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ZigBee-Based Wireless Sensor Network Topology Design and Comparison in Residential Areas

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ABSTRACT

When designing a ZigBee-based wireless sensor network, choosing the right network topology is important, especially in networks with multiple nodes. Choosing the wrong topology will have an impact on the performance of the wireless sensor network as a whole because it will cause a large delay value. This research has the main objective to find the right type of topology that can be applied to densely populated residential areas with a large number of houses and a large area of land. This research will provide benefits for housing developers who want to implement a ZigBee-based wireless sensor network for various purposes in each unit in their residential area, such as recording electricity and water usage, security systems, and so on. This research will use three types of ZigBee topologies, namely star, tree, and mesh topologies. The housing used for the simulation in this study is Citraland Waterfront City Housing located in Palu City, Central Sulawesi Province, Indonesia. By using simulation-based calculations using the Opnet Modeler 14.5 application, it is known that the star topology on the ZigBee network is suitable for application to residential areas with a large number of nodes and areas. This can be seen from the highest throughput and media access delay, end-to-end delay, number of hops, and the lowest packet drop value compared to the tree and mesh topologies.

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1. INTRODUCTION

The application of wireless sensor networks, especially in residential areas, is currently experiencing rapid development, along with the increasing number of home features offered by developers. One of the smart home features owned by several housing estates which are starting to be implemented at this time, among others, is the electronic recording of electricity and water consumption. So far, the recording of the use of electricity and water is carried out by authorized officers. This is of course a waste of human resources amid very high demands for efficiency. Microcontroller-based electronic recording supported by wireless sensor networks can be recorded online. One type of device that is often used in wireless sensor networks is ZigBee. With ZigBee, all data belonging to the microcontroller can be sent directly to the server.

ZigBee is an IEEE 802.15.4 standard for data transmission between commercial and consumer electronic devices [1,2,3]. ZigBee is made to operate on low-level personal networks and consumes less power [4,5]. Devices with ZigBee technology are frequently used as wireless sensors or to control other devices [6,7]. A feature of ZigBee allows it to control both its network and the flow of data on the network [8,9]. ZigBee also has the benefit of requiring little power, making it suitable for use as a wireless control system that only needs to be installed once [10,11,12]. ZigBee has the advantage of

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very low power consumption and if it is not operating, then ZigBee will always be in sleep mode and has a maximum data rate of 250 Kbps [13,14]. With these advantages, ZigBee is suitable to be placed in applications that require devices with low power consumption [15]. Compared to other WPANs like Bluetooth, which has a transmission rate of 1 Mbps, ZigBee has a transfer rate of roughly 250 Kbps [16]. The operating range or distance of ZigBee is around 76 m, which is greater than Bluetooth. Like a LAN network, ZigBee also has a network topology which is the concept of the ZigBee network infrastructure. Based on the IEEE 802.15.4 standard, ZigBee has three network topologies, namely Star, Mesh, and Tree. [17].

Numerous research has been conducted about the topology of the ZigBee network. Hamdy [18] has assessed how the ZigBee topology affects throughput and end-to-end latency when used in the IoT space. The result obtained from the tree topology can produce the greatest results at a frequency of 2.4 GHz, while the star topology can produce the best results at frequencies of 915 and 868 MHz, according to testing including the star, mesh, and tree topologies. Opnet Modeler 14.5 was also used for this test's execution. Other studies have also been carried out by Söğüt [19] by comparing the performance of star, mesh, and tree topologies. Through the simulations carried out, it can be seen that by considering a large number of hob values, the star topology can provide the best end-to-end delay results. Research related to other ZigBee network topologies was also carried out by Ibrahim [10]. Through his research, he examines the effect of response time on the three types of ZigBee topologies. The results of his research show that the mesh topology can provide better throughput and latency values compared to the star and tree topologies.

Based on previous research, a simulation of the ZigBee network is carried out in this study by spreading out the number of nodes over a greater area that includes residential areas. This is done to determine which topology is appropriate for use given the location and node count. The findings of this study can be used as a guide for developers to choose the best wireless sensor network topology for use in residential areas with a lot of densely populated homes and a variety of purposes. Citraland Waterfront City Housing, a middle- to upper-class housing model situated in Palu City, Central Sulawesi Province, Indonesia, was selected as the housing model. This residential area was chosen as a reference not only because the housing design is characterized by today's housing, it is also supported by the number of units and a very large area.

2. RESEARCH METHOD

2.1. Site Survey

The first step in this research is a site survey. This survey was conducted to determine the area of housing, the location of each house, and the number of units in it. The design and simulation of the wireless sensor network in this paper take the design of the existing residential area model at Citraland Waterfront City Housing in Palu City, Central Sulawesi Province, Indonesia. Citraland Waterfront City housing consists of several blocks of houses, shops, and public areas. Overall Citraland Waterfront City Housing has a total of 160 shop units and 352 housing units. The design of Citraland Waterfront City Residential can be seen in Figure 2.

The design of the ZigBee network topology will focus on residential areas located in blocks B6, B5, B3, B7, and A1. Each house will have one end device unit and in this model, it is assumed that each end device is placed in the front yard of each house and every house in Citraland Waterfront City is next to each other. The total simulated houses are 113 units.

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Figure 1. Citraland Waterfront City Residential Master Plan

2.2. Topology Design

The second stage of this research is topological design. After the site survey and house mapping have been completed, the next step is to design the topology used. In this study, a comparison of three types of topology owned by ZigBee was carried out, namely star, mesh, and tree. Topology design will refer to the three types of topology.

2.2.1. ZigBee Component

ZigBee is made up of three major components: the ZigBee Coordinator, the ZigBee End Device, and the ZigBee Router [8]. The ZigBee coordinator coordinates overall network actions and is in charge of network bootstrapping [18]. The ZigBee routers create a network among themselves to exchange packets [6]. The ZigBee end device is in charge of requesting any outstanding messages from its parent [16]. If an end device moves, it must notify the network that it has rejoined a new parent.

2.2.2. Star Topology

The first topology is the star topology. The star topology is made up of a coordinator and a few end devices. It is the most basic and limited ZigBee protocol. All devices are linked to a single coordinator node, through which all communication is routed. The star topology is significant because it is defined by the underlying 802.15.4 specification on which ZigBee is based [9]. The disadvantage of this architecture is that there is no alternative path from the source to the end devices, which may be a hindrance.

Based on the star topology concept, a star topology design was developed and used for the Citraland Waterfront City Residential area, as shown in Figure 2. It can be seen in Figure 2, that in the star topology model, each house block will have one coordinate unit. This coordinator will control every ZigBee device that acts as an End Device in every resident's house. Each coordinator will have a different PAN ID (Personal Area Network Identifier). So that all existing end devices will only connect to the coordinator with the same PAN ID. This is done to minimize delay and the possibility of collisions in the network caused by the number of nodes in it.

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Figure 2. Design of star topology

2.2.3. Tree Topology

Tree topology is the second type of ZigBee topology. It is made up of a coordinator, a few routers, and end devices that work together to form a central node or root tree. Routers extend network coverage. Children are end nodes that are linked to the parent (coordinators or routers) [6]. Only the end devices have access to the parent. The disadvantage of the tree topology is that if one parent is disabled, the disabled parent's children cannot connect with other devices in the network, even if they are close to one another [9]. Figure 3 depicts a tree topology design for the Citraland Waterfront City Residential area based on the tree topology concept.

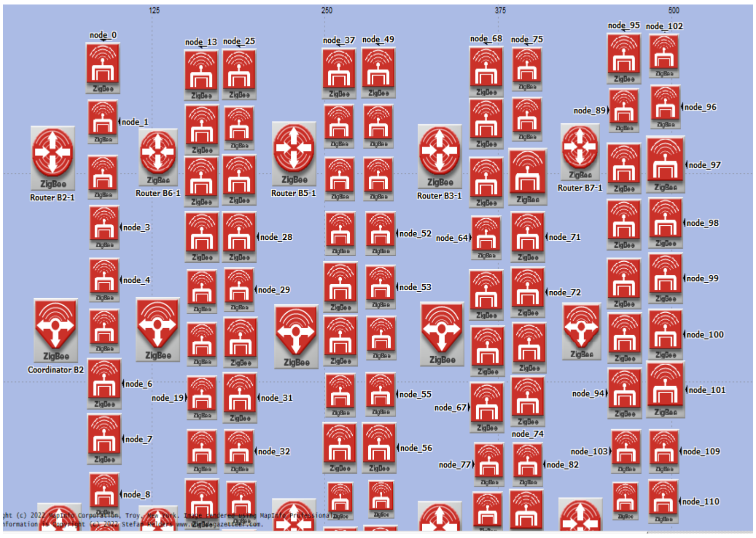

Figure 3. Design of tree topology

The tree topology applied to this housing model uses two routers and one coordinator for each house block. Each end device in each home will be connected to both routers, and both routers will be connected to a coordinator who will control the network as a whole. As in the star topology, each coordinator in each block will have a different PAN ID so that the end devices and routers in each house will only be connected to the coordinator who has the same PAN ID as theirs.

2.2.4. Mesh topology

The third and final topology is peer-to-peer or mesh topology. This topology is made up of a coordinator, a few routers, and an end device [3]. The coverage area can be expanded by adding new devices to the network. If one of the paths fails during transmission, the node will find another path to

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the destination, reducing dead zones [9]. Users can easily add or delete devices when using this mesh topology because they can connect to any target device in the network [6]. Figure 4 depicts a mesh topology design based on the mesh topology concept for the Citraland Waterfront City Residential area.

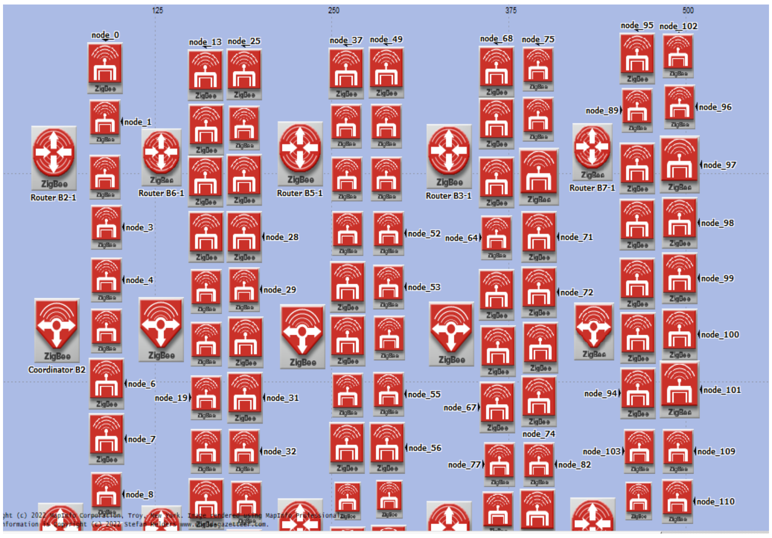

Figure 4. Design of mesh topology

The components used in the mesh topology are the same as those used in the tree topology, involving two routers and one router. The difference between the two lies only in the connecting path between the two routers and the topology configuration of the unit that acts as a coordinator.

2.3. Topology Simulation

The next stage is simulation. The simulation is carried out to determine the performance of the three ZigBee network topology designs. This simulation also aims to collect data based on the specified parameters to find out which topological design is appropriate to be applied to residential areas.

The design along with the ZigBee-based wireless sensor network topology simulation in this study uses the Opnet Modeler 14.5 application. This application itself is widely used by students and researchers who focus on research related to communication between devices and telecommunication networks, computer networks, and wireless sensor networks [20].

2.4. Evaluation

The last stage is evaluation. Evaluation is carried out by looking at all the results of parameter measurements that have been carried out through a simulation process which will then be analyzed to find out the causes and determine what type of topology is suitable for use as a ZigBee network topology in residential areas.

3. RESULTS AND DISCUSSION

The three topology designs were simulated using the Opnet Modeler 14.5 application. Parameter settings in Opnet can be seen in Table 1:

Table 1. Simulation parameter.

Parameter	Value
Area size	1000 m x 1000 m
Destination	Parent
Packet size	Constant (200 bytes)
Frequency	2.4 GHz
Start time	Uniform (20,21)
Simulation time	1 Hour
Number of units	113

Volume 10, Issue 1, April 2023, pp. 42-51
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Testing is done by looking at parameters: throughput, media access delay, end-to-end delay, hop number, and packet dropped. The results of the tests carried out on the three topological designs can be seen as follows.

3.1. Throughput

Throughput is the total number of bits (in bits/sec) forwarded from the 802.15.4 MAC to higher layers in all network WPAN nodes. The simulation results are shown in Figure 5.

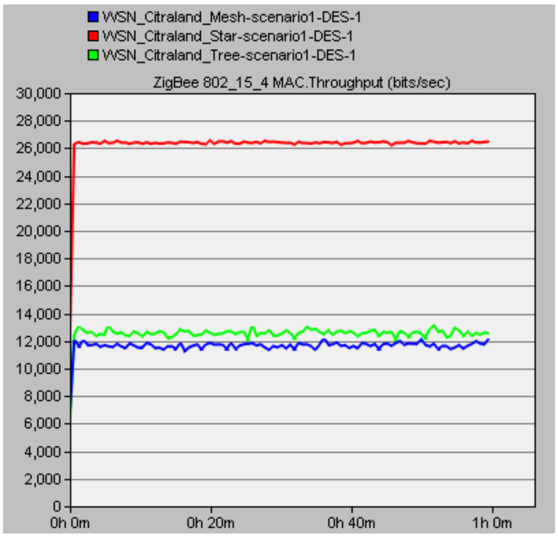

Figure 5. Throughput from the three topologies

The throughput measurement results show that the star topology can pass more data within a certain period compared to the tree and mesh topologies. It can be seen from the graph that the star topology has a throughput value of 26000 kbps, far superior to the tree and mesh topologies. This is because the star topology has a simpler design so that data can be passed more easily and quickly.

3.2. Media Access Delay

The sum of the contention and queuing delays for all 802.15.4 MACs is known as the media access delay. This delay is determined for each frame as the amount of time that passes between the time the frame is added to the transmission queue, which is the arrival time for higher layer data packets and the creation time for all other frame types, and the time the frame is sent to the physical layer for the first time. The media access delay value obtained from the three topologies can be seen in Figure 6.

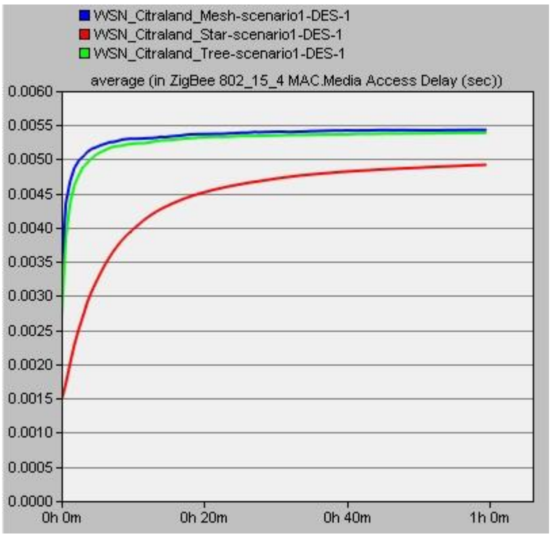

Figure 6. Media access delay parameter of the three topologies

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From the results of the tests carried out, the design with a star topology still provides advantages compared to a tree with a mesh where the star topology has the smallest media access delay value.

3.3. End-to-End Delay

The end-to-end delay depicts the total amount of delay experienced when sending data from the sender to the recipient. Figure 7 displays the end-to-end delay measurement results for the three topology designs.

From the simulation results carried out on the three topologies designs, it can be seen that the star topology can provide better performance than the tree and mesh. This can be seen from the end-to-end delay value of the star topology which is much lower than the tree and mesh topology.

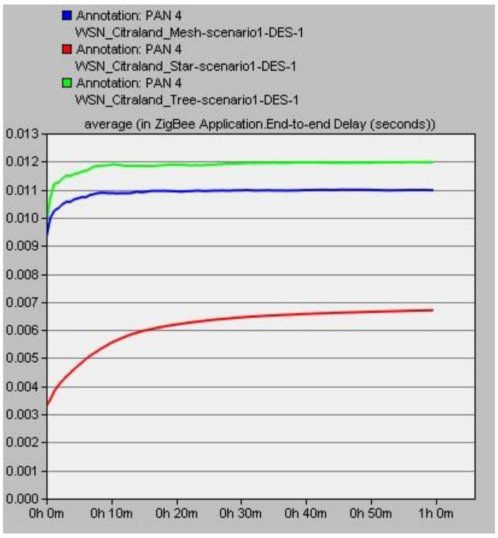

Figure 7. End-to-end delay parameters from the three topologies

3.4. Hop Number

The hop number refers to the number of intermediate devices that data must pass through for transmission from the source node to the destination node to be successful. Figure 8 depicts the hop number measurement results for the three topology designs. The simulation results show that the star topology has the fewest hops when compared to the mesh and tree topologies.

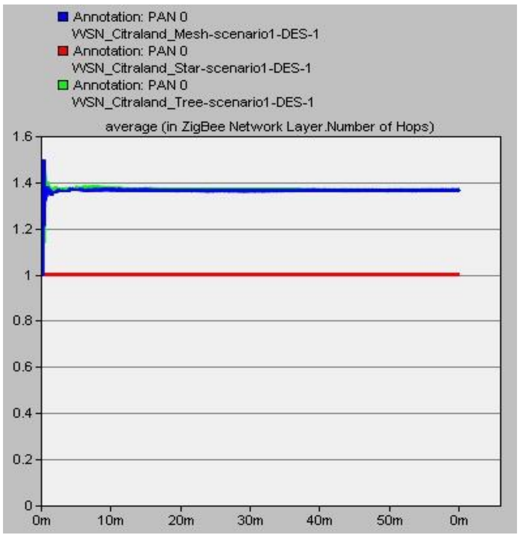

Figure 8. Hop number parameter from the three topologies

JURNAL ECTIPE
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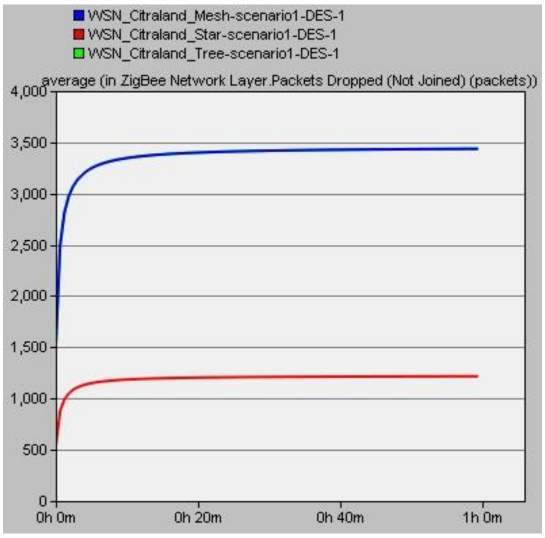

Figure 9. Packet dropped parameter from the three topologies

3.5. Packet Dropped

Packets dropped to show the number of data packets lost during the data transmission process. Based on the simulations performed, the star topology appears to have the smallest packet drop value compared to the mesh and tree topologies. The values in the tree and mesh topologies have the same packet dropped values. The values of packet dropped from the three topologies can be seen in Figure 9.

3.6. Result Evaluation

Through the results of all parameter simulations, it can be seen that a network with a star topology has its advantages when compared to a network with a tree or mesh topology. This can be caused because the star topology has simpler components when compared to the tree and mesh topologies, where the star topology does not use routers. Just like on a LAN network, routers on a ZigBee network also work by using a routing table. The router works to receive each data packet it receives and matches the information in it with its routing table. On a network with a small number of nodes, the resulting delay is not large, but the delay value will increase as the number of nodes in the network increases [21]. It can also be seen from the hop number parameter that data packets in the mesh and tree topologies must pass through more nodes to reach their destination compared to the star topology. This will further increase the existing delay, thereby reducing the overall network capacity. Phenomena like this can also be seen in the research conducted by Hamdy [18] and Ibrahim [10] where when the number of nodes and the area used is relatively small, the tree and mesh topologies can provide better results. However, for large-scale networks with a large number of nodes, star topology can provide better results, as in the research conducted by Söğüt [19].

4. CONCLUSION

The purpose of this study is to find the best type of ZigBee network topology that is suitable for use in residential areas. From the calculation results obtained through the simulation process, by looking at parameters such as throughput, media access delay, end-to-end delay, hop number, and packet dropped, it can be concluded that the ZigBee network with a star topology is suitable for residential areas. This is possible because the component design is simpler so that it minimizes the possibility of large latencies that impact network performance. However, it is known that the star topology has a drawback where because all the communication that runs is centered on the coordinator device, this topology will be prone to interference if the coordinator has problems and does not have a backup line. Further research is needed to enable the star topology to have a backup path like that of the mesh and tree topologies.

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REFERENCES

[1] H.-Y. Chang, "A connectivity-increasing mechanism of ZigBee-based IoT devices for wireless multimedia sensor networks," *Multimed Tools Appl*, vol. 78, no. 5, pp. 5137–5154, Mar. 2019, doi: 10.1007/s11042-017-4584-2.

[2] A. Haka, V. Aleksieva, H. Valchanov, and D. Dinev, "Analysis of ZigBee Network Using Simulations and Experiments," in *2020 International Conference Automatics and Informatics (ICAI)*, Varna, Bulgaria, Oct. 2020, pp. 1–4. doi: 10.1109/ICAI50593.2020.9311328.

[3] C. A. G. Silva, E. L. Santos, A. C. K. Ferrari, and H. T. S. Filho, "A Study of the Mesh Topology in a ZigBee Network for Home Automation Applications," *IEEE Latin Am. Trans.*, vol. 15, no. 5, pp. 935–942, May 2017, doi: 10.1109/TLA.2017.7910209.

[4] V. D. Vaidya and P. Vishwakarma, "A Comparative Analysis on Smart Home System to Control, Monitor and Secure Home, based on technologies like GSM, IOT, Bluetooth and PIC Microcontroller with ZigBee Modulation," in *2018 International Conference on Smart City and Emerging Technology (ICSCET)*, Mumbai, Jan. 2018, pp. 1–4. doi: 10.1109/ICSCET.2018.8537381.

[5] P. Mounika, "Performance analysis of wireless sensor network topologies for Zigbee using riverbed modeler," in *2018 2nd International Conference on Inventive Systems and Control (ICISC)*, Coimbatore, Jan. 2018, pp. 1456–1459. doi: 10.1109/ICISC.2018.8399050.

[6] T. Nimi and P. Samundiswary, "Comparative analysis of ZigBee network with tree and mesh topology for different range of frequencies," in *2017 2nd International Conference on Communication and Electronics Systems (ICCES)*, Coimbatore, Oct. 2017, pp. 560–564. doi: 10.1109/CESYS.2017.8321140.

[7] S. W. Nourildean, M. D. Hassib, and Y. A. Mohammed, "Internet of things based wireless sensor network: a review," *IJEECS*, vol. 27, no. 1, p. 246, Jul. 2022, doi: 10.11591/ijeecs.v27.i1.pp246-261.

[8] B. Rajesh kanna and M. Anitha, "Congruent routing protocols in diverse tree topology ZigBee built home area networks," *Materials Today: Proceedings*, vol. 33, pp. 4592–4601, 2020, doi: 10.1016/j.matpr.2020.08.194.

[9] Ompal, V. M. Mishra, and A. Kumar, "Zigbee Internode Communication and FPGA Synthesis Using Mesh, Star and Cluster Tree Topological Chip," *Wireless Pers Commun*, vol. 119, no. 2, pp. 1321–1339, Jul. 2021, doi: 10.1007/s11277-021-08282-w.

[10] S. A. Abdulhussien and S. K. Ibrahim, "Effects of Wireless Sensor Network Topology on Response Time," in *2020 International Conference on Electrical, Communication, and Computer Engineering (ICECCE)*, Istanbul, Turkey, Jun. 2020, pp. 1–5. doi: 10.1109/ICECCE49384.2020.9179353.

[11] G. Liang and X. Xu, "Residential area streetlight intelligent monitoring management system based on ZigBee and GPRS," presented at the MATERIALS SCIENCE, ENERGY TECHNOLOGY, AND POWER ENGINEERING I: 1st International Conference on Materials Science, Energy Technology, Power Engineering (MEP 2017), Hangzhou, China, 2017, p. 020213. doi: 10.1063/1.4982578.

[12] Y. Zhao, "Research on Wireless Sensor Network System Based on Zigbee Technology for Short Distance Transmission," *J. Phys.: Conf. Ser.*, vol. 1802, no. 2, p. 022008, Mar. 2021, doi: 10.1088/1742-6596/1802/2/022008.

[13] M. F. Shaik, M. M. Subashini, and N. Swathi, "Implementation of a ZigBee Based Network for WBAN," in *2021 7th International Conference on Advanced Computing and Communication*

Volume 10, Issue 1, April 2023, pp. 42-51
ISSN 2355-5068 ; e-ISSN 2622-4852
DOI: 10.33019/jurnalecotipe.v10i1.3704

Systems (ICACCS), Coimbatore, India, Mar. 2021, pp. 188–192. doi: 10.1109/ICACCS51430.2021.9442016.

[14] B. Pavkovic, N. Matic, D. Glisic, L. Berbakov, and I. Pap, “Simple detection of network anomalies and topology control in ZigBee networks,” in *2017 25th Telecommunication Forum (TELFOR)*, Belgrade, Nov. 2017, pp. 1–4. doi: 10.1109/TELFOR.2017.8249346.

[15] R. Das and J. N. Bera, “ZigBee based Small-World Home Area Networking for Decentralized Monitoring and Control of Smart Appliances,” in *2021 5th International Conference on Smart Grid and Smart Cities (ICSGSC)*, Tokyo, Japan, Jun. 2021, pp. 66–71. doi: 10.1109/ICSGSC52434.2021.9490482.

[16] S. F. Shende, R. P. Deshmukh, and P. D. Dorge, “Performance improvement in ZigBee cluster tree network,” in *2017 International Conference on Communication and Signal Processing (ICCSP)*, Chennai, Apr. 2017, pp. 0308–0312. doi: 10.1109/ICCSP.2017.8286367.

[17] M. A. Moridi, Y. Kawamura, M. Sharifzadeh, E. K. Chanda, M. Wagner, and H. Okawa, “Performance analysis of ZigBee network topologies for underground space monitoring and communication systems,” *Tunnelling and Underground Space Technology*, vol. 71, pp. 201–209, Jan. 2018, doi: 10.1016/j.tust.2017.08.018.

[18] Y. R. Hamdy and A. I. Alghannam, “Evaluation of ZigBee Topology Effect on Throughput and End to End Delay Due to Different Transmission Bands for IoT Applications,” *J. commun. softw. syst. (Online)*, vol. 16, no. 3, pp. 254–259, Sep. 2020, doi: 10.24138/jcomss.v16i3.975.

[19] E. Söğüt and O. A. Erdem, “Performance Comparison of the IEEE 802.15.4 Standard (ZigBee) Topologies”.

[20] M. G. Al-Hamiri, H. J. Abd, and H. M. Al Abboodi, “Performance evaluation of WLAN in enterprise WAN with real-time applications based on OPNET modeler,” *IJEECS*, vol. 21, no. 2, p. 911, Feb. 2021, doi: 10.11591/ijeecs.v21.i2.pp911-918.

[21] A. S. Tanenbaum and D. Wetherall, *Computer networks*, 5th ed. Boston: Pearson Prentice Hall, 2011.