The Evaluation of IEEE 802.11ah Performance Based on the Effect of Mobility, Node’s Number, and Traffic Using the Markov Chain Model

Tengku Ahmad Riza*, Dadang Gunawan, and Ajib S. Arifin

Electrical Engineering Department, University of Indonesia, Indonesia; Email: guna@eng.ui.ac.id (D.G.), ajib@eng.ui.ac.id (A.S.A.)
*Correspondence: tengku.ahmad@ui.ac.id (T.H.R.)

***Abstract*—The Internet of Things (IoT) is currently growing rapidly and one of the technologies supporting it is wireless fidelity (Wi-Fi) standard IEEE 802.11ah. This technology supports mobility and has a large number of nodes or devices with small energy consumption; hence it is capable of functioning for a long time. In this study, three work scenarios were proposed, namely 1) the mobility, which involves changing the distance between the access point (AP) and the nodes, 2) changing the node’s number, and 3) testing the variations in traffic by changing the collision possibilities and the RAW (Restricted Access Window) (the full title). slot duration in order to analyze the IEEE 802.11ah network performance parameters. The results showed that there was a decrease in throughput, an increase in energy consumption, and a delay due to changes in the nodes’ number and movement/mobility. Also, the variation in traffic by changing the collision probability causes a change in throughput, hence when the collision probability is large, the throughput decreases, while the delay value increases, and vice versa. In conclusion, this study proved that changes in the nodes’ number, movement/mobility, and traffic collision probability affected the IEEE 802.11ah network's performance in throughput, delay, and energy consumption parameters.**

***Keywords*——IoT, 802.11ah, throughput, delay, energy consumption**

I. INTRODUCTION

The Internet of Things (IoT) is a technology that is currently growing rapidly into the Internet of Everything (IoE), in which all devices are connected for data exchange [1, 2]. IoT can connect humans, devices, and software over the Internet, thereby creating intelligent technology as a service solution for people [3].

One of the supporting technologies is Wireless Fidelity (Wi-Fi), which does not require much infrastructure and offers fast network access [4].

A wireless network standard issued by the IEEE that works at frequencies below 1 GHz is the IEEE 802.11ah. Furthermore, it is capable of reducing energy consumption and supporting mobility because the range reaches 1 kilometer [5]. and can communicate with about 8,000 stations [6]. has a large number of nodes/stations, which causes collisions. Meanwhile, one way of reducing the collision is to use the EDCA Enhanced Distributed Channel Access (EDCA) algorithm technique. This research has not conducted a traffic analysis [7].

Another study focused on the performance of changing RAW slot duration and found an energy efficiency mechanism in IEEE 802.11ah but did not perform any collision mechanism [8].

A Markov chain that works under saturation and non-saturation conditions was proposed in [9], this study proposed a Markov chain that works in saturation and non-saturation conditions. The study focused on how access points (APs) overcome network bottlenecks using voice data.

Consequently, this work proposes to use the Markov Chain Model in IEEE 802.11ah networks. This is due to the Markov Chain mathematical modeling can improve the IEEE 802.11ah network performance quality even though it is affected by the number of nodes, movement/mobility, and changes in traffic by changing the collision probability.

II. RELATED WORKS

Previously, a mobility impact was analyzed using a traffic pattern change scheme with three models, namely Random Walk, Gauss-Markov, and Random waypoints [2]. In [7] the Enhanced Distributed Channel Access (EDCA) algorithm system was used to reduce collisions. The EDCA algorithm here focuses on the contention window parameter settings implemented in IEEE 802.11e networks.

Furthermore, the EDCA algorithm was applied on the IEEE 802.11ah network by changing the Arbitration Inter-Frame Space (AIFS) parameters [8].

In [10], the Doppler’s effect on IEEE 802.11ah network performance was conducted by analyzing changes in the parameters of the RAW slot and its duration using Random Waypoint Mobility modeling.

The study of [11], the author simulated five mobility models, namely the Entity, Group, Urban, City-Section, and realistic mobility. All this modeling is used on the Vehicular Ad-Hoc Networks (VANET).

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Also, the author of [12] analyzed proactive Destination Sequence Distance Vector (DSDV) and reactive Ad-hoc On-demand Distance Vector (AODV), and Dynamic Source Routing (DSR) ad hoc network routing protocols using three mobility models, which include Random way Point, Manhattan Grid, and Gauss Markov. Another simulation and analysis were performed using a randomness index (α) and the Gauss-Markov mobility model with a certain number of nodes.

In [13], it was observed that each interval beacon has only one RAW group, hence it was further divided into multiple RAW slots, with stations having equal priority placed evenly. This proposal uses a random discrete time Markov model.

Meanwhile, the author of [14] studied the Underwater Wireless Sensor Network (UWSN) by simulating the nodes as sensors that change due to seawater movement. The study was conducted using the Energy Efficient Localization Scheme algorithm based on mobility and propagation Delay Prediction (EEL-MPDP).

In [15], Underwater Wireless Sensor Network (UWSN) was examined by increasing the wireless network performance using Mobile Sink (MS) as a cluster head instead of existing sensor nodes. Subsequently, the data is directly sent from the MS in order to detect leaking pipes. The author of [16] further attempted to improve performance by reducing costs, in terms of time, power consumption, and computing resources using the Cloud-Assisted Energy-Saving and Performance-Improving Routing Mechanism (CEPRM) applied to the MANET network.

III. System Model

A. *IEEE 802.11*

The IEEE 802.11 standard was released by the IEEE (Institute of Electrical and Electronic Engineers) in 1997. In the beginning, IEEE 802.11 exclusively used the 2.4 GHz and 5 GHz frequencies, but it is now more widely used.

The derivatives of the IEEE 802.11 standard include :

- 802.11a [17]
  The IEEE 802.11a was first published in September 1999. Furthermore, it operates at a frequency of 5 GHz, with a 5, 10, and 20 MHz bandwidth, and reaches a maximum speed of 54 Mbps.
- 802.11b [17]
  The IEEE 802.11b was introduced together with IEEE 802.11a in September 1999. It has a 2.4 GHz working frequency and a bandwidth of 22 MHz, with a maximum speed of 11 Mbps.
- 802.11g [18, 19].
  IEEE 802.11g ini di pekernalakna pada Juni 2003 dengan frekuensi yang digunakan 2,4 GHz dan bandwidth 5, 10 dan 20 MHz serta memiliki maksimum kecepatan 54 Mbps.
- 802.11n [20]
  In October 2009, the IEEE 802.11n was introduced and it has 2.4 and 5 GHz working frequencies. It also has bandwidths ranging from 20 to 40 MHz and a maximum speed of 288.8 Mbps to 600 Mbps.
- 802.11ax [21]
  The September 2019 release of 802.11ax operates at 2.4 GHz, 5 GHz, and 6 GHz, with bandwidths of 20, 40, and 80 MHz and a throughput of 9608 Mbps.
- 802.11ad [22]
  802.11ad was first introduced in September 2019 and operates at 60 GHz, with a 7 Gbps throughput and a 2160 MHz bandwidth.
- 802.11af [23]
  In February 2014, 802.11af was released, with a frequency range of 54 to 790 MHz, a bandwidth between 6 to 8 MHz, and a maximum speed of 568.9 Mbps.
- IEEE 802.11ah [24]
  The IEEE 802.11ah was introduced in December 2016, with frequencies below 1 GHz (700/800/900 MHz), bandwidth ranging from 1 MHz to–16 MHz, and 346 Mbps maximum speed.

B. *Markov Chain*

Markov Chain is the model used for the packet transfer function in the Distributed Coordination Function (DCF) system of the IEEE 802.11 standard. In this study, an 802.11ah network was used, which is then proposed with the Markov chain model shown below [25]:

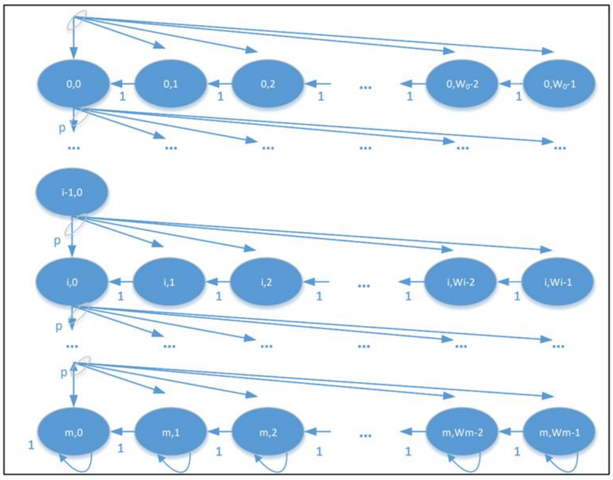

Figure 1. Model markov chain [25].

All nodes access the medium but when it is busy, the system duplicates the contention window and calculates the back-off time [17]. The Markov Chain model shown in Figure 1 is interpreted as follows:

m = The Maximum Number of Back Stages

W = Contention window (CW)

ρ = Transmission failure probability

The following is a calculation of the transition probability (P) on the Markov chain [17]:

$$\begin{cases} P\{i,k \mid i,k+1\} = 1 & k \in (0,W_i-2) & i \in (0,m) \\ P\{0,k \mid i,0\} = (1-\rho)/W_0 & k \in (0,W_0-1) & i \in (0,m) \\ P\{i,k \mid i-1,0\} = \rho/W_i & k \in (0,W_i-1) & i \in (1,m) \\ P\{m,k \mid m,0\} = \rho/W_m & k \in (0,W_m-1) \end{cases} \quad (1)$$

The respective conditions for:

a. Back-off timer down,
b. Successful transmission, back off stage 0 for new packets,
c. Transmission not successful, back off stage increased,
d. If the back-off stage is maximum, it will not grow in the subsequent packet transmission.

Then calculate the Probability (τ) using the Eq. (2). below [17]:

$$\tau = \frac{b_{0,0}}{1-\rho} = \frac{2(1-\rho)}{(1-2p)(W+1)+\rho W(1-(2\rho)^m)} \quad (2)$$

where:

$$b_{0,0} = \frac{2(1-p)(1-p)}{(1-2p)(W+1)+pW(1-(2p)^m)} \quad (3)$$

Furthermore, the p-value is calculated using the following equation [25, 26].

$$\rho = 1-e^{-\rho_i} \quad (4)$$

The value of ρi is determined with Eq. (4) [27]

$$\rho_i = \lambda T \quad (5)$$

where [27]:

λ = Average packet length in one second
T = the time it takes to send the package

C. Analysis Parameters

The parameters analyzed in this research include:

- Throughput
  Throughput is the data transfer rate measured in bits per second (bps). The throughput equation is as follows [25]:

$$S = \frac{P_s P_{tr} lpayload}{(1-Ptr)\sigma + P_{tr}P_sT_s + P_{tr}(1-P_s)T_c} \quad (6)$$

where:

S = Throughput
σ = slot duration
T_s = successful transmission time
T_c = Collision Time
P_{tr} = Transmission probability (at least one transmission)
P_s = Probability of successful transmission

After that, it will look for other parameters: P_{tr}, P_s, T_s, and T_c with the following Eq.(7-10) [28]:

$$P_{tr} = 1-(1-\tau)^N \quad (7)$$

$$P_s = \frac{N\tau(1-\tau)^{N-1}}{1-(1-\tau)^N} \quad (8)$$

$$T_s = DIFS + T_{DATA} + T_{ACK} + T_{PHY} \quad (9)$$

$$T_c = DIFS + T_{DATA} + T_{PHY} \quad (10)$$

where:

N = number of nodes
W = equal to value CW_{min} = 15
T_{data} = Data Frame Duration
T_{ack}, T_{PHY} = Control Frame Duration

- Delay
  This is the time delay in the process of sending data from source to destination. The delay value is calculated with the following Eq. (11). [28]:

$$Delay = \frac{(1-P_{tr})\sigma + P_{tr}(1-P_s)T_c + (P_{tr}P_sT_s)}{P_{tr}P_s} \quad (11)$$

- Energy Efficiency Analysis
  The energy consumption amount for transmitting a data packet in Joules is as follows [25, 28]:

$$e = \frac{(1-P_{tr})\sigma + P_{tr}P_sT_s + P_{tr}(1-P_s)T_c}{P_sP_{tr}l_{payload}} \quad (12)$$

D. System Design

In this study, Matlab software version 2021a was used to simulate and obtain the results of the parameters being tested.

Fig. 2 shows the block diagram of this study system. The Markov parameter was implemented in the IEEE 802.11ah network and tested with three simulation scenarios, namely changes in 1) distance, 2) slot duration and nodes' number, and 3) collision probability. After the simulation, three IEEE 802.11ah network performance parameters were analyzed for each scenario, namely throughput, delay, and energy consumption. These three parameters represent an analysis of IEEE 802.11h network performance.

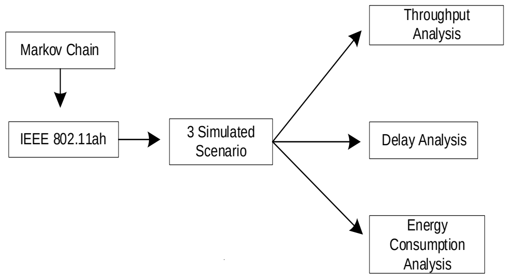

Figure 2. Research System Model

The flowchart for this study is shown in Fig. 3, and it starts from the IEEE 802.11ah network standard incorporated with the Markov Chain scheme and the existence of mobility. Furthermore, the basic MatLab parameters highlighted in Table 1, namely nodes, backoff stage, payload, contention window, RAW slot duration, SIFS, DIFS, physical layer time, ACK time, and data time were inputted into the system. Followed by entering the simulation scenario parameters, which are prepared for 1) the distance between nodes and access points (AP), such as 100 m, 200 m, 300 m, 400 m, 500 m, 600 m, 700 m, 800 m, and 900 m, 2) the RAW slot duration, including 100 ms, 200 ms, and 400 ms, as well as 3) the collision probability, namely 0.15, 0.20, 0.25, 0.30, 0.35 and 0.40. The flow chat design utilized is shown in Fig. 3:

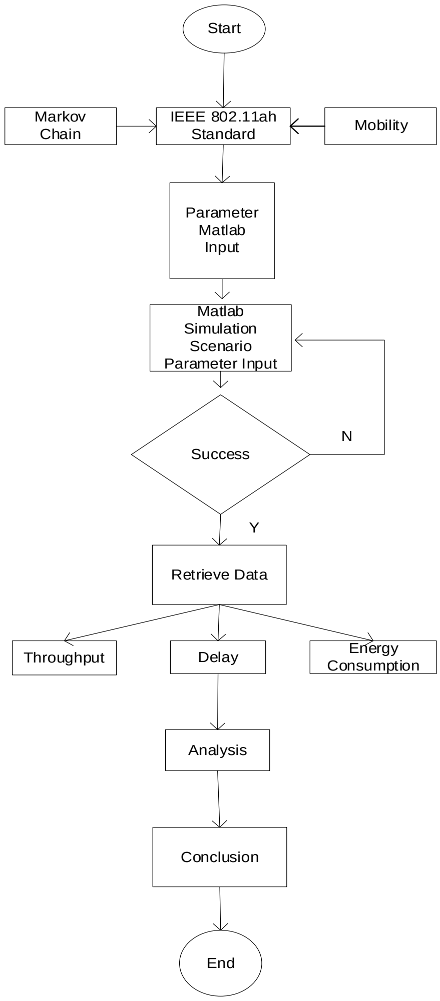

Figure. 3. Research flow diagram.

A test was conducted using a network model according to the IEEE 802.11ah standard. The parameters analyzed include throughput, delay, and energy consumption. Additionally, the changes in the distance between nodes and access points (AP) were observed in the simulation at 100 m, 200 m, 300 m, 400 m, 500 m, 600 m, 700 m, 800 m, and 900 m.

The test scenario was then intended to describe the normal network and conditions influenced by changes in distance, as well as the effect of fixed and changing collision probability values. The simulation scenario is as follows:

1) Distance Change
   The changes in distance between nodes and access points (AP), which include 100 m, 200 m, 300 m, 400 m, 500 m, 600 m, 700 m, 800 m, and 900 m, were analyzed. This was performed under the condition that the distance between the AP and RAW slot duration remains 52 µs.
2) Change of nodes and RAW slot duration
   The simulation scenario has RAW slot durations of 100 ms, 200 ms, and 400 ms.
3) Collision probability change
   The scenarios for changing the collision probability include 0.15, 0.20, 0.25, 0.30, 0.35, and 0.40, with a fixed number of 100 nodes, while the duration of the RAW slot remains 52 µs.

The network specification in this research is as follows:

TABLE I: NETWORK SPECIFICATIONS

Parameter	Value
Number of nodes	50, 100, 150, 200, 250, 300
Slot Duration	52 µs
Back off stage (m)	6
CWmin	15
Payload	8184 bits
SIFS	160 µs
DIFS	264 µs
AIFS	316 µs
T_{sym}	40 µs
T_PHY, T_ACK	240 µs
T_Data	348 µs

The table below contains the energy consumption values. It is important to note that energy consumption is a significant parameter because it affects network performance. Furthermore, it shows the energy consumed by each STA/node and is measured in units of Joule/Packet [25, 29].

TABLE II: ENERGY CONSUMPTION

Mode	Energy Consumption (mW)
Transmit	250
Receive	135
Idle	1.5

The specification of the simulation scenario used in this study is as follows:

TABLE III: RESEARCH SPECIFICATIONS

Parameter	Variable
Number of nodes	50, 100, 150, 200, 250, 300
RAW slot duration	100 ms, 200ms, 400 ms
AP and node distance	100, 200, 300, 400, 500, 600, 700, 800, 900
Collision Probability	0.15, 0.20, 0.25, 0.30, 0.35, 0.40
Analysis	Throughput, delay, Energy consumption

IV. RESULT

The three scenarios considered in this study were analyzed in the form of IEEE 802.11ah network performance parameters, namely throughput, delay, and energy consumption.

A. Throughput

- Throughput with distance change

The effect of changes in distance and node number on throughput is as follows:

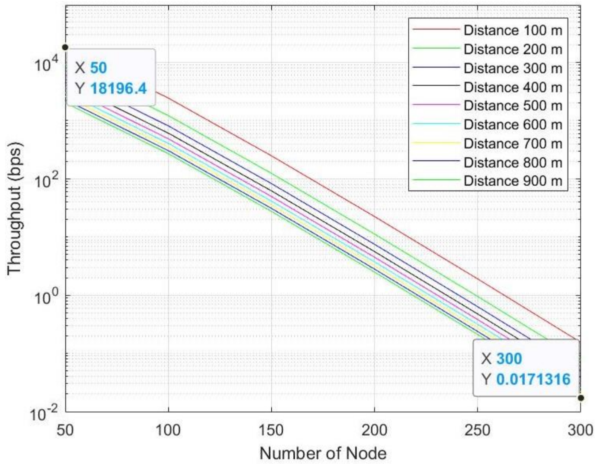

Figure 4. Throughput with changes in AP to Node distance

Fig. 4 shows that when the node's number was 50, the largest throughput was 18196.4 bps/0.0181964 Mbps and the maximum distance between the AP and the node was 100 m. Also, the smallest decrease of 0.0171 bps was recorded when the nodes' number was 300 and the distance between AP and node was 900 m.

This simply means that the throughput value was influenced by the node's number as well as the distance between the AP and the node. Specifically, when the node's number increases, the throughput value tends to decrease. This is because when the node's number rises, the channel becomes full, and the more difficult it is for nodes to access the channel, thereby decreasing the throughput value. Also, as the distance between the AP and the node becomes farther, the throughput value is lowered because there is a delay in data transmission.

- Throughput with changing RAW slot duration

The effect of changes in RAW slot duration and the node's number on throughput is as follows:

According to Fig. 5, the largest throughput value of 201396 bps/0.201396 Mbps was obtained at 50 nodes' number and a RAW slot duration of 50 ms. When the nodes' number increases, the smallest throughput value was 15.4177 bps/0.154177 Kbps provided that the nodes' number was 300 and 400 ms RAW slot duration.

In Eq. (5), the RAW slot duration value is in the denominator, hence it is inversely proportional to the throughput. In other words, the increase in the RAW slot duration value causes a decrease in the throughput. Considering Eq. (6) (Ptr = transmission equation) and 7 (Ps = successful transmission equation), the Ptr and Ps values are the denominator. This implies that when the node's number increases, the *Ptr* and Ps values tend to increase, thereby causing the throughput value to decrease since it is inversely proportional.

It can be concluded that the node's number and the RAW slot duration value affect the IEEE 802.11ah network performance, specifically the throughput parameter.

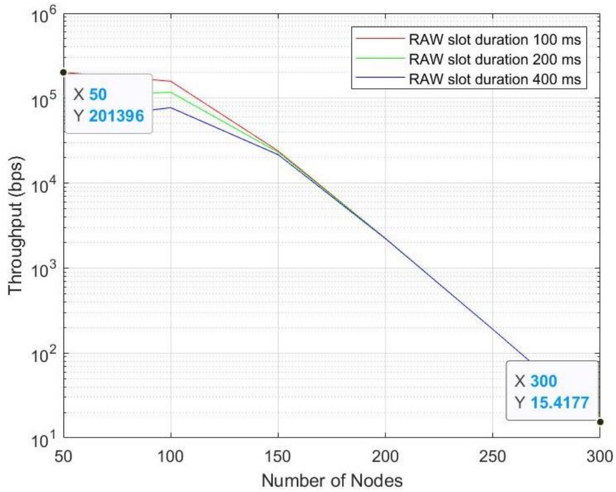

Figure 5. Throughput with RAW Slot Duration

- Throughput with Change in Collision Probability

The effect of changing the collision probability on throughput with a fixed number of nodes at 50 and RAW slot duration of 100 ms is expressed as follows:

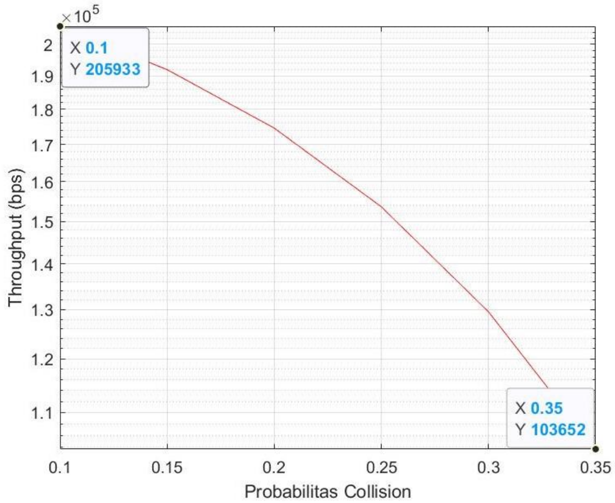

Figure 6. Throughput with Change in Collision Probability

Fig. 6 shows that the fixed RAW slot duration was 100 ms and the collision probability was 0.1 s, hence the throughput value was 205,933 bps or 0.205933 Mbps (highest throughput). When the collision probability was 0.35, the throughput was 103,652 bps or 0.10362 Mbps (lowest throughput).

The throughput is inversely proportional to collision probability, hence when the collision probability is large, the throughput value decreases, and vice versa. This is because the probability value is related to the packet drop rate. In other words, as the collision probability increases, the packets dropped also rise.

B. Delay

- Delay with Distance Change

The effect of changes in distance and the node's number on delay is as follows:

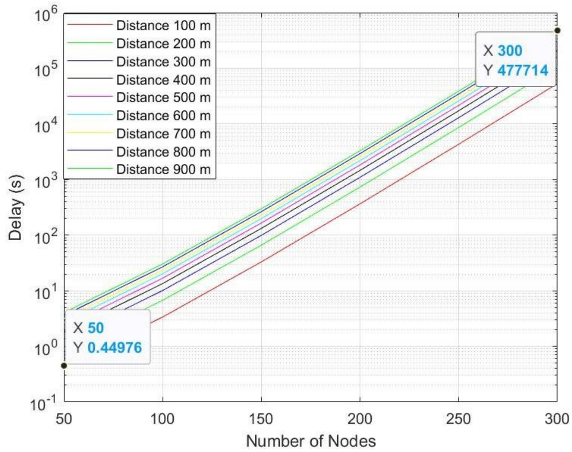

Figure 7. Delay with changes in AP distance to node

Fig. 7 shows the smallest delay of 0.44976 s when the node's number was 50 and the distance between the AP and the node was 100 m. It was also observed that the highest delay value of 477,714 s was obtained when there are 300 nodes with a 900 m distance between the AP and the node.

This proved that as the nodes connected to the AP increase, there is a queue, and it eventually causes delays. Also, the change in distance causes the time required to communicate with the AP to be longer, thereby causing more delay. It is concluded that the node's number as well as the distance between the AP and the nodes greatly affect the delay value. In other words, when there is more nodes' number with a farther distance between the AP and the nodes, then the delay value tends to be greater.

- Delay with Change of RAW Slot Duration

The effect of changes in RAW slot duration and changes in the number of nodes on delay is as follows:

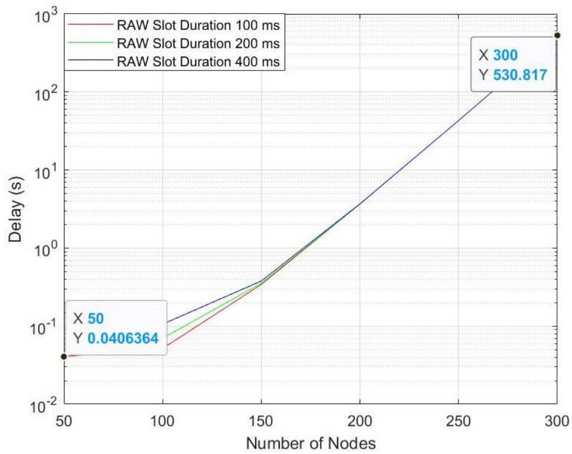

Figure 8. Delay with change of RAW slot duration.

Fig. 8 shows the smallest delay value of 0.0406364 s when the node's number was 50 and the RAW slot duration was 100 ms. Also, the biggest delay value was 530,817 s when the node's number was 300 and the RAW slot duration was 400 ms.

It was observed that as the packet sent increases, coupled with longer slot duration, the node queues in RAW, causing the packet to be sent late, thereby leading to delay. It is important to mention that there is a change in the node's number or density in this scenario, hence when more nodes are connected, the RAW slot duration tends to be longer.

These parameter changes in the node's number and the RAW slot duration greatly affect the IEEE 802.11ah network performance, particularly the delay value. Therefore, the node's number and the RAW slot duration are directly proportional to the delay parameter.

- Delay with Change in Collision Probability

The following is the effect of changing the collision probability of the delay with a fixed node's number and RAW slot duration of 50 and 100 ms, respectively:

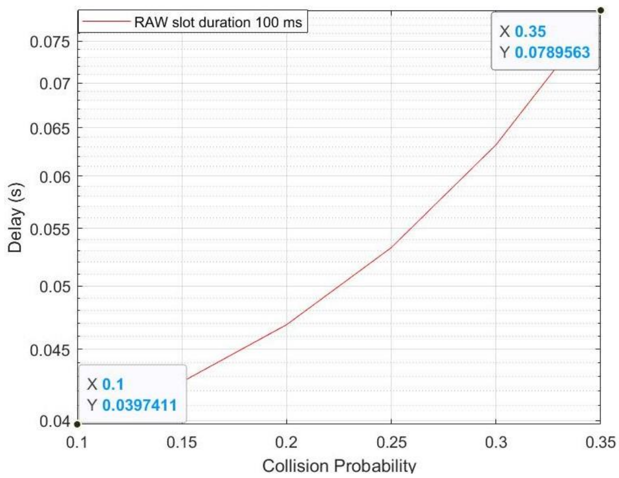

Figure 9. Delay with change in collision probability.

In Fig. 9, the smallest delay value of 0.0397411 s and a collision probability condition of 0.1 was shown. Furthermore, the largest delay value of 0.0789563 s was obtained at a collision probability condition of 0.35. It was observed that as the collision probability value increases, there seems to be a higher delay. This is expressed in equation 10, which relates to the collision probability value calculated from equations 6 (Ptr) and 7 (Ps). Based on equation 10, the delay is directly proportional to Ptr and Ps, this simply indicates when the collision probability increases, then the values of Ptr and Ps Ps are large, thereby causing the delay to also increase and vice versa.

C. Energy Consumption

- Energy Consumption with distance change

The effect of changes in distance and the node's number on energy consumption is as follows:

Fig. 10 shows that the smallest energy consumption was 0.00942964 Joule/DataPacket under the condition of 50 node's number with the distance between the AP and the node being 100 m. Meanwhile, the largest energy consumption was 10622 Joule/DataPacket under the condition that the node's number was 300 and the distance between the AP and the nodes was 900 m.

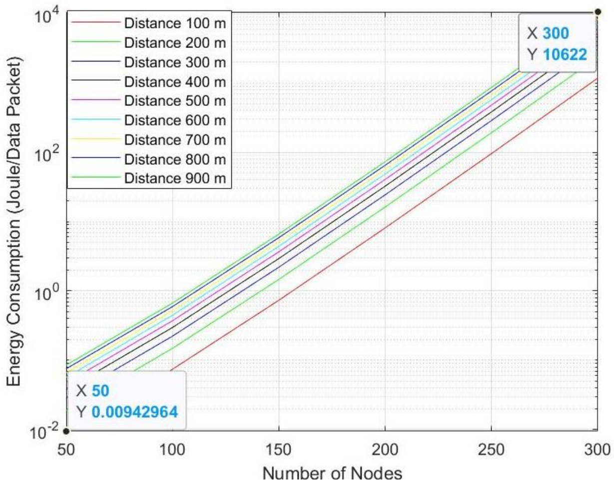

Figure 10. Energy consumption with change of AP distance to node.

The two parameters affecting the delay value in Figure 10 include the node's number and the distance between the AP and the node. It was observed that when the node's number is much, more energy was consumed in order to communicate with the AP, and vice versa. Meanwhile, when there is a short distance between the AP and the node, the energy consumption tends to be low, hence large amount of energy is not required to transmit data packets and vice versa.

- Energy Consumption with Change of RAW Slot Duration

The effect of changes in RAW slot duration and the number of nodes on energy consumption is explained below:

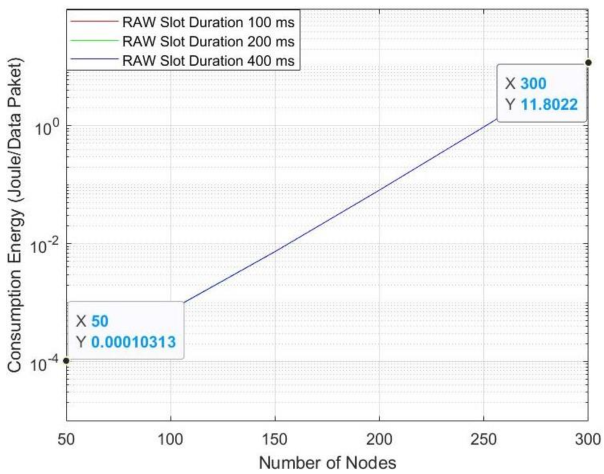

Figure 11. Energy consumption with change of RAW slot duration

Fig. 11 shows the smallest energy consumption of 9.87121 × 10-5 Joules/Data Packet when the node's number was 50 and the RAW slot duration was 100 ms. Meanwhile, the highest energy consumption value was 11.8022 Joules/Data Packet when the node's number was 300 and the RAW slot duration was 400 ms.

It was observed that when more nodes are connected and with a high duration of RAW slots, the energy consumption tends to increase, and vice versa. Therefore, the parameter changes in the node's number and the duration of RAW slots greatly affect the IEEE 802.11ah network performance, particularly the energy consumption value. In equation 11, the effect of changes in the number of nodes and the duration of RAW slots are derived from Ptr and Ps in Eq. (6-7), written at the numerator.

V. Conclusions

The changes in nodes' number caused mobility or alteration in the distance between the AP and the node. Also, the changes in traffic due to the variations in collision probability affected the IEEE 802.11ah network performance regarding throughput, delay, and energy consumption parameters.

It was discovered that the mobility or changes in the distance between the AP and nodes, the node's number, and RAW Slot Duration, affected the IEEE 802.11ah network performance, particularly the throughput, delay, and energy consumption parameters. When there is an increase in the node's number and the distance between the AP and the node, the throughput was decreased. For example, when the node's number was 50 at a distance of 100 m, the throughput was 0.0181964 Mbps but when the node's number was 300 at a distance of 900 m, the throughput decreased to 0.0171316 bps. Similarly, when there is an increase in the node's number and RAW slot Duration, the throughput value decreases. For example, when the node's number and RAW Slot Duration were 50 and 100 ms, respectively, the obtained value of throughput was 0.1396 Mbps. Meanwhile, when there is an increase in the node's number to about 300 and a RAW slot duration of 400 ms, the throughput decreased to 154,177 Kbps.

It was also discovered that the delay value increased when there is a corresponding increase in the node's number and the distance between the AP and the node. At 50 node's number with a distance of 100 m, the delay value was 0.44976 s. This value increased to 477,714 s when there was a corresponding increase in the node's number to 300 and the distance between the AP and the node was 900.

The result also showed that when there was an increase in the node's number as well as the distance between the AP and the node, the energy consumption was increased. For example, when the node's number was 50 at a distance of 100 m, the energy consumed was 0.00942964 Joule/Data Pack. Moreover, it increased to 10,622 Joule/Data Pack when the number was 300 at a distance of 900 m. This energy consumption was also affected by the node's number and the RAW slot duration parameter. At 50 node's number and RAW slot duration of 100 ms, the energy was 9.87121 × 10^-5 Joule/Data Packet. This value increased to 11,8022 Joule/Data Packet when the node's number was 300 at 400ms RAW slot duration.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTION

As the first author, Tengku Ahmad Riza did the design, the simulation, and the analysis and then wrote this paper. Dadang Gunawan and Ajib S. Arifin reviewed the simulation and analysis results. Then all authors make final approval of the final paper.

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REFERENCES

[1] I. Khan, "Performance analysis of 5G cooperative-NOMA for IoT-intermittent communication," *Int. J. Commun. Networks Inf. Secure.*, vol. 9, no. 3, pp. 314–322, 2017.
[2] R. M. N. Ajinegoro, D. Perdana, and R. M. Negara, "Performance analysis of mobility impact on IEEE 802.11ah standard with traffic pattern scheme," *Int. J. Commun.* Networks *Inf. Secure.*, vol. 10, no. 1, pp. 139–147, Apr. 2022.
[3] 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," *Wirel Commun Mob Comput*, vol. 2022, 2022, doi: 10.1155/2022/3229294.
[4] T. A. Riza and D. Gunawan, "IEEE 802 . 11ah : Future research challenges and opportunities," pp. 2–5, 2020.
[5] T. A. Riza and D. Gunawan, "IEEE 802 . 11ah network challenges supports Covid-19 prevention team," pp. 10–13, 2020.
[6] E. Khorov *et al.*, "Enabling the Internet of Things With WiFi Hallow—Performance Evaluation of the Restricted Access Window," *IEEE Access*, vol. 7, pp. 127402–127415, 2019.
[7] S. Prasetya, B. Rahmat, and E. Susanto, "Quality of service improvement with 802.11e EDCA scheme using enhanced adaptive contention window algorithm," in *Proc. 2015 IEEE International Conference on Communication, Networks, and Satellite (COMNESTAT)*, 2015, pp. 80–85.
[8] A. Oktaviana, D. Perdana, and R. M. Negara, "Performance analysis on IEEE 802.11ah standard with enhanced distributed channel access mechanism," *Commit (Communication Inf. Technol. J.*, vol. 12, no. 1, p. 35, May 2018.
[9] A. Abu-Khadrah, Z. Zakaria, M. Othman, and M. S. I. M. Zin, "Using markov chain model to evaluate the performance of EDCA protocol under saturation and non-saturation conditions," *Int. Rev. Comput. Softw*., vol. 10, no. 3, p. 315, Mar. 2015.
[10] A. A. Marwan, D. Perdana, and D. D. Sanjoyo, "Performance analysis of RAW impact on IEEE 802.11ah standard affected by doppler effect," *Int. J. Comput. Commun. Control*, vol. 14, no. 2, pp. 212–219, Apr. 2019.
[11] C. Arora and P. K. K Saini, "Survey of various mobility generators in VANETS," *Int. J. Sci. Res*., vol. 2, no. 4, pp. 150–151, Jun. 2012.
[12] A. Rai, S. Datia, V. Srivastava, I. Gwalior, and P. Khare, "Effect of mobility models on the performance of proactive and reactive routing protocols," *Ijeit*, vol. 3, no. 12, pp. 115–119, 2014.
[13] S. M. Soares and M. M. Carvalho, "Throughput Analytical Modeling of IEEE 802.11ah Wireless Networks," 2019 16th IEEE Annu. Consum. Commun. Netw. Conf. CCNC 2019, pp. 1–4, 2019.
[14] C. Arora and P. K. K Saini, "Survey of Various Mobility Generators in VANETs," *Int. J. Sci. Res.*, vol. 2, no. 4, pp. 150–151, Jun. 2012.
[15] M. Nain and N. Goyal, "Energy efficient localization through node mobility and propagation delay prediction in underwater wireless sensor network," *Wireless Personal Communications.*, vol. 122, no. 3, pp. 2667–2685, Feb. 2022.
[16] N. Goyal, A. Kumar, R. Popli, L. K. Awasthi, N. Sharma, and G. Sharma, "Priority based data gathering using multiple mobile sinks in cluster based UWSNs for oil pipeline leakage detection," *Cluster Comput*, vol. 25, no. 2, pp. 1341–1354, Apr. 2022.
[17] V. K. Quy, L. N. Hung, and N. D. Han, "CEPRM: A cloud-assisted energy-saving and performance-improving routing mechanism for MANETs," *Journal of Communications*, vol. 14, no. 12, pp. 1211–1217, Dec. 2019.
[18] S. Banerji and R. S. Chowdhury, "On IEEE 802.11: Wireless LAN technology," *Int. J. Mob. Netw. Commun. Telemat.*, vol. 3, no. 4, pp. 45–64, Jul. 2013.
[19] A. Corinna, "Wireless networking in the developing world," *Traffic*, p. 425, 2007.
[20] AirMagnet Inc, "802.11n primer," 2008.
[21] D. J. Deng, K. C. Chen, and R. S. Cheng, "IEEE 802.11ax: Next generation wireless local area networks," in *Proc. 10th International Conference on Heterogeneous Networking for* Quality, *Reliability, Security, and Robustness*, 2014, vol. 1, pp. 77–82.
[22] Anonymous, "wireless LAN at 60GHz IEEE 802.11ad explained," *Agilent*, pp. 1–28, 2013.
[23] X. Feng, Q. Zhang, and B. Li, "Enabling co-channel coexistence of 802.22 and 802.11af systems in TV white spaces," in *Porc. 2013 IEEE International Conference on Communications (ICC)*, 2013, pp. 6040–6044.
[24] E. Kocan, B. Domazetovic, and M. P. Djurisic, "Range extension in IEEE 802.11ah systems through relaying," *Wirel. Pers. Commun.*, vol. 97, no. 2, pp. 1889–1910, 2017.
[25] J. Cesar and A. Leon, "Evaluation of IEEE 802.11ah technology for wireless sensor network applications," p. 69, 2015.
[26] A. Jain, A. K. Dubey, R. Upadhyay, and S. V. Charhate, "Performance evaluation of wireless network in the presence of hidden node: A queuing theory approach," in *Porc. 2008 Second Asia International Conference on Modelling and Simulation (AMS)*, 2008, pp. 225–229.
[27] L. Xin and D. Starobinski, "Countering cascading denial of service attacks on wifi networks," *IEEE/ACM Trans. Netw.*, vol. 29, no. 3, pp. 1335–1348, Jun. 2021.
[28] P. C. Jain and S. Taneeru, "Performance evaluation of IEEE 802.11ah protocol in wireless area network," in *Porc. 2016 International Conference on Micro-Electronics and Telecommunication Engineering (ICMETE)*, 2016, pp. 578–583.
[29] V. Hugo, "Contributions to IEEE 802, 11-based long-range communications," pp. 1–109, 2020.