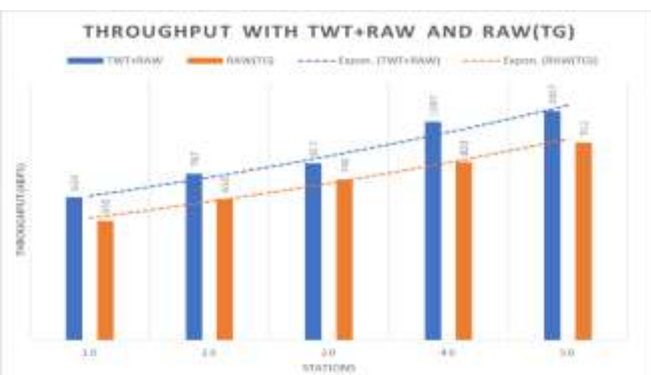

Figure 4: Effect of number of stations on Throughput for TWT+RAW and RAW (TG) Scheme

Table 2 presents a descriptive summary of the achieved network throughput by TWT+RAW and raw slot mechanism (TG scheme). The proposed TWT+RAW and raw slot mechanism (TG scheme) achieved average throughput of 861kbps and 734kbps, respectively. The scheme that has the highest network throughput value is rated to perform better than the other scheme. The TWT+RAW achieved 14.75% improvement (increase) in throughput

4.2 *Effect of TWT+RAW on Network Delay*

Figure 5 shows the graph of the network delay obtained from the integrated mechanism approach (TWT+RAW). The graph shows the effect of network delay on the association and authentication procedures amongst the station in a particular environment as the number of station vary. The network experiences a gradual delay as the number of station increase from 10 to 50.

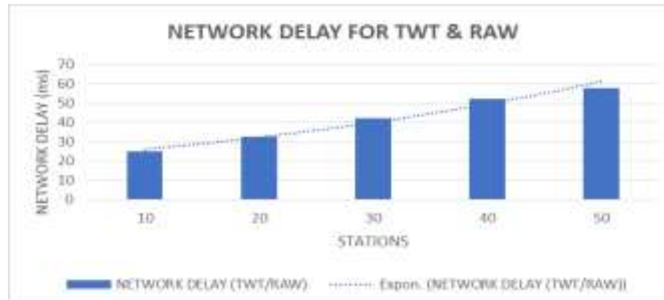

Figure 5: Effect of number of stations on Network delay for TWT+RAW Scheme

In Figure 6, the TWT+RAW scheme is validated with raw slot mechanism (Transitive grouping scheme). The effects on the network delay of TWT+RAW scheme is better than raw slot mechanism (Transitive grouping scheme). As TWT schedules sleep/wake cycles, allowing devices to transmit data without waiting for long periods, combined with RAW's slot allocation, this reduces contention and delays.

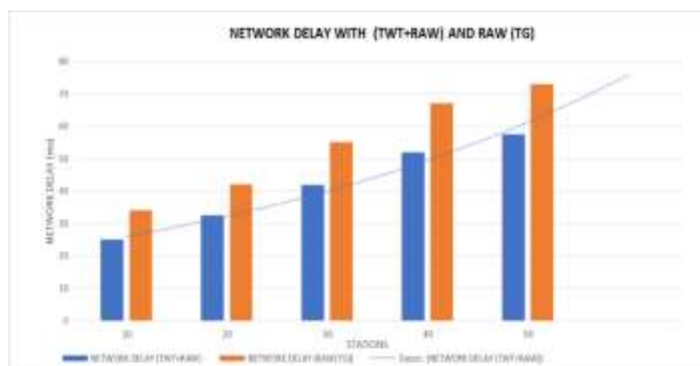

Figure 6: Effect of number of stations on Network delay for TWT+RAW and RAW (TG) Scheme

Furthermore, Table 3 presents a summary of the achieved network delay by TWT+RAW and raw slot mechanism (TG scheme). The proposed TWT+RAW and raw slot mechanism (TG scheme) achieved average network delay of 44ms and 53ms respectively. The scheme that has the lowest network delay value is rated to perform better than the other scheme. TWT+RAW scheme achieved 20.5% improvement (decrease) in network delay.

4.3 Effect of TWT+RAW on Channel Utilization

Channel utilization was used to assess the resource utilization performance. Figure 7 presents the graph of the channel utilization obtained from the integrated mechanism approach (TWT+RAW). The graph shows the relationship between the channel utilization as the number of stations increase from 10 to 50 stations. As the number of station in the network increase, there is a continuous but gradual increase in the channel utilization percentage all through.

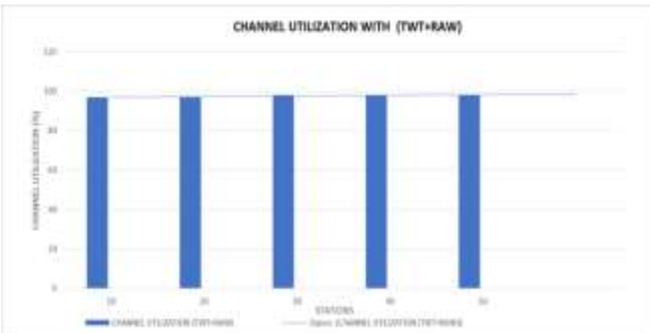

Figure 7: Effect of number of stations on channel utilization for TWT+RAW Scheme

In order to validate the TWT+RAW scheme, Figure 8 also presents the plot of TWT+RAW scheme with raw slot mechanism (Transitive grouping scheme). Channel utilization must be as high as possible thus enhancing the overall network performance. Figure 8 shows that TWT+RAW scheme is better in channel utilization than raw slot mechanism (Transitive grouping scheme), this is because TWT ensures that devices only transmit when necessary, leading to fewer channel access requests that go unused, while RAW employs a better RAW slot allocation mechanism that resulted to a better channel utilization.
Generally, the scheme that has a high channel utilization value is rated to perform better than the other schemes. The average channel utilization is 96% and 93% respectively for both the TWT+RAW scheme and raw slot mechanism (Transitive grouping scheme). It is observed that TWT+RAW scheme increases the channel utilization than raw slot mechanism (Transitive grouping scheme), and TWT+RAW scheme achieved 3% improvement (increase) in channel utilization.

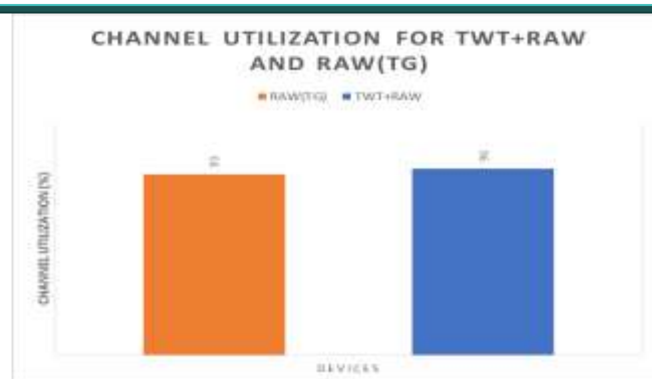

Figure 8: Effect of number of stations on channel utilization for TWT+RAW and RAW (TG) scheme

4.4 Effect of TWT+RAW on Energy Efficiency

Energy efficiency was use to assess how well the network minimizes energy consumption while maintaining acceptable performance levels for data transmission. Figure 9 presents the graph of the energy efficiency obtained from the integrated mechanism approach (TWT+RAW). The graph shows the relationship between the energy efficiency as the number of stations increase from 10 to 50 stations. The integration of both TWT and RAW yields significant energy efficiency improvements. The TWT mechanism ensures devices wake up only when necessary, reducing idle listening, while RAW reduces energy expenditure due to channel contention and collisions. This synergy ensures efficient network operation with minimal energy consumption.

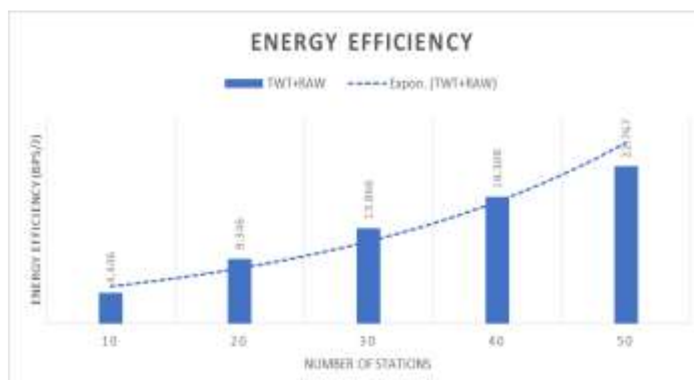

Figure 9: Effect of number of stations on energy efficiency for TWT+RAW

5. CONCLUSION

The integrated approach of TWT+RAW scheme is an improved version of raw slot mechanism (Transitive grouping scheme). The performance of TWT+RAW was evaluated on the basis of network throughput, network delay, channel utilization and energy efficiency metrics. The results showed that the integrated approach TWT+RAW recorded a remarkable improvement over the reference model raw slot mechanism (Transitive grouping scheme). In terms of network throughput, the integration of TWT with RAW has demonstrated a substantial improvement (increase) of 14.75% in network throughput compared to raw slot mechanism (Transitive grouping scheme). In terms of channel utilization, the integration of TWT with RAW has demonstrated a substantial improvement (increase) of 3% in channel utilization compared to raw slot mechanism (Transitive grouping scheme). In terms of network delay, the integration of TWT with RAW has demonstrated a substantial improvement (decrease) of 20.5% in terms of delay compared to raw slot mechanism (Transitive grouping scheme). The TWT + RAW mechanism significantly enhances energy efficiency by allowing devices to remain in sleep mode until their scheduled wake-up time, the combined approach minimizes idle listening and unnecessary energy consumption, which is crucial for battery-powered IoT devices.

REFERENCE

[1] L. Babun, K. Denney, Z. B. Celik, P. McDaniel, and A. S. Uluagac, "A survey on IoT platforms: Communication, security, and privacy perspectives," *Comput. Networks*, vol. 192, 2021, doi: 10.1016/j.comnet.2021.108040.

[2] J. Y. Khan, "Introduction to IoT Systems," *Internet of Things (IoT)*, vol. Internatio, no. January, pp. 1–24, 2019, doi: 10.1201/9780429399084-1.

[3] O. Raeesi, J. Pirskanen, A. Hazmi, T. Levanen, and M. Valkama, "Performance evaluation of IEEE 802.11ah and its restricted access window mechanism," *2014 IEEE Int. Conf. Commun. Work. ICC 2014*, pp. 460–466, 2014, doi: 10.1109/ICCW.2014.6881241.

[4] Muhammad Qutab-Ud-Din "Enhancements And Challenges In IEEE 802.11ah-A Sub-Gigahertz Wi-Fi For IoT Applications", *M.Sc Thesis in wireless communication circuits and systems*, Tampere University of Technology, Finland, November, 2015.

[5] M. Nurchis and B. Bellalta, "Target wake time: Scheduled access in IEEE 802.11ax WLANs," *IEEE Wirel. Commun.*, vol. 26, no. 2, pp. 142–150, 2019, doi: 10.1109/MWC.2019.1800163.

[6] M. Baniata, H. T. Reda, N. Chilamkurti, and A. Abuadbba, "Energy-efficient hybrid routing protocol for IoT communication systems in 5G and beyond," *Sensors (Switzerland)*, vol. 21, no. 2, pp. 1–21, 2021, doi: 10.3390/s21020537.

[7] N. Ahmed and M. I. Hussain, "Relay-based IEEE 802.11ah network: A Smart City solution," *2016 Cloudification Internet Things, CIoT 2016*, no. March, 2017, doi: 10.1109/CIOT.2016.7872922.

[8] A. S. Aminah, D. Perdana, and I. Wahidah, "Energy Consumption Performance on IEEE 802.11ah Networks with Station Grouping Scheme," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 982, no. 1, 2020, doi: 10.1088/1757-899X/982/1/012030.

[9] L. Tian, J. Famaey, and S. Latre, "Evaluation of the IEEE 802.11ah Restricted Access Window mechanism for dense IoT networks," *WoWMoM 2016 - 17th Int. Symp. a World Wireless, Mob. Multimed. Networks*, 2016, doi: 10.1109/WoWMoM.2016.7523502.

[10] X. Lei and S. H. Rhee, "Performance Improvement of Sub 1 GHz WLANs for Future IoT Environments," *Wirel. Pers. Commun.*, vol. 93, no. 4, pp. 933–947, 2017, doi: 10.1007/s11277-017-3947-3.

[11] M. Mahesh and V. P. Harigovindan, "ANN-based optimization framework for performance enhancement of Restricted Access Window mechanism in dense IoT networks," *Sadhana - Acad. Proc. Eng. Sci.*, vol. 45, no. 1, 2020, doi: 10.1007/s12046-020-1287-6.

[12] O. U. Nwogu, U. N. Nwawelu, and C. I. Ani, "Transitive Grouping for Internet of Things Support IEEE 802.11ah using Integrated Approach," *Proc. 5th Int. Conf. Inf. Technol. Educ. Dev. Chang. Narrat. Through Build. a Secur. Soc. with Disruptive Technol. ITED 2022*, pp. 1–8, 2022, doi: 10.1109/ITED56637.2022.10051221.

[13] S. Zafar, A. Bashir, and S. A. Chaudhry, "Mobility-aware hierarchical clustering in mobile wireless sensor networks," *IEEE Access*, vol. 7, pp. 20394–20403, 2019, doi: 10.1109/ACCESS.2019.2896938.

[14] L. Tian, M. Mehari, S. Santi, S. Latre, E. De Poorter, and J. Famaey, "IEEE 802.11ah Restricted Access Window Surrogate Model for Real-Time Station Grouping," *19th IEEE Int. Symp. a World Wireless, Mob. Multimed. Networks, WoWMoM 2018*, 2018, doi: 10.1109/WoWMoM.2018.8449738.

[15] L. Tian, E. Khorov, S. Latré, and J. Famaey, "Real-time station grouping under dynamic traffic for ieee 802.11ah," *Sensors (Switzerland)*, vol. 17, no. 7, pp. 1–24, 2017, doi: 10.3390/s17071559.

[16] S. Santi, L. Tian, E. Khorov and J. Famaey "Accurate Energy Modeling and Characterization of IEEE802.11ah RAW and TWT" *Sensors, vol 19, Issue 11, 2019, doi: 10.3390/s19112614.*

[17] J. Aranda, M. Schölzel, D. Mendez, and H. Carrillo, "Multi modal wireless sensor networks based on wake-up radio

receivers: An analytical model for energy consumption," *Rev. Fac. Ing.*, no. 91, pp. 113–124, 2019, doi: 10.17533/udea.redin.20190401.