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QOS ANALYSIS OF LEO SATELLITE BROADBAND NETWORK FOR IOT IN SMART FARMING

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ABSTRACT
The need for food in the form of agricultural products is currently increasing along with the growth of the world's population. However, the workforce in the agricultural sector in the modern era is decreasing because many young people are reluctant to become farmers. Therefore, the concept of Smart Farming emerged to overcome this problem by helping farmers manage and run agriculture efficiently using modern technology that can work automatically or be monitored or operated remotely using the internet network, for example, the Internet of Things (IoT) Smart Farming. However, agricultural areas located in remote or isolated villages are difficult to reach by terrestrial internet network infrastructure. Therefore, Low Earth Orbit (LEO) satellite broadband network infrastructure can be a new solution, so it needs to be researched. This research analyzes the Quality of Service (QoS) of LEO satellite broadband networks in IoT Smart Farming. The methods used consist of prototyping, experimentation, and analysis. QoS analysis based on throughput, packet loss, delay, and jitter parameters. The results of the experiment and analysis of this study indicate that the throughput value is 1243 bps. The speed test results show an average download speed of 88,89 Mbps and an upload speed of 14,08 Mbps. The packet loss value is 0%, which means that all packets were successfully sent. The average delay value is 97 ms. The jitter value is 26 ms. The results of this study can be further studied and developed for other use cases that are constrained by terrestrial internet network infrastructure.

I. INTRODUCTION

THE need for food in the form of agricultural products is currently increasing along with the growth of the world's population [1]. However, the workforce in the agricultural sector in the modern era has decreased because the majority of young workers in Indonesia are less interested in becoming farmers and prefer to work in the manufacturing or service sectors in urban areas [2]. To overcome this problem, Smart Farming technology can be a new solution in increasing the production of agricultural products with minimal labor and costs because it can work automatically [3]. Smart Farming is a new idea to manage agriculture more efficiently by utilizing modern technologies such as IoT and broadband networks [4]. One of the advantages of Smart Farming, based on the research of Agbenyo et. al. in 2022 in Ghana, it was shown that the application of Smart Farming in the fields of weather and irrigation can increase agricultural production productivity and increase farmer income by 8.6% to 11.1% [5]. Research results from Samuel et. al. in 2024 showed that the adoption of Smart Farming for climate technology increased farmers' incomes by 40% in India [6]. Based on an online article (published on March 20, 2025) on the website of Balai Besar Pelatihan Pertanian (BBPP) Ketindan, Lawang, Malang, Indonesia, it was stated that in recent years, the transformation of the agricultural sector towards Smart Farming has grown rapidly in Indonesia. Therefore, the Indonesian government continues to encourage agricultural digitalization as part of the national food security strategy and improving farmer welfare [7]. In a scientific article, Lestari et. al. in 2024 proposed that the implementation of Smart Farming [8], especially smart irrigation systems, is expected to increase agricultural productivity so that it can increase farmers' income. Smart Farming certainly has the potential to increase farmers' income by reducing manual labor and minimizing waste of resources such as water. In addition, it will also support national food security by optimizing agricultural output due to data-based decision making.

IoT can improve the production and quality of agricultural products because it allows farmers to monitor crop conditions in real time and control agricultural equipment remotely [9]. IoT based on Wireless Sensor Network (WSN) is an efficient technology for IoT Smart Farming in large agricultural areas [10], [11]. Therefore, it is necessary to install wireless internet network infrastructure in large agricultural areas to support IoT in Smart Farming. There are three types of broadband network infrastructure that can provide wireless internet with Wi-Fi interfaces to support IoT connectivity in Smart Farming: cable, cellular, and satellite [12]. Only cellular or LEO satellite broadband networks are suitable for implementation in Smart Farming on large agricultural lands and in rural or remote areas [13], [14]. However, cellular networks in remote agricultural areas are sometimes inadequate or even unavailable [15]. Therefore, the LEO satellite broadband network can be a new solution, so it needs to be studied, especially Starlink, a SpaceX product that has been marketed to Indonesia in 2024.

In many cases, Smart Farming equipment relies on wireless communications, such as WSN, using radio frequencies, such as cellular or satellite networks [16]. Farmers in Smart Farming use satellite-based, cellular, and fixed wireless broadband network technologies with Wi-Fi interfaces to make real-time decisions about their fields, crops, equipment, and farming facilities [12]. Cellular communication technologies such as 3G, 4G, LTE, and 5G are suitable technologies that can be relied on for IoT Smart Farming because they can transmit and manage farming data in real-time [15]. However, in most cases, farmland in remote areas is not fully covered by cellular networks and other forms of internet connectivity. Satellite internet technology is a promising solution in providing internet connectivity throughout the earth, including remote areas where terrestrial broadband network infrastructure is difficult to build [13]. In particular, LEO satellites can provide broadband connection services with high bandwidth and low latency. LEO satellites are popular communication satellites [17], with an altitude of between 100 - 2000 Km orbiting the earth very quickly [15]. LEO satellites move in and out of the line of sight (LOS) regularly every 9 - 10 minutes. LEO satellite networks offer extensive coverage and flexibility when compared to alternatives such as mesh networks or hybrid solutions that combine several terrestrial network infrastructures, such as cellular networks and fiber optic cables, whose infrastructure is static and relatively expensive to scale. The study of QoS of LEO satellite networks which is limited in Indonesia will be answered in this research, especially in the IoT Smart Farming use case. In Indonesia there are still many rural areas, mountains and remote islands. The advantage of the LEO Starlink satellite is that it can provide internet access in areas that are difficult to reach by conventional internet network infrastructure, such as fiber optic cables and cellular networks that are not economical to build in these areas due to high installation costs and low potential returns on investment [18]. Starlink can provide broadband internet connection without geographical barriers. Users need to install a LEO Starlink satellite signal receiver antenna with a direct view of the sky and subscribe to get an internet connection that is claimed to be comparable to broadband services in urban areas. The LEO Starlink satellite has an altitude of 1110-1325 km using the Ku and Ka bands with a latency of 25 - 35 ms, while at an altitude of 340 km it has a latency of 10 - 15 ms [19]. The latency of LEO satellite communication is affected by its altitude. Therefore, this study uses the LEO Starlink satellite because it has the lowest latency when compared to OneWeb and Telesat.

In Indonesia, there have been several studies related to the application of LEO satellites in several fields, such as testing natural disaster data collection in Indonesia via satellite-based Long Range (LoRa) [20], designing a data collection platform using LEO satellite-based LoRa for disaster management in Indonesia [21], a method for monitoring forest temperatures in Indonesia using IoT and with LEO satellites [22], and designing microsatellite imaging using LEO satellites to prevent illegal fishing in Indonesia [23]. In addition, there is also research related to the calculation of Equivalent Power Flux Density (EPFD) for downlink evaluation in Indonesia with non-GSO (LEO) satellites using Starlink, and for GSO satellites using Telkom 3S at Ku band frequencies [24], an investigation to determine uplink interference between NGSO (LEO) and GSO satellites at Ku band frequencies using Starlink and Telkom 3S satellites as case studies in Indonesia [25], and a case study on Starlink and Telkom 3S satellites in Indonesia to investigate interference between LEO and GSO satellites at Ku band frequencies [26]. Based on the results of literature searches on online scientific databases and open sources, there has been no research related to the implementation and analysis of LEO satellite networks for the IoT Smart Farming use case in Indonesia. Therefore, this research implements a LEO satellite broadband network for IoT Smart Farming and analyzes QoS. This research analyzes the QoS of LEO satellite broadband networks on IoT Smart Farming to determine the quality of its performance. The methods used in this research consist of prototyping, experiments, and analysis. Prototyping refers to the System Development Life Cycle (SDLC) [27]. Experiment to collect and measure QoS of LEO satellite broadband network with data packet delivery test scenario on IoT Smart Farming. Analysis based on QoS parameters in the Telecommunications and Internet Protocol Harmonization Over Networks (TIPHON): throughput, packet loss, delay, and jitter value [28].

The results of this research are expected to be used as recommendations for stakeholders such as farmers, entrepreneurs, government in the field of agriculture, or researchers in determining the suitable broadband network infrastructure for IoT Smart Farming in remote areas. Referring to and improving previous studies, this study will provide empirical data on the QoS of LEO satellite broadband networks based on experimental results from real implementations using Starlink on IoT Smart Farming in agricultural land in rural areas of Indonesia. The results of this study offer new insights and empirical data gaps in the existing literature.

II. METHOD

As explained in the background, the research methods used in this research are prototyping, experimentation, and analysis. Prototyping to develop devices and systems in this study. Prototyping refers to the SDLC, which consists of the stages of requirements analysis, design, implementation, and testing [27]. Experiments for broadband network QoS measurement based on the TIPHON to determine the QoS parameter values consisting of throughput, packet loss, delay, and jitter value [28]. The analysis represents the experimental data to determine the QoS of LEO satellite broadband networks for IoT Smart Farming. The research stages are based on this research method. This research stage consists of literature study, system requirements identification, system design, implementation, testing, experiment, data collection, analysis, and publication of research results. The research stages diagram is presented in Figure 1.

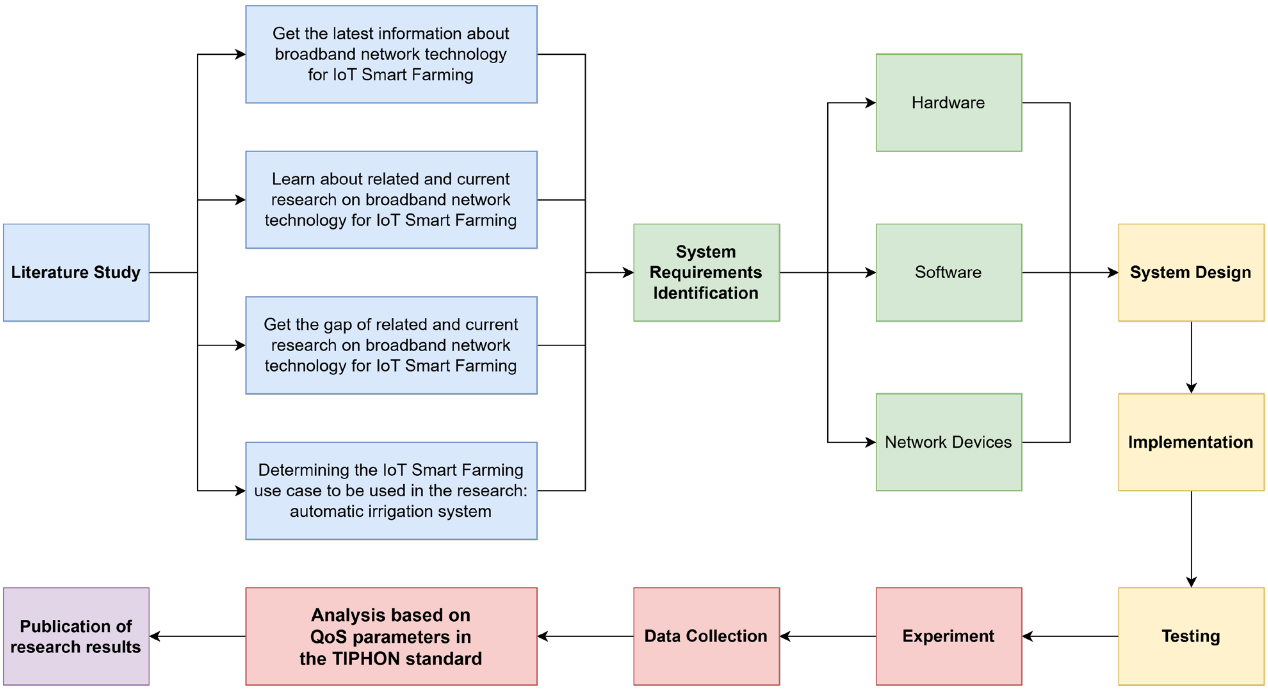

Figure 1. Research Stages Diagram

This research is carried out sequentially according to the stages of this research. Starting from the stages of literature study, system requirements identification, system design, implementation, testing, experiments, data collection, and publication of research results. This research began on 3 January 2025 to 7 May 2025. Literature search at the literature study stage in online scientific databases and open sources that provide literature and research related to this research. System requirements identification based on the results of literature studies and the results of the gap discovery process from previous literature and research. The system design refers to the literature and the objectives of this research. Implementation is in accordance with the system design and is carried out with the required technical competencies, such as IoT programming skills and network configuration. Testing after the implementation stage is complete to ensure that the implementation results are ready to be used for experimental activities in this research. Experiments are the core of this research which aims to obtain empirical data in accordance with the objectives of this research. Data collection is the process of collecting data from experiments. Analysis is a stage for interpreting experimental research data to become knowledge as a result of this research. Publication aims to report the results of this research to the public so that they can be used for further research and decision making. The stages of this research are explained in detail in each sub-chapter of this section.

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A. Literature Study

The literature study stage is to find out the latest information and research on broadband technology in IoT Smart Farming in order to find gaps in previous research and determine the novelty in this research. In addition, the literature study stage is also used to determine the scope and use cases used in the research or being researched. The IoT Smart Farming use case used in this research is an automatic irrigation system with the MQTT protocol using the Telkom IoT Platform. Irrigation is an important factor in agriculture [29]. IoT Smart Farming technology can improve the quality of agricultural production by monitoring soil water levels using sensors and actuators to effectively manage irrigation systems in agricultural areas [30]. Automatic irrigation systems are at the heart of Smart Farming [31]. The function of the automatic irrigation system is to provide and maintain a stable and optimal water supply for plants so that plants can grow ideally and the impact of agricultural production will increase. IoT Smart Farming consists of sensors that collect data on agricultural environmental conditions, data communication networks from sensors in agricultural areas with control stations for decision-making, control systems and actuators based on data from sensors, and data visualization applications for analysis [32]. The automatic irrigation system in IoT Smart Farming autonomously turns on or off the irrigation pump motor based on the data on the level of soil moisture content of the agricultural land read by the sensor [29]. The IoT Smart Farming architecture of the automatic irrigation system is presented in Figure 2.

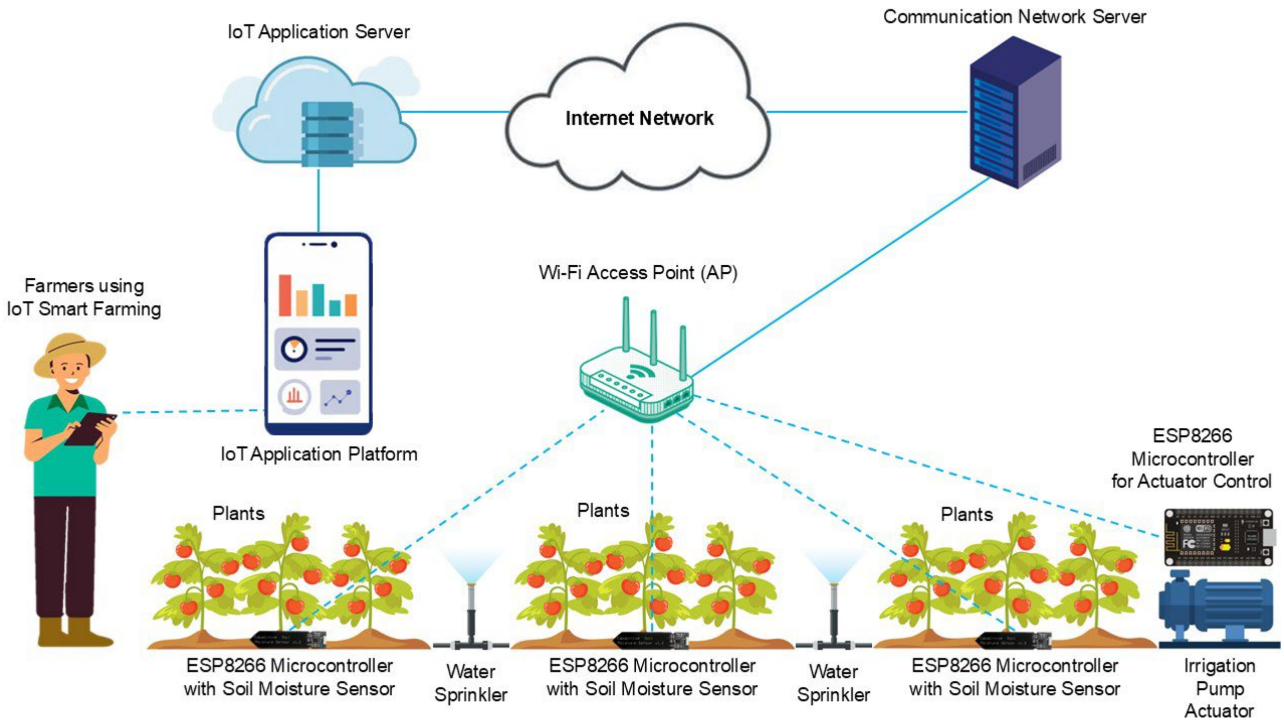


Figure 2. IoT Smart Farming Architecture of Automatic Irrigation System

Broadband networks in rural areas are related and useful to support agriculture with IoT Smart Farming technology [33]. Reliable and fast broadband network access is not only a necessity in many aspects of daily life but also an important component of activities related to the agricultural sector [34], such as IoT Smart Farming. The application of broadband network connectivity to agricultural technology, such as IoT Smart Farming, can generate added value and economic benefits. Several studies have found that the availability of broadband networks has a significant impact on profitability in the agricultural sector. In remote areas where connectivity through cellular communication is not available, satellite systems are considered a better alternative to cellular systems to provide internet network connectivity [15]. Currently, LEO satellite broadband network services are increasingly available and affordable [35]. The aspects that make LEO satellites attractive are coverage, system capacity, latency, and cost [17]. In addition, the relatively lower latency compared to MEO and GEO satellite systems, path loss, and production and launch costs make LEO satellites very attractive to various industries [19], as illustrated in Figure 3. Therefore, this research analyzes the QoS of LEO satellite broadband networks.

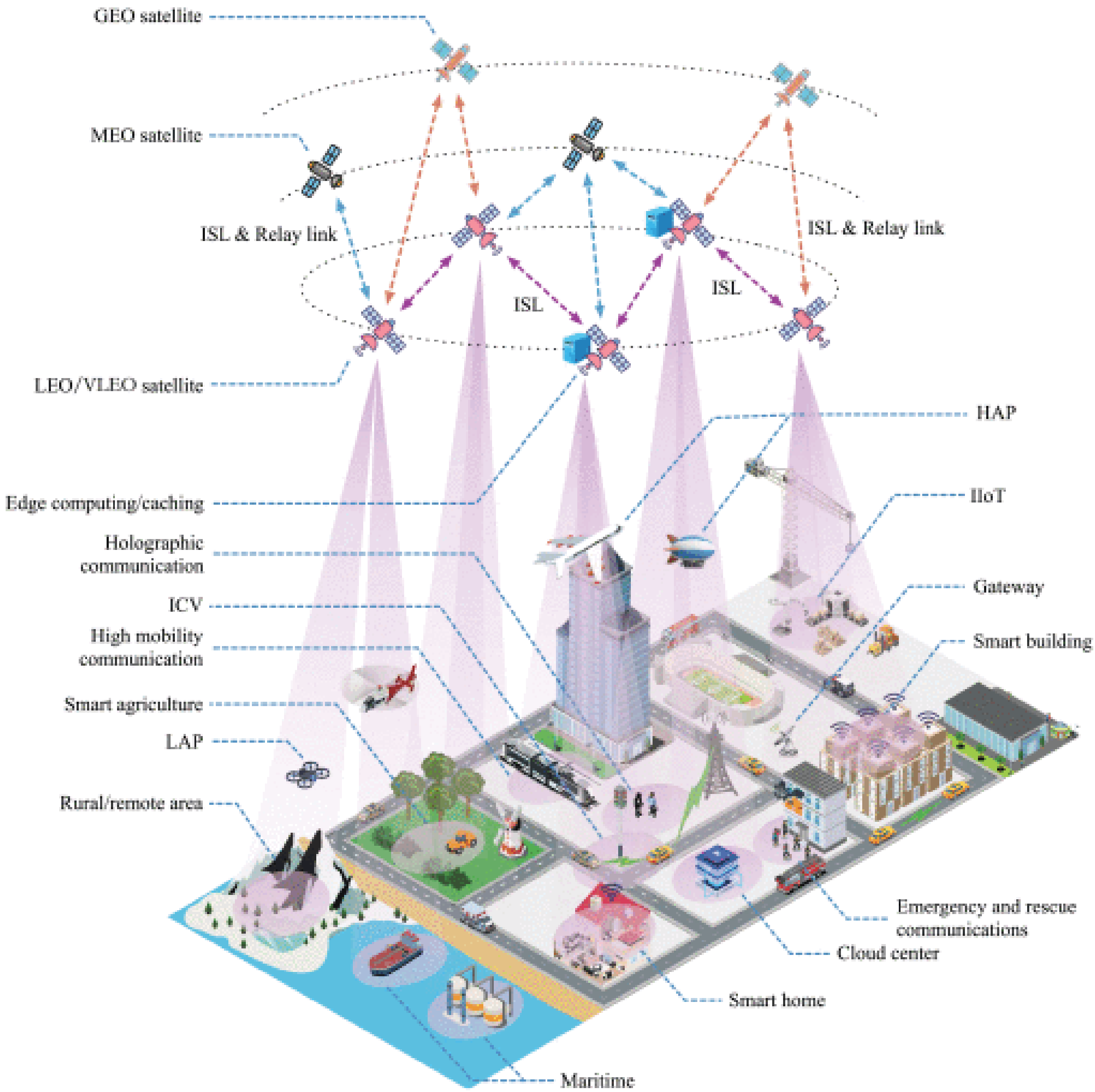


Figure 3. Potential Applications of LEO Satellite Communications [36]

B. System Requirements Identification

The system requirements identification stage is to identify the system requirements studied and used in this research, such as hardware, software, and network infrastructure device requirements. To support this research, researchers use a combination of hardware, software, and network devices. Hardware devices are used as the IoT system media. Software is used to program the IoT. Network devices are used for communication between the IoT. There are several hardware, software, and network infrastructure devices used in this research. The hardware consists of an ESP8266 microcontroller [37], [38], [39], v1.2 capacitive soil moisture sensor [40], [41], DHT22 temperature and humidity sensor [42], [43], relay for actuator control, 18650 battery, and cables. The software used are Arduino IDE, draw.io, Telkom IoT Platform [44], MQTT protocol [45], and Microsoft Excel for analyzing research data. The network devices used are Wi-Fi AP and LEO satellite antennas from Starlink [46].

C. System Design

The system design stage involves designing the system and devices used and studied in this research. System design according to the objectives of this research. The schematic design of the IoT Smart Farming automatic irrigation system in this research is presented in Figure 4.

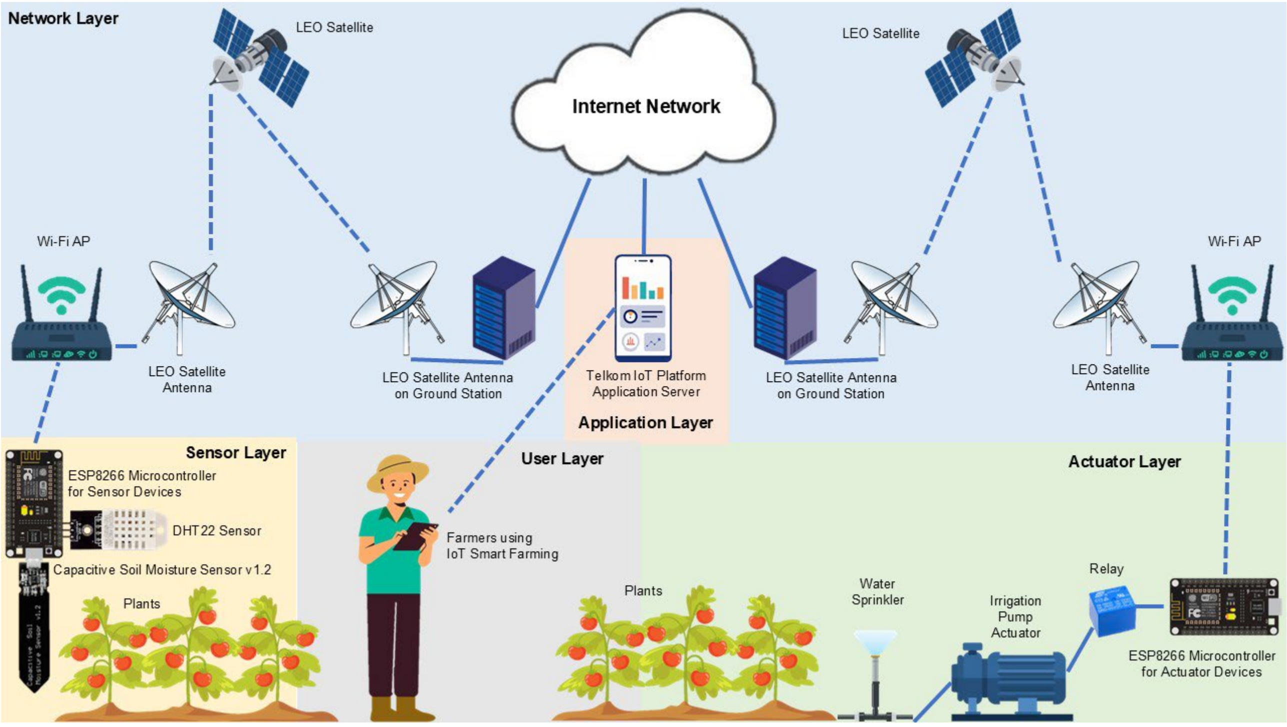


Figure 4. IoT Smart Farming Scheme Design in This Research

Data of the soil moisture, temperature, and air humidity values in the agricultural environment are sent from the sensor device to the actuator device via the LEO satellite broadband network. Sending data packets using the MQTT protocol with an MQTT broker provided by the Telkom IoT Platform. Farmers can monitor data on soil moisture, temperature, and air humidity in their agricultural environment via the Telkom IoT Platform dashboard. Data on temperature and humidity in agricultural environments can be used to analyze the relationship between temperature and humidity and the health of agricultural plants using statistics [47]. Soil moisture value data is used as a parameter to determine the activation of the plant irrigation water pump actuator based on the values determined according to the type of plant. Therefore, it is important to measure and analyze the QoS of the network used, especially the LEO satellite broadband network used in the study, because the QoS of the network will affect the performance and response time of the IoT Smart Farming automatic irrigation system.

D. Implementation

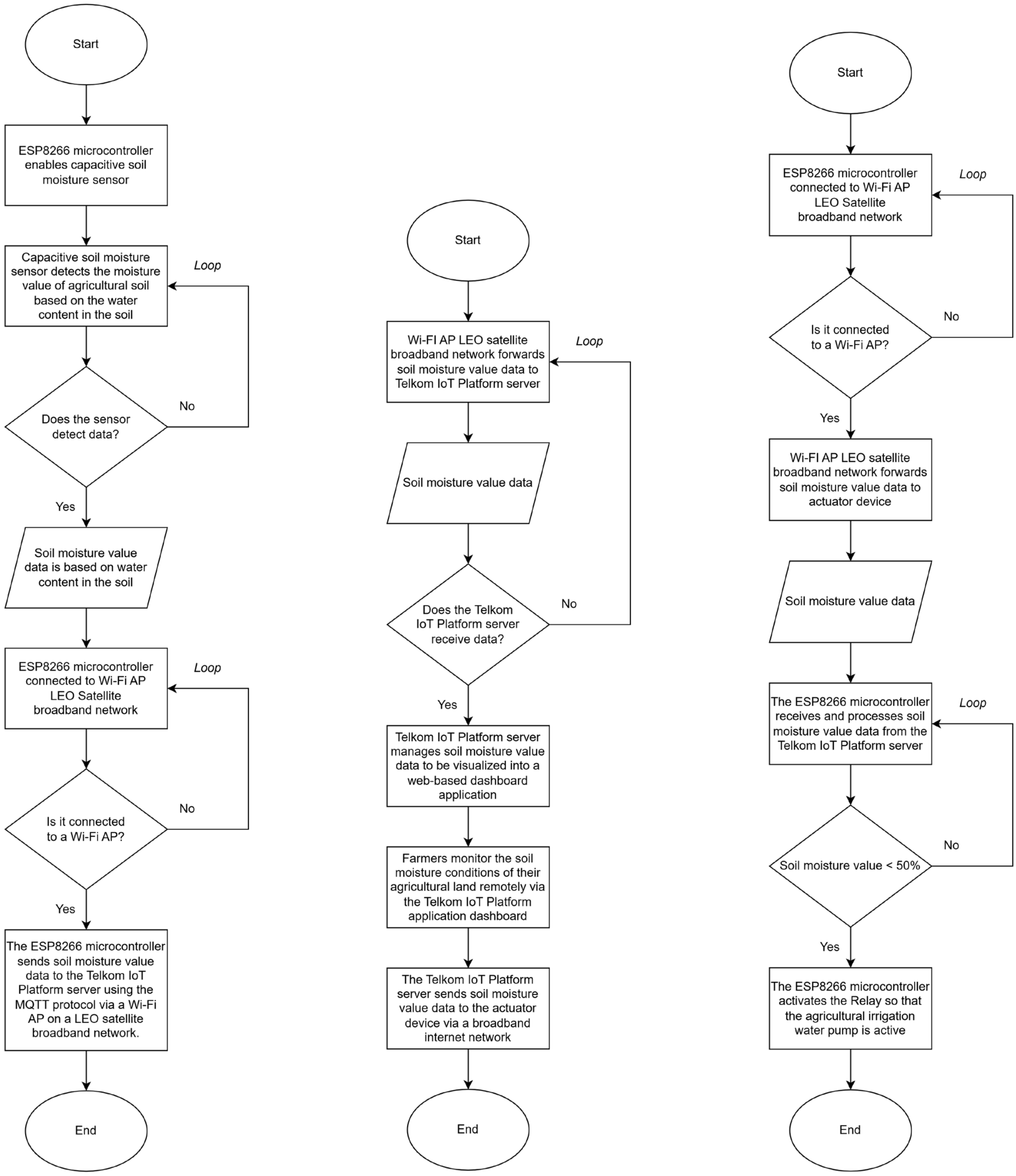
The implementation stage consists of assembling the devices used for research and programming the IoT Smart Farming automatic irrigation system. The programming language used is C++ for implementing the programming source code on the hardware microcontroller. The flowchart diagram of the IoT Smart Farming program in this research is presented in Figure 5.

E. Testing

The testing stages to ensure that the assembled and programmed device can run and function properly according to the design and research objectives. Testing is performed in the laboratory after the research device is assembled and programmed. Testing aims to ensure that the devices and systems are ready to be used for experiments with the variables determined in this research. Testing is also to ensure that devices and systems are ready for use in scenarios in research experiments.

F. Experiment

The experimental stage is conducting experiments on research scenarios and variables. The experimental scenario consists of sending data packets from a sensor device to an actuator. The scenario was conducted in two sessions. Each session was 100 times sending data packets from the sensor device to the actuator. The location of this research experiment is in the agricultural land area belonging to Balai Besar Pelatihan Pertanian (BBPP), Lembang, Bandung Barat, Jawa Barat, Indonesia.



(a) Sensor Device Program (b) Network Layer Program (c) Actuator Device Program

Figure 5. Flowchart diagram of the IoT Smart Farming Program

G. Data Collection

The data collection stages to collect data from the results of the experimental stages. The data collected includes the size of data packets for throughput analysis, the number of data packets sent by the sensor device and data successfully received by the actuator device for packet loss analysis, the duration of the transmission time from the sensor device to the actuator for delay and jitter analysis. In this research, a serial monitor is used to monitor the time when data packets are sent from sensors and the time when data packets are received by actuator devices. The time values for sending data packets and receiving packets displayed on the serial monitor are then recorded and collected for delay and jitter analysis. Using a serial monitor because it can show time to millisecond accuracy. Data collection of data packet sending time from sensor devices and data packet receiving time on actuator devices displayed on the serial monitor is presented in Figure 6.

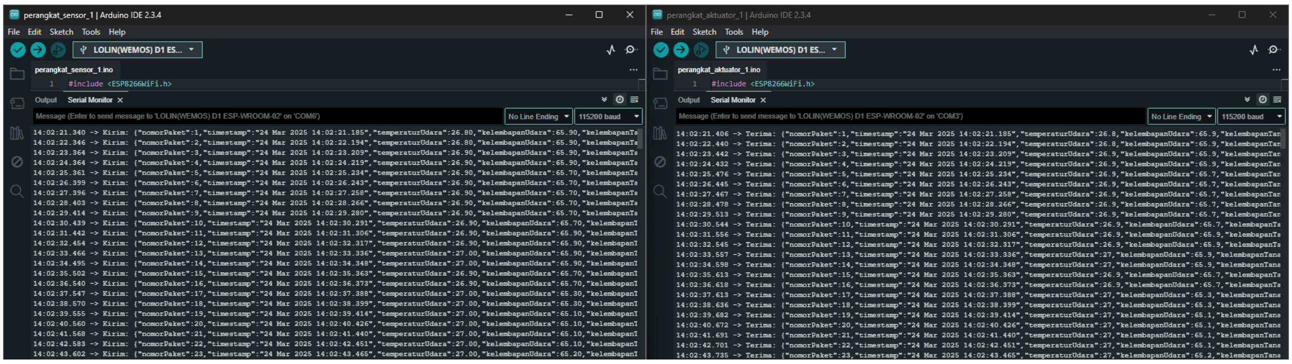


Figure 6. Data Collection of Data Packet Delivery Time on Serial Monitor

H. Analysis

The analysis stage involves analyzing research data that has been collected from the results of experiments. Analysis based on QoS parameters according to TIPHON including throughput, packet loss, delay, and jitter [48]. The throughput parameter measures the data transmission capability on a network by dividing the number of data packets received by the transmission time [49]. Throughput is equal to the total number of large data packet sizes that enter the network and successfully reach the recipient during a certain time interval divided by the duration of that time [48]. The calculation of the throughput value is presented in Equation 1.

$$Throughput\ (bps) = \frac{\sum size\ of\ data\ packet\ sent\ (b)}{\sum data\ packet\ delivery\ time\ (s)} \quad (1)$$

Packet loss parameters are parameters used to determine the percentage of data packets that fail to reach their destination [49]. The packet loss value is obtained by calculating the number of data packets sent minus the number of data packets that were successfully sent to their destination, then divided by the number of data packets sent, then multiplied by 100% to obtain the packet loss value in percentage form. The calculation of the packet loss percentage is presented in Equation 2. The result of the calculation of Equation 2 is the percentage value of packet loss which can be a QoS parameter based on the QoS category that represents the QoS of a network. Packet loss is a QoS parameter that describes a condition that shows the number of lost data packets, which can occur due to data packet collisions and congestion during the transmission process in the network.

$$Packet\ loss\ (\%) = \frac{\sum data\ packet\ sent - \sum data\ packet\ received}{\sum data\ packet\ sent} \times 100\% \quad (2)$$

Delay refers to the duration of time required for a data packet to be sent from the sender to the receiver, indicating the length of time the data packet is transmitted [49]. The delay value is obtained by calculating the time the data packet is sent to its destination minus the data delivery time [48]. The average delay value is obtained by calculating the sum of the delays of all packets sent divided by the number of data packets sent. The average delay is presented in Equation 3. The average delay value can be a QoS parameter.

$$Average\ delay\ (ms) = \frac{\sum Delay\ (ms)}{\sum data\ packet\ sent} \quad (3)$$

Jitter is the variation in the arrival time of data packets at the destination on a network [48]. Jitter occurs due to the difference in arrival time of data packets at the receiver [50]. The smaller the jitter value, the better the network [51]. To calculate the jitter value, a delay variation value is required which is formulated by subtracting the data sending delay from the previous delay, then after the delay variation value is obtained, jitter can be determined by dividing the delay variation value by the number of packets received minus one [48]. The calculation of the jitter value is presented in Equation 4.

$$Jitter\ (ms) = \frac{\sum_{i=1}^{n} Delay_i - Delay_{i-1}}{n - 1} \quad (4)$$

n = data packets received

I. Publication of Research Results

The stages of publication of research results to publish the results of this research. The results of this research are expected to be utilized by stakeholders, such as farmers, agricultural government, entrepreneurs, and researchers. It is also hoped that the results of this research can be studied further by researchers and practitioners.

III. Result and Discussion

The results of the implementation of this research system design are in the form of IoT Smart Farming automatic irrigation devices and systems. The devices and systems are used as use cases to analyze the QoS of LEO satellite broadband networks. The sensor devices and actuator modules of the IoT Smart Farming automatic irrigation system are presented in Figure 7.

(a) Sensor Device (b) Actuator Module Device

Figure 8. Wi-Fi AP Devices and LEO Satellite Broadband Network Antennas

The sensor device consists of an ESP8266 microcontroller, a v1.2 capacitive soil moisture sensor, a DHT22 temperature and humidity sensor, a 99000 mAh 18650 battery, jumper cables, and a waterproof plastic packaging box to protect the device from rain and irrigation water. The actuator module device as an on/off control switch connected to the irrigation water pump consists of an ESP8266 microcontroller, a 3v relay, a 99000 mAh 18650 battery, jumper cables, and a waterproof plastic packaging box to protect the device. The sensor device and actuator module are connected to the Wi-Fi AP of the LEO satellite broadband network wirelessly using the ESP8266 microcontroller. The Wi-Fi AP device and LEO satellite broadband network antenna are presented in Figure 8.

(a) Wi-Fi AP Device (b) Starlink Satellite Antenna

Figure 8. Wi-Fi AP Devices and LEO Satellite Broadband Network Antennas

Sending data packets from sensor devices to actuator module devices using the MQTT protocol with an MQTT broker from Telkom IoT Platform. The payload is sent in JSON format. Here is an example of the payload sent:

Payload = {"packageNumber":1,"timestamp":"24 Mar 2025 14:02:21.185","airTemperature":26.80,"airHumidity":65.90,"soilMoisture":0, "ADCvalue":658," packageSize":156}

The payload is sent from the sensor device to the actuator using the MQTT protocol via the Telkom IoT Platform server and application. The payload is processed in the Telkom IoT Platform server and displayed on the application dashboard so that farmers can monitor the environmental conditions of their farms through IoT Smart Farming sensors placed on their farmland. Data on soil moisture, temperature and agricultural air humidity can be used by farmers to analyze the relationship between soil moisture, temperature and air humidity with the health of agricultural plants using statistical methods. The Telkom IoT Platform application display is presented in Figure 9.

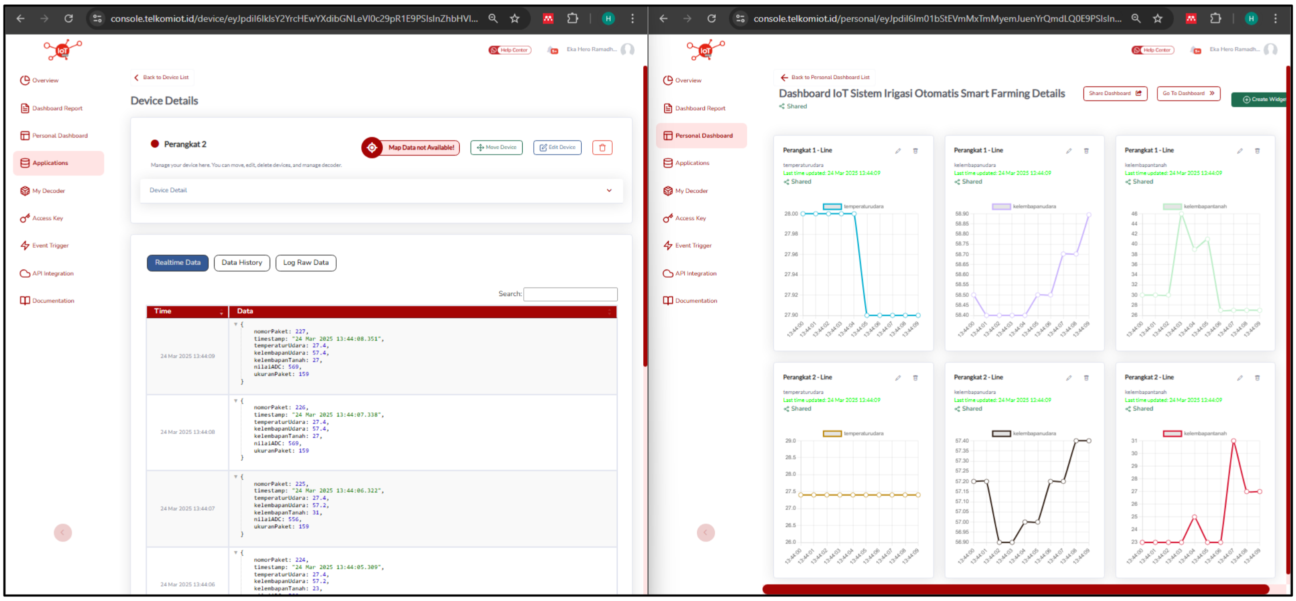


Figure 9. Telkom IoT Platform Application Dashboard

The IoT Smart Farming automatic irrigation system and devices built as a use case in this research can work well according to design. The sensor device can send data to the actuator device for irrigation pump control via a wireless network using the MQTT protocol. If the soil moisture value is less than the set parameter of 60%, which means the soil is dry, then the automatic irrigation system will be active. If the soil moisture value is more than 60%, which means the soil is wet or normal, then the automatic irrigation system will be deactivated. With an automatic irrigation system, farmers do not need to water the plants manually, of course it will save farmers energy and time. After the entire IoT Smart Farming automatic irrigation system and devices are completed and can run according to their function, the next step is to analyze the QoS of the LEO satellite broadband network.

The main focus of this research is to analyze the QoS of LEO satellite broadband network from Starlink, especially for IoT Smart Farming in agricultural areas at BBPP Lembang, Bandung Barat, Jawab Barat, Indonesia. The data analyzed is based on the experimental results according to the scenario. QoS analysis based on TIPHON parameters, including throughput, packet loss, delay, and jitter.

A. Throughput

In the first experiment, 100 data packets were sent. The size of the first to tenth data packet is 156 bytes (1248 bits). The size of the eleventh to ninety-ninth data packets is 157 bytes (1256 bits). The size of the hundredth data packet is 158 bytes (1264 bits). Total data packet size in the first experiment:

(10 packets x 1248 bits) + (89 packets x 1256 bits) + (1 packet x 1264) = 125528 bits

Based on Equation 1, the throughput value is equal to the total number of large data packet sizes that enter the network and successfully reach the recipient during a certain time interval divided by the duration of that time. In the first experiment, 100 data packets from the sensor device to the actuator device were successfully sent, and all packets were successfully received. The first packet was sent from the sensor device at 14:02:21.340 UTC+7.

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The hundredth packet was received by the actuator device at 14:04:01.888 UTC+7. So, the duration of time from sending the first data packet from the sensor device to the hundredth packet being received by the actuator device is 00:01:40.548 (101 seconds). Throughput values from the first experiment:

$$Throughput\ (bps) = \frac{125528\ bits}{101\ seconds} = 1242{,}9\ bps$$

The throughput value obtained in the first experiment was 1242,9 bps (rounded to 1243 bps). In the second experiment, the size and number of data packets sent from the sensor device to the actuator device were the same as in the first experiment. The first data packet in the second experiment was sent from the sensor device at 14:37:54.931 UTC+7. The hundredth data packet of the second experiment was received by the actuator device at 14:39:35.581 UTC+7. So, the duration of sending the first to hundredth data packets in the second experiment is 00:01:40.650 (101 seconds). The data packet size and packet delivery duration in the first and second experiments were the same, so the throughput value calculation results were the same: 1242,9 bps. Because the data packet size of the IoT device is relatively small, for example, the throughput value of the experimental results in this study was only 1243 bps, then a measurement was carried out using speedtest.net. The results of 10 internet speed measurement tests of the LEO satellite broadband network in the agricultural area of Lembang, Bandung Barat, were an average download speed of 88,89 Mbps and an upload speed of 14,08 Mbps. The internet speed test of the LEO satellite broadband network is presented in Figure 10. The results of the LEO satellite broadband network speed test are presented in Table 1.

Figure 10. LEO Satellite Broadband Network Internet Speed Test Results

TABLE I
LEO SATELLITE BROADBAND NETWORK SPEED TEST RESULTS

Test	Date and Time (UTC+7)	Ping (ms)	Download Speed (Mbps)	Upload Speed (Mbps)	Server Location	Provider
1	24 March 2025 12.11 PM	44	98,71	12,91	PT. Telekomunikasi Indonesia, Bandung	SpaceX Starlink
2	24 March 2025 12.12 PM	50	93,86	19,19	PT. Telekomunikasi Indonesia, Bandung	SpaceX Starlink
3	24 March 2025 12.13 PM	44	104,06	18,78	PT. Telekomunikasi Indonesia, Bandung	SpaceX Starlink
4	24 March 2025 12.14 PM	40	114,59	7,09	PT. Telekomunikasi Indonesia, Bandung	SpaceX Starlink
5	24 March 2025 12.15 PM	60	93,46	12,24	PT. Telekomunikasi Indonesia, Bandung	SpaceX Starlink
6	24 March 2025 12.16 PM	42	80,13	11,85	PT. Telekomunikasi Indonesia, Bandung	SpaceX Starlink
7	24 March 2025 12.16 PM	88	77	16,49	PT. Telekomunikasi Indonesia, Bandung	SpaceX Starlink
8	24 March 2025 12.17 PM	43	40,28	21,34	PT. Telekomunikasi Indonesia, Bandung	SpaceX Starlink
9	24 March 2025 12.18 PM	47	108,15	7,07	PT. Telekomunikasi Indonesia, Bandung	SpaceX Starlink
10	24 March 2025 12.19 PM	39	78,63	11,87	PT. Telekomunikasi Indonesia, Bandung	SpaceX Starlink

The maximum bandwidth of the Starlink LEO satellite is up to 220 Mbps [46]. Based on the calculation of the percentage comparison of the throughput value with the bandwidth, the percentage value of the throughput of the LEO Starlink satellite broadband network is very small, which is less than 1%, so it is categorized as bad based

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on TIPHON. It can be concluded that if the data sent is relatively small (a common data from IoT use cases) to an internet network that has a large bandwidth, the results of the throughput value calculation will always be small. However, this throughput parameter is sometimes ignored for IoT use cases because the data size is relatively small and the current internet network bandwidth is relatively large [28]. If the number of IoT devices used as use cases is increased, it will increase the size of the data sent. This will certainly increase the percentage value of the throughput parameter so that it will increase the value of the QoS category based on TIPHON.

B. Packet Loss

The packet loss parameter is used to measure the QoS of a network based on the number of data packets lost (failed to be delivered) during transmission on the network. In the first and second experiments in this research, 100 data packets from the sensor device to the actuator device were successfully sent using the MQTT protocol via the LEO satellite broadband network. Based on the calculation of Equation 2, the result of the packet loss calculation in this experiment is 0%. Based on the QoS category on TIPHON [28], the packet loss value is 0%, which means it is in the very good category. The results of this study show that Starlink can provide good performance in sending IoT Smart Farming data packets. In the experiment, there were no packets lost. All data packages were successfully sent so that the data can be used for accurate and precise decision making in the system developed in this research, IoT Smart Farming automatic irrigation system.

C. Delay

Delay parameters to know the duration of time for sending each data packet from the source device (sensor) to the destination device (actuator). Delay calculation is the arrival time of the data packet minus the sending time of the data packet. Based on the method in this research, to measure the delay using the Arduino IDE serial monitor, as presented in Figure 6, with the same NTP server reference. In this research, the Arduino IDE serial monitor was used because it can determine the time of sending data packets from sensor devices and the time of receiving data packets from actuator devices with an accuracy of up to milliseconds with a fair and equal NTP server from time.windows.com. At the beginning of the experiment, we thought about the right and accurate way to measure the time the data packet started to be sent and the time the data packet was received with the same time reference. If the reference time data is obtained directly from the NTP server to each device (sensor and actuator), then there will be a time difference between the sensor device and the actuator device because the duration of the reference time data is different for each device. This is due to the difference in routing paths on each device because this system being developed is a WSN. In addition, there is radio wave interference, which causes delays in sending data packets, the reference time being the timestamp for packets sent and packets received. Therefore, we are looking for a way for both devices to have the same reference time from the same NTP server.

The solution we found and proposed for this study is to use the Arduino IDE serial monitor on the same computer device. The sensor device and the actuator device are both connected to the computer device that is actively monitoring the serial monitor. From there, we can see the time the data packet is sent from the sensor device and the time the data packet is received at the actuator device. This research focuses on analyzing the performance and quality of the LEO satellite network, especially in this section is, the delay. So, to make it easier to obtain data on the delay in sending data packets from the sensor device to the actuator device, we use a tool that can provide the same reference time and up to millisecond accuracy, such as the Arduino IDE serial monitor. The method we found and used in this study can be used by other researchers on the topic of quality analysis of various networks in the context of using IoT applications in various fields/sectors. Despite its advantages for this research, the limitation of using the Arduino IDE serial monitor is that the sensor device and actuator device analyzed must be connected to the same computer device that actively monitors the serial monitor to obtain data. However, it is a consequence that must be accepted to achieve fairness of reference time in analyzing data packet delivery delay between two IoT devices. Of course, if a more accurate method is found in the future, it will be very useful and become a reference for further research.

In the first experiment, 100 data packets were sent from the sensor device to the actuator. Samples of data packet sending and receiving times in first experiment for calculating delay parameters are presented in Table 2. The samples of data packet sending and receiving times in the second experiment for calculating delay parameters are presented in Table 3.

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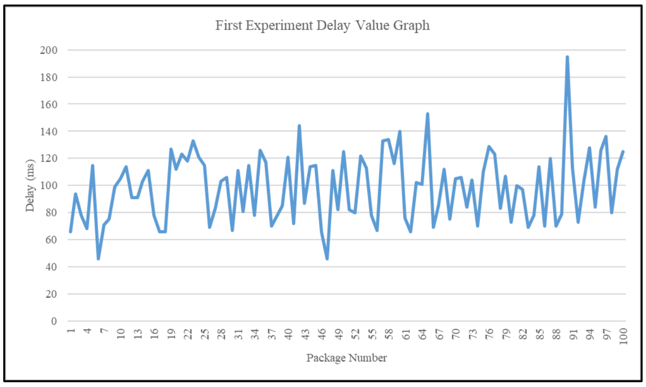
TABLE II
SAMPLE TIME OF SENDING AND RECEIVING DATA PACKETS IN THE FIRST EXPERIMENT FOR CALCULATING DELAY

Package Number	Data Packet Sent Time (UTC+7)	Data Packet Received Time (UTC+7)	Delay (ms)
1	14:02:21.340	14:02:21.406	66
2	14:02:22.346	14:02:22.440	94
3	14:02:23.364	14:02:23.442	78
4	14:02:24.364	14:02:24.432	68
5	14:02:25.361	14:02:25.476	115
6	14:02:26.399	14:02:26.445	46
7	14:02:27.396	14:02:27.467	71
8	14:02:28.403	14:02:28.478	75
. . .	. . .	. . .	. . .
99	14:04:00.745	14:04:00.857	112
100	14:04:01.763	14:04:01.888	125

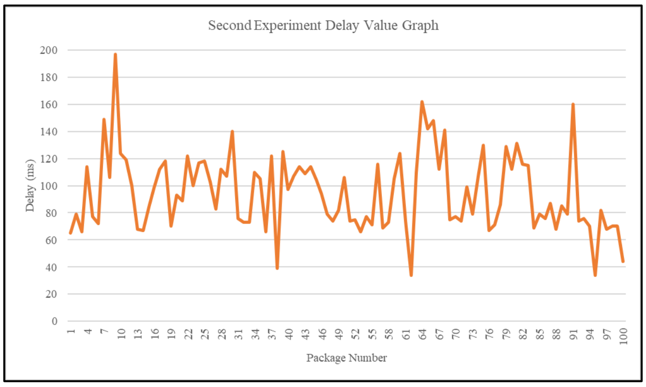
TABLE III
SAMPLE TIME OF SENDING AND RECEIVING DATA PACKETS IN THE SECOND EXPERIMENT FOR CALCULATING DELAY

Package Number	Data Packet Sent Time (UTC+7)	Data Packet Received Time (UTC+7)	Delay (ms)
1	14:37:54.931	14:37:54.996	65
2	14:37:55.949	14:37:56.028	79
3	14:37:56.942	14:37:57.008	66
4	14:37:57.940	14:37:58.054	114
5	14:37:58.994	14:37:59.071	77
6	14:37:59.976	14:38:00.048	72
7	14:38:01.004	14:38:01.153	149
8	14:38:01.999	14:38:02.105	106
. . .	. . .	. . .	. . .
99	14:39:34.497	14:39:34.567	70
100	14:39:35.537	14:39:35.581	44

Based on the calculation of Equation 3, the average delay value of the first experiment is 98,27 ms (98 ms). The result of the average delay value calculation from the second experiment was 94,7 ms (95 ms). The average delay value of the first and second experiments was 96.49 ms (97 ms). Based on the QoS category on TIPHON [28], the delay value is 97 ms, which means it is in the very good category. The delay value graphs for the first and second experiments are presented in Figure 11. There is no significant effect between the size of the data packet in this experiment on delay value, because the variation in the size of the data packet is very small (156 - 158 bytes).



(a) First Experiment



(a) Second Experiment

Figure 11. Delay Value Graph

D. Jitter

Jitter is closely related to the delay that occurs in data packet transmission on the network. Jitter is caused by the length of the transmission queue, data processing time, and also the time it takes to combine data packets in the transmission of a data packet. Jitter testing is done by dividing the total delay variation by the data packets received. Based on the calculation of Equation 4, the jitter value in the first experiment was 28,08 ms (28 ms). The jitter value in the second experiment was 25,57 ms (26 ms). The average jitter value from the first and second experiments was 26.83 ms (27 ms). Based on the QoS category on TIPHON [28], the jitter value is 27 ms, which means it is in the very good category. A small jitter value indicates good network quality.

The results of research by Yongtao Su et. al. in China [19], OneWeb has a delay of 30 ms, Telesat has a delay of 30 to 50 ms, and Starlink has a delay of 25 to 35 ms. The results of this study in rural agricultural areas in

Lembang, Bandung Barat, Jawa Barat, Indonesia, showed that the delay of LEO satellite communication (Starlink) was 97 ms from the experimental results. Based on the QoS category in TIPHON [28], a delay of 97 ms and jitter of 27 ms are included in the very good network QoS category. QoS categories based on TIPHON are presented in Table 4. The relatively very small delay value (97 ms) from the results of this research is sufficient for real-time applications in the IoT Smart Farming automatic irrigation system. The difference in the results of this research with previous research may be due to differences in research locations. However, it is not significant. The delay value of this research result with the previous research is still in the same QoS category, which is very good with a value of less than 150 ms. This may occur due to several factors, such as the propagation of the satellite antenna to the satellite orbit, the satellite orbit path, the coverage of the satellite beam from the sky to the earth, the presence of obstacles such as clouds, and the presence of other radio frequency interference around the research area. Therefore, the results of this research can be used as a reference for conducting similar research in other locations, especially in areas in Indonesia, to enrich the empirical data of the research results on the topic of LEO satellite broadband network analysis.

TABLE IV
QOS CATEGORIES BASED ON TIPHON AND THE RESULTS OF THIS RESEARCH FOR DELAY PARAMETERS

Delay (ms)	QoS Categories	Delay Value of This Research Result	QoS Category Delay Parameters of This Research Result
< 150	Very Good	97 ms	Very Good
150 - 300	Good		
300 - 450	Fair		
> 450	Bad		

IV. CONCLUSION

This research has conducted stages of literature study, system requirements identification, system design, implementation, testing, experimentation, data collection, and QoS analysis of LEO satellite broadband networks on IoT Smart Farming. This research succeeded in creating an IoT Smart Farming automatic irrigation system as a use case for this research. QoS analysis of LEO satellite broadband network on IoT Smart Farming based on TIPHON consisting of throughput, packet loss, delay, and jitter. The experimental results show that the throughput value is 1243 bps with a test data sample of 100 IoT data packets in JSON format. The packet loss value is 0%, which means that all data packets were successfully sent from the sensor device to the actuator device using the MQTT protocol via the LEO satellite broadband network. The average delay value from the experimental results is 97 ms. The jitter value of the experimental results was 27 ms. The results of this study can be used as an alternative and recommendation for stakeholders such as farmers, governments in the agricultural sector, and entrepreneurs to use LEO satellite broadband networks for IoT Smart Farming to overcome internet network infrastructure constraints on agricultural land in rural and remote areas.

V. FUTURE WORK

The results of this research can certainly be researched further and developed with various use cases. It can also be with the same use case as IoT Smart Farming in a different location, or a use case that is in accordance with the intended use of the LEO satellite broadband network. Other use cases such as Smart Fisheries, Smart Forestry, or Smart Rivers. The areas used for further research can also be in mountains, forests, deserts, islands, poles, or areas that are difficult to reach by terrestrial internet network infrastructure. Experiments can also be conducted with various weather condition scenarios, such as sunny, cloudy, rainy, and heavy rain. Further research can also compare QoS with terrestrial broadband network infrastructure or satellite internet networks from other products. It is hoped that this research can be further researched and developed for the development of science and technology that is beneficial to humanity and the environment.

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