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Smart Home System Automation Based on Zigbee Protocol with Internal Cloud Server

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ABSTRACT

The standard protocols used in educational, business, residential, and industrial environments in Indonesia still rely on standard protocols such as Wi-Fi and Bluetooth. This applied research is related to a standard protocol called Zigbee, which is IEEE 802.15.4 standard that has begun to be widely used in networks for IoT-based control purposes. In smart home technology, connectivity is very important. To build a smart home system, users must consider the connectivity or communication between one smart home device and another. The most familiar and widely used communication protocol network for smart home devices is currently Wi-Fi. However, alternative wireless connectivity protocols are now emerging, one of which is Zigbee. Zigbee is a global standard for low-power, short-range networks, offering a complete and operable Internet of Things (IoT) solution for homes and buildings. Zigbee has features that enable it to manage its own network and data exchange on the network, and it can support hundreds of devices and has reliable security features. In this applied research, monitoring uses the Zigbee protocol with a cluster topology consisting of a Zigbee coordinator and several Zigbee end devices that will be installed in locations with or without wall obstructions.

Keywords: *Zigbee, IoT, Smart Home.*

1. INTRODUCTION

In the digital age, with the widespread use of smartphones, lifestyle changes are evolving to provide convenience in improving the quality and efficiency of daily life. These lifestyle changes cannot be separated from the use of electrical energy to power devices that provide convenience to users. However, the source of electrical energy still generally relies on fossil fuels such as coal and fuel oil (BBM), which are considered less environmentally friendly. In this regard, the use of electrical energy requires awareness to conserve energy while reducing the cost of daily electricity consumption in the environment. One solution that can be offered is for the community, as energy consumers, to conserve energy by limiting the use of electrical devices according to their needs and at the same time monitoring their electricity usage. This applied research aims to present an IoT-based technology application that can limit and monitor electricity usage, namely a 1-phase electrical parameter control and monitoring system based on an internal cloud server using the Zigbee protocol. The provision of cloud servers will use a Raspberry Pi connected to an electrical load via a Zigbee protocol, which has very low energy requirements. The software used on the Raspberry Pi server is open-source Home Assistant (HA), which is connected to a local network but can be accessed from outside the network (external network) through the use of the Zerotier application.

In this decade, the development of automation systems utilizing the internet for control and monitoring purposes has continued to grow rapidly to deliver smart homes that provide convenience and increase energy efficiency. IoT-based automation is an innovative leap in the evolution of home automation systems that prioritize comfort, efficiency, and cost-effectiveness (Ubong E. Etuk, et al. 2023) [1]. Within an IoT and smart home ecosystem, there are several communication standards that can be used, such as Wi-Fi, Bluetooth, Zigbee, and BLE, which are supported by hardware produced by several well-known vendors. The choice of communication standard for smart homes and IoT depends on the objectives to be achieved. If low-power devices are a priority, then the best alternative is to use the Zigbee communication standard. Technically, Zigbee is a communication standard from IEEE 802.15.4 for personal and business data communication.

ZigBee has the ability to manage its own network and regulate data exchange on the network. Another advantage of ZigBee is that it requires low power and is responsive to switching from sleep mode to active mode, which only takes about 15 milliseconds. Additionally, ZigBee features a mesh network topology, enabling it to form broader networks with up to 65,000 nodes (Ms. Mubeena Begum, et al. 2022) (Yuhan Du, 2024) [2]. The reasons for ZigBee's popularity are its support for various network topologies, scalability, and the ability for ZigBee devices to connect to local networks without sacrificing reliability, making ZigBee suitable for home automation and smart systems as an alternative to Wi-Fi and Bluetooth (Vishwas K V, et al. 2021) [3].

Wireless sensor networks (WSNs) are a combination of wireless technologies that are widely used in various industries, including agriculture, medicine, and the military. In most cases, this technology is used to monitor environmental or physical parameters, including sound, pressure, and temperature. WSNs use a variety of technologies, including radio frequency (RF), Wi-Fi, Bluetooth, ZigBee, and Z-Wave. Zigbee in particular has greater potential for energy savings in long-distance transmission, making it a preferred standard for use in WSNs.

In a network that uses Zigbee, there are three main data communication devices: the ZigBee coordinator, the router, and the node. The coordinator device collects, stores, and processes data before forwarding it to the next appropriate node or base station. The amount of data traffic received grows proportionally with the number of routers. Meanwhile, data remains unaffected by the number of coordinators. Sent data traffic is subject to the same rules. When the number of coordinators (and/or) routers increases, the amount of MAC (Media Access Control layer) management traffic sent decreases (Naseem K. Baqer, et al. 2024) [4].

2. METHODS

2.1. Data Analysis Method

The method used in this applied research is a quantitative method, namely by collecting experimental data by placing the Zigbee Coordinator at a specific location. Then, the Zigbee end user is placed in a location with and without obstructions.

2.2 System Development Method

This system development includes two discussions: Zigbee communication standards and system design.

2.2.1. Zigbee Communication Standard

Zigbee is an IEEE 802.15.4 standard for data communications on personal and business-scale consumer devices. ZigBee is designed with low power consumption and works for low-level personal networks. ZigBee devices can be used to control other devices or act as sensors wirelessly. ZigBee also has a "mesh" network topology, enabling it to form a wider network and provide reliable data. A Zigbee device is a combination of Zigbee logic and physical devices, as explained below:

A. Zigbee Physical Device

In IEEE 802.15.4, based on their data processing capabilities, physical devices are divided into two types: Full Function Devices (FFDs) and Reduced Function Devices (RFDs). FFDs can perform all the functions of the 802.15.4 standard, including routing, coordination, sensing, coordinator, router, and endpoint. FRDs perform the functions of the 802.15.4 standard with the lightest processing capabilities. These devices do not perform packet routing and are always associated with an FFD. The purpose of an RFD is to discover an available network for data transfer, check for queued data, and simultaneously issue a data request to the network coordinator. Some end devices, for example, sensors and actuators, have limited working functions, for example reading temperature data, monitoring light lumens, or adjusting other devices.

B. Zigbee Logical Devices

There are three logical Zigbee devices: Coordinator, Router, and End Device, as shown in Figure 1.

B.1. Coordinator

This device forms the root of the network tree and attempts to build bridges to other networks. Each network has exactly one coordinator. The coordinator oversees network selection and specifications, such as radio frequency channels, network identities, and so on. The coordinator also stores security and network key information.

B.2 Router

A Zigbee router is a device within the network. This device routes data from source to destination. Routers can join existing networks. With the help of a Zigbee router, the network can be expanded, and the router can also accept connections from other devices and function as a network retransmitter.

B.3 End Device

An FFD or RFD can be used as an end device. Sensors and switches provide a set of data to these devices. End devices rely on the coordinator or router to send data and cannot relay data from other devices. These devices can be low-power or battery-powered and have limited computing capabilities. The end devices don't need to remain awake at all times, although the other two devices do. Each device has 240 end nodes, each representing a separate application with equal power consumption.

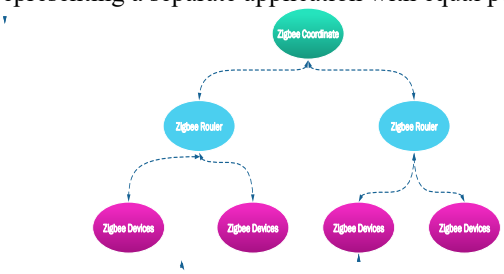


Figure 1: ZigBee Device

2.2.2 Zigbee Topologies

There are three topologies in a ZigBee network: Star, Mesh, and Cluster Tree.

A Star Topology:

This topology consists of a coordinator and end devices (Figure 2). All end devices are connected to a coordinator and are physically and electrically separated. The coordinator must handle all packet exchanges between devices. The advantage of a star topology is its simplicity, as packets only need to travel two hops to reach their destination. The disadvantage is that all packets must pass through the coordinator, which can cause congestion, and there is no other path from source to destination.

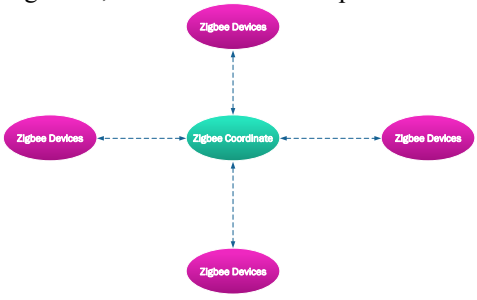


Figure 2: Star Topology

B. Mesh Topology

A peer-to-peer network is another name for a mesh topology. This network consists of a coordinator, as well as many routers and end devices (Figure 3). This network is an extension of the cluster tree topology. A mesh topology is a multi-hop network where packets pass through many obstacles before reaching their destination. If one path fails, the packet will try to reach its target via another route. In a mesh topology, adding or removing devices is easy. Any device on the network can communicate with any other device.

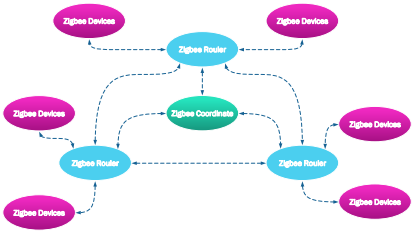


Figure 3: Mesh Topology

C. Cluster Topology

A peer-to-peer topology, which is a subset of the tree topology, is called a cluster tree topology (Figure 4). A cluster consists of a parent and child clusters, each identified by a cluster ID. The cluster tree topology is supported by IEEE 802.15.4 but not by Zigbee. Routers increase the network range, so end devices do not have to be within range of the coordinator. End devices cannot interact directly with each other; however, routers can connect to other routers and the coordinator.

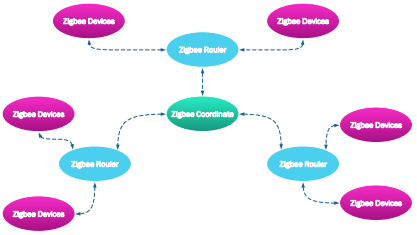


Figure 4: Cluster Topology

2.2.3 System Design

The system design or model to be created consists of: a laptop, a Raspberry Pi cloud server, a Zigbee coordinator, and a Zigbee end user, as shown in Figure 5.

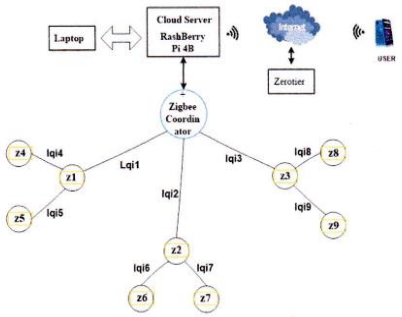


Figure 5: System Design

i. Laptop: Used to install Home Assistant (HA) software, configure HA, configure Zerotier, and control and monitor electrical parameters on the load.
ii. Rashberry: Serves as a server responsible for handling external requests.
iii. Zigbee Coordinator (ZC): Serves as the IEEE 802.15.4 Personal Area Network (PAN) coordinator, responsible for integrating and removing devices from the PAN and transforming them into Full-Function Devices (FFDs).
iv. Zigbee End Devices (Z1-Z9): Send and receive data or commands to the ZC and ZR (Zigbee Router), and each Zigbee End Device is connected to a single-phase electrical load.
v. Zerotier: A distributed networking solution that allows users to securely connect devices in multiple locations, even if they are on the same network.

2.3 Research Stages

The stages of this applied research are shown in Figure 6, consisting of Home Assistant Installation, Hardware Integration (Zigbee ZC & End Device), HA & Zero Tier Configuration, and culminating in System Testing, Evaluation, and Implementation.

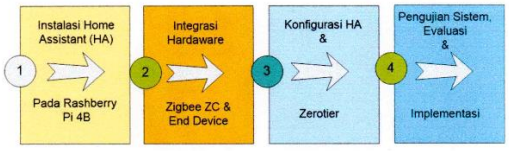


Figure 6: Research Stages

2.3.1 Home Assistant (HA) Installation on Raspberry Pi 4B

HA installation begins with preparing the Raspberry Pi Imager, SD card, and a laptop. This process takes 5-10 minutes to complete. The end devices are distributed across several rooms, and the ZC and end devices are connected using a star-tier connection.

2.3.2 Zigbee Coordinator (ZC) and End Device Hardware Installation

Hardware installation begins by placing the Raspberry Pi Cloud Server in a central position so that the Zigbee signal can be received properly. This is followed by installing several end devices distributed across several rooms, connecting the ZC and end devices using a star-tier connection.

2.3.3 HA and Zerotier Configuration

HA configuration is performed to connect the ZC and end devices so that both are connected to the HA. The next step is to configure the zero-tier by creating a Network ID and connecting the HA hardware, smartphones, laptops, and other devices to that Network ID. The zero-tier configuration will create a table containing device addresses and associated Network IDs, consisting of several columns: Address Name/Description, Managed IPs, Last Seen, Version, and Physical IP.

2.3.4. System Testing

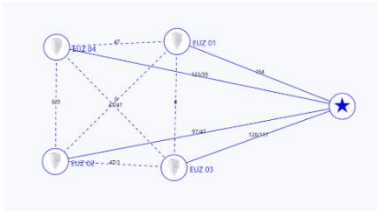
This system testing involves controlling and monitoring the electrical parameters of loads connected to the HA on the Cloud Server. The next stage is evaluation and implementation, aimed at refining the system so that control and monitoring activities can be implemented properly and correctly.

3. RESULTS AND ANALYSIS

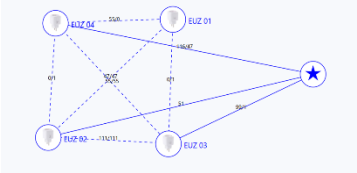
The results of this experiment are an image or map taken from an application taken from an add-on on Home Assistant (HA). The application is called Zigbee2MQTT, which is an "open-source project" that functions to provide the ability for Zigbee devices to communicate with HA via MQQT (message quering telemetry transport) and at the same time users are allowed to easily control and monitor electrical loads. MQTT is the most commonly used messaging protocol for the Internet of Things (IoT). It comes with a set of rules that define how IoT devices can "Publish and Subscribe" to data over the Internet. Using Zigbee2MQTT produces an image showing the connection between the ZC and Euz, both connected and disconnected, while also displaying the signal strength in Lqi (Link Quality) units, which ranges from 0 to 255.

3.1 Euz Placement in Room A

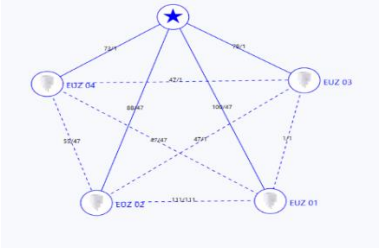
The Euz were placed in several locations: R1, R2, R3, R4, R5, R6, and R7, with LED lights as the electrical load. Using the Zigbee2MQTT application, several data points were obtained on the Lqi connection quality and the relationship between the devices (ZC and Euz), as shown in Figure 7.



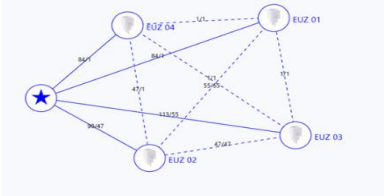
a). Euz I-R1, Euz 2-R2, Euz 3-R3, Euz 4-R4.



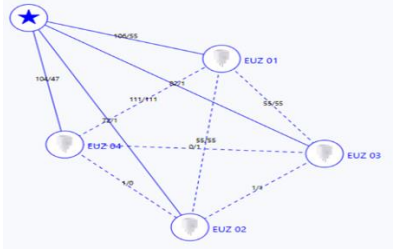
b). Euz4-R4, Euz 3-R5, Euz 2-R6, Euz 1-R7



c). Euz 1-R4, Euz 2-R5, Euz 3-R6, Euz 4-R7



d). Euz 3-R4, Euz 4-R6, Euz 1-R7, Euz 2-R5



e). Euz 1-R5, Euz 2-R6, euz 3-R7, Euz 4-R4,

Figure 7: Connectivity and Lai Values on the Zigbee2MQTT map in room A

Table 1: LQI (LINK QUALITY) Room A

Test a

No.		EUZ01	EUZ02	EUZ03	EUZ04	ZC
1	EUZ01	NN	0	0	47	154
2	EUZ02	.47/47	NN	47/1	0	97/47
3	EUZ03	0	47/1	NN	47/47	120/117
4	EUZ04	47	0	47/47	NN	123/55

Test b

No.		EUZ01	EUZ02	EUZ03	EUZ04	ZC
1	EUZ01	NN	47/47	116/47	55/0	0
2	EUZ02	55/55	NN	111/111	0/1	51
3	EUZ03	0/1	111/111	NN	55/55	99/1
4	EUZ04	55/0	0/1	47/47	NN	116/47

Test c

No.		EUZ01	EUZ02	EUZ03	EUZ04	ZC
1	EUZ01	NN	111/111	1/1	47/47	100/47
2	EUZ02	111/111	NN	47/1	55/47	88/47
3	EUZ03	1/1	47/1	NN	47/1	79/1
4	EUZ04	47/47	55/47	47/1	NN	73/1

Test d

No.		EUZ01	EUZ02	EUZ03	EUZ04	ZC
1	EUZ01	NN	1/1	1/1	1/1	84/1
2	EUZ02	55/55	NN	47/47	47/1	90/47
3	EUZ03	1/1	47/47	NN	1/1	84/1
4	EUZ04	1/1	47/1	1/1	NN	84/1

Test e

No.		EUZ01	EUZ02	EUZ03	EUZ04	ZC
1	EUZ01	NN	55/55	55/55	82/1	106/55
2	EUZ02	55/55	NN	1/1	1/0	72/1
3	EUZ03	55/55	1/0	NN	0/1	82/1
4	EUZ04	111/111	1/0	0/1	NN	104/47

In general, the relationship or connectivity of the three experimental results (figure 7 a, c, d and e) between ZC and Euz is a star relationship because ZC can be connected directly with a solid line on all Euz as shown in figure 8. The quality of the relationship marked with Lqi is still in the good category, namely above 100 from the highest value of 255. Meanwhile, the Lqi value between Euz varies greatly and is very dependent on the distance between devices whose Lqi value is less than 100.

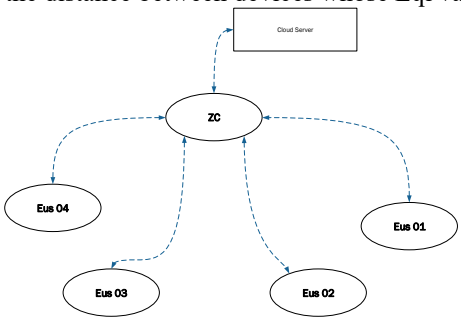


Figure 8: Star topology connection pattern in room A (experiments A, C, D, and E)

Meanwhile, in Figure 9b, the relationship between ZC and EUZ is a Semi Cluster topology. This Semi Cluster relationship occurs because there is one ZUE that is not directly connected to ZC, but must go through other EUZs to reach ZC as shown in Figure 9.

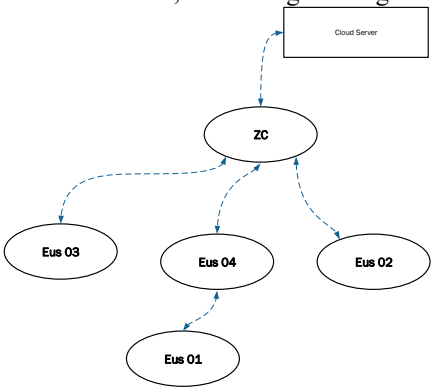


Figure 9: Semi-ClusterTopology Relationship Pattern in Room A (Experiment B)

3.2 Placement of Euz in Room B

Euz was placed in several locations, namely R1(R….), R2(R….), R3(….), R4(R….), R5(R…..), and R6(R….) with an electrical load in the form of an LED lamp. Through the Zigbee2MQTT application, several Lqi connection quality data were obtained as shown in Figure 10.

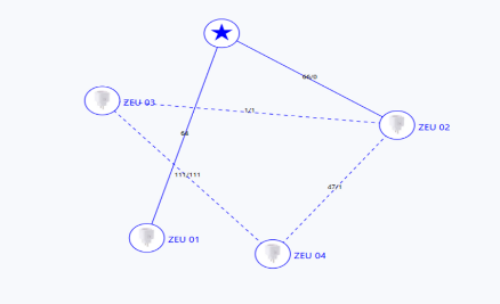


Figure 10: Lai value on Zigbee2MQTT map in Room B

Table 2: LQI (LINK QUALITY) Room B

Test 01

No.		EUZ01	EUZ02	EUZ03	EUZ04	ZC
1	EUZ01	NN	0	0	0	111/111
2	EUZ02	0	NN	1/1	47/1	64/0
3	EUZ03	0	1/1	NN	111/111	0
4	EUZ04	0	47/1	111/111	NN	0

The connectivity in Figure 11 shows that the Lqi value between the ZC and the EUZ is relatively lower compared to the placement in the Electrical Laboratory. This is because the ZC and EUZ are blocked by a high wall in Room B. However, all EUZs can still be served by the ZC, either directly or indirectly through other nearby EUZs. The direct connection between the ZC and the EUZ and EUZs to other EUZs forms a topology resembling a cluster, as shown in Figure 11.

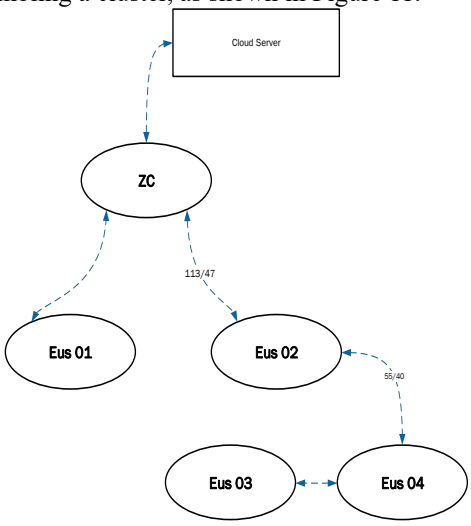


Figure 11: Semi Cluster Topology relationship pattern in room B.

The achievement in this research is a Zigbee Protocol-based Control and Monitoring System with a Dashboard display shown in Figure 12. Meanwhile, monitoring of the Internal Cloud server is shown in Figure 13.

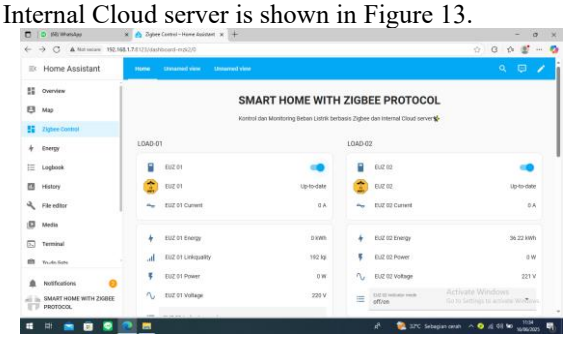


Figure 12: Zigbee-based Control and Monitoring Dashboard Display

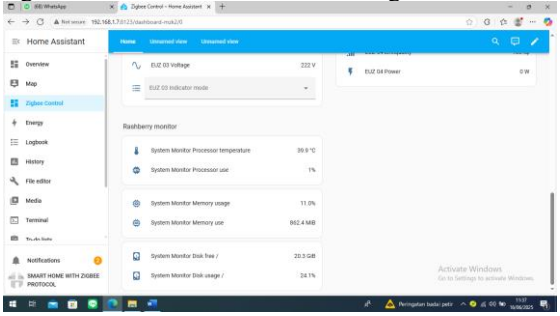


Figure 13: Monitoring Display on Rashberry as a Cloud Server

Other facilities owned by the control and monitoring application are the existence of a Terminal and SSH which function to access the HA Server as an internal cloud to make necessary changes, find out and overcome problems that occur as shown in Figure 14.

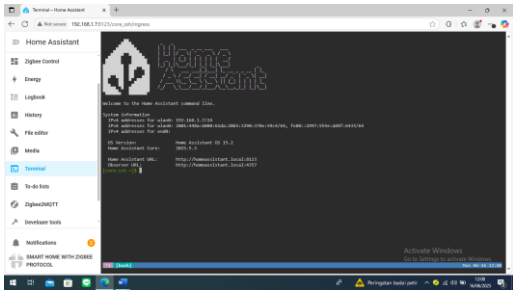


Figure 14: Terminal and SHH View

4. CONCLUSION

Based on the experimental results, Home Assistant (HA) has been developed as a comprehensive and flexible control and monitoring application for various technology products, enabling efficient building automation without requiring high investment costs. Furthermore, users can customize the Dashboard System (Lovelace) to meet their control and monitoring needs.

1. Experimental results show that the ZC and EUZ in Room A can be directly connected to each other, resulting in a better Lqi value. This is because the distance between the ZC and EUZ is not too far and there are fewer wall obstructions.
2. The second experimental results show that the ZC and EUZ in Room B have lower Lqi values. This is because the ZC is further away from the EUZ and has wall obstructions, making it difficult for the Zigbee signal to reach each EUZ.
3. The second experimental results show that the ZC and EUZ in Room B have lower Lqi values. This is because the ZC position is further away from the EUZ, and has obstacles in the form of workshop walls so that the Zigbee signal has some difficulty reaching each EUZ. The Smart Home Control and Monitoring System based on the Zigbee Protocol with a configuration using a cluster topology with the use of Zigbee Euz that does not have a strong enough Lqi (less than 55) can be connected to the Zigbee coordinator via another Zigbee Euz that has a stronger Lqi (more than 55) to the Zigbee Coordinator.

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