Comparative Analysis of QoS Between LEO Satellite and Cellular Internet Networks for IoT Smart Farming

Eka Hero Ramadhani[1], I Ketut Agung Enriko[2], Ahmad Tossin Alamsyah[3], Muhammad Azza Ulin Nuha[4], and Erika Lety Istikhomah Puspita Sari[5]

[1] Master of Applied Electrical Engineering, Politeknik Negeri Jakarta, Indonesia
[1] Cryptographic Hardware Engineering, Politeknik Siber dan Sandi Negara, Indonesia
[2] Department of Telecommunication and Electrical Engineering, Telkom University, Indonesia
[3] Department of Electrical Engineering, Politeknik Negeri Jakarta, Indonesia
[4] Master of Electrical Engineering, Universitas Indonesia, Indonesia
[5] School of Applied Science, Telkom University, Indonesia
eka.hero@poltekssn.ac.id

Abstract. The implementation of IoT technology in rural or remote areas with limited internet infrastructure poses a significant challenge, particularly in the context of IoT Smart Farming in Indonesia's agricultural regions. Generally, IoT Smart Farming technology is based on WSN with devices spread across agricultural land. To support IoT Smart Farming, in this research, we propose the implementation of a wireless internet network based on LEO satellite and cellular, then analyze its quality of service (QoS). The LEO satellite network in this research is Starlink from SpaceX, a new satellite internet provider product in Indonesia, and the cellular network being compared is by.U from Telkomsel. The research methods used include prototyping, experiments, and comparative analysis. In this research, IoT Smart Farming has been successfully developed in the form of an automatic irrigation system with LEO satellite and cellular internet network connectivity in agricultural areas in BBPP Lembang, Indonesia. The QoS analysis of LEO satellite and cellular internet networks in this research is based on TIPHON, which consists of throughput, packet loss, delay, and jitter parameters. The experimental results show that the QoS of the LEO Starlink satellite network and by.U cellular network are categorized as good based on TIPHON, but the quality of the LEO Starlink satellite network will decrease during rainy weather conditions, especially in the delay parameter whose value is greater when compared to by.U cellular network which is relatively stable.

Keywords: Cellular, IoT Smart Farming, LEO Satellite, QoS, THIPHON

1 Introduction

Food needs continue to increase as population growth is estimated to reach 9.7 billion people in 2050, so the need for agricultural harvests is expected to increase by up to 110% (Maja & Ayano, 2021). However, in Indonesia, the agricultural sector faces the challenge of a labor shortage due to the low interest of the younger generation in working as farmers (Eistrup et al., 2019; Ngadi et al., 2023). To overcome this problem, Smart Farming technology is a solution because it can increase agricultural products with minimal costs and labor (Idoje et al., 2021; Moysiadis et al., 2021; Rose et al.,

A. A. N. G. Sapteka et al. (eds.), *Proceedings of the International Conference on Sustainable Green Tourism Applied Science - Engineering Applied Science 2025 (ICOSTAS-EAS 2025)*, Advances in Engineering Research 280,
https://doi.org/10.2991/978-94-6463-878-3_53

2021). Smart Farming utilizes modern technologies such as the Internet of Things (IoT), which enables real-time monitoring of plant environmental conditions and remote control of agricultural equipment (Ivanochko et al., 2024; Morchid et al., 2024).

IoT based on Wireless Sensor Networks (WSN) is efficient for use on large agricultural land, so it requires the installation of a wireless internet network infrastructure to support its implementation (Huo et al., 2024). Three types of network infrastructure can provide wireless internet with a Wi-Fi interface to support IoT in Smart Farming, namely, wired networks (Boursianis et al., 2022), cellular (Islam et al., 2020), and satellite (Gupta et al., 2020). However, only cellular and LEO satellite networks are suitable for application in large agricultural areas (Popli et al., 2021), rural (Citoni et al., 2020), or remote areas (Bujari et al., 2023). However, cellular networks in remote areas are often inadequate or even unavailable (Islam et al., 2021), so that the LEO satellite internet network is a potential solution that needs to be investigated. One of the LEO satellites that can be studied is Starlink, which will be available in Indonesia in 2024. Starlink has the advantage of providing internet access in areas that are difficult to reach by fiber optic cables or cellular networks (Lisnawati, 2024).

This study conducted a comparative analysis of the QoS between LEO satellite internet networks and cellular networks in the implementation of IoT Smart Farming to determine which network is better and recommended. The research methodology used is prototyping, experimentation, and comparative analysis. The study's results are expected to provide stakeholders, including farmers, government officials, business actors, and researchers, with recommendations on implementing effective internet network infrastructure to support IoT Smart Farming.

2 Methodology

This study uses prototyping, experimentation, and comparative analysis methods. The prototyping method is used to develop the device studied based on the System Development Life Cycle (SDLC) (Olorunshola & Ogwueleka, 2022). Experimental methods are used to measure the QoS of the studied network based on parameters from Telecommunications and Internet Protocol Harmonization Over Networks (TIPHON) (Enriko et al., 2023). The comparative analysis method is used to analyze the results of the QoS comparison to determine which network infrastructure quality is better and recommended for IoT Smart Farming. The stages of this research consist of literature study, identification of system requirements, system design, implementation, testing, experiments, data collection, comparative analysis, and publication of research results.

2.1 Design

The system design begins with the identification of hardware, software, and network device requirements based on literature studies, previous research gap findings, and observations. The system is designed by integrating these three components. The hardware used includes an ESP8266 microcontroller, a capacitive soil moisture sensor v1.2, a DHT22 temperature and humidity sensor, a relay, a 3.7 Volt battery, and a cable. The software used includes Arduino IDE, Telkom IoT Platform, draw.io, MQTT protocol, and Microsoft Excel. Network devices include Wi-Fi Access Points (AP), Telkomsel Orbit E5576 GSM 4G LTE modems, by.U SIM cards, and LEO Starlink satellite antennas. The system architecture design in this study is presented in Figure 1.

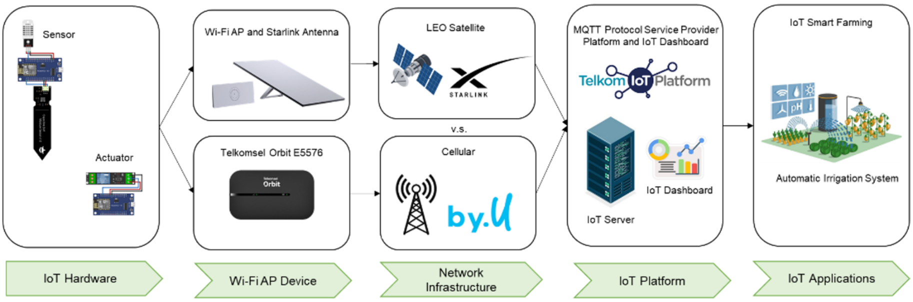


Figure 1. IoT Smart Farming System Architecture Design in This Research

2.2 Implementation

The implementation phase involves assembling the device and programming the system according to the design, utilizing the C++ language through the Arduino IDE. Communication between devices is done using the MQTT protocol and the Telkom IoT Platform broker. The IoT Smart Farming automatic irrigation system was tested on lettuce farming land at BBPP Lembang, with a minimum soil moisture limit of 65%.

2.3 Testing

Testing was conducted in two stages: laboratory and field. Laboratory testing aims to ensure that the device functions as designed, while field testing is conducted to obtain empirical data from the scenario of sending sensor data packets to actuators in the IoT Smart Farming automatic irrigation system. Measurements were made based on the QoS parameters of the LEO satellite and cellular internet networks, referring to TIPHON (Enriko et al., 2023), including throughput, bandwidth, packet loss, delay, and jitter as described in Tables 1 and 2. The trial was conducted in two sessions, each with 100 data packets, located in the BBPP Lembang agricultural land during the day in sunny weather conditions. Data collection was carried out using a serial monitor on the Arduino IDE, which displays the sending and receiving times of packets accurately to milliseconds, synchronized with the NTP server.

Table 1. Parameters QoS of TIPHON

Category (Index) / Parameters	Very Good (4)	Good (3)	Fair (2)	Bad (1)
Throughput (%)	76 – 100	51 – 75	26 – 50	0 – 25
Packet Loss (%)	0 – 2	3 – 14	15 – 24	≥ 25
Delay (ms)	< 150	150 – 300	300 – 450	> 450
Jitter (ms)	< 150	150 – 300	300 – 450	> 450

Table 2. QoS Assessment Categories Based on TIPHON

Average index value of each QoS parameter	Category
3.8 – 4	Very Good
3 – 3.79	Good
2 – 2.99	Not Good
1 – 1.99	Bad

3 Result and Discussion

The implementation of the system in this study resulted in an IoT Smart Farming automatic irrigation device and system that was used as a use case to analyze the QoS of the LEO satellite and cellular internet networks by.U in the lettuce farming land of BBPP Lembang. The sensor device consists of an ESP8266 microcontroller, a v1.2 capacitive soil moisture sensor, a DHT22 temperature and humidity sensor, a 3.7 Volt battery, jumper cables, and a waterproof protective box to prevent damage from rain and irrigation splashes. The actuator module that functions to control the irrigation pump uses similar components, with the addition of a relay as an automatic switch. Both devices are wirelessly connected to a Wi-Fi AP from LEO satellite internet network or by.U cellular network via an ESP8266 microcontroller. The components of the developed system are presented in Figure 2.

(a) IoT Sensor Hardware (b) LEO Satellite Antenna

Figure 2. IoT Smart Farming Hardware with LEO Satellite Network Antenna

Sending data packets from sensor devices to actuator devices is done using the MQTT protocol with an MQTT broker from the Telkom IoT Platform. The data is processed and visualized on the application dashboard, allowing farmers to monitor agricultural environmental conditions in real-time. Information such as soil moisture, temperature, and air humidity can be used to analyze the relationship with plant health using statistical methods. Data is sent in JSON payload format, as in the following example:

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

The IoT Smart Farming system developed in this study has functioned as designed. The sensors successfully sent data to the actuators via a wireless network using the MQTT protocol to control the irrigation pump. Irrigation is automatically activated when soil moisture drops below 65%, and deactivated when the value exceeds the threshold. This system improves the efficiency of farmers' labor and time because it does not require manual intervention. After successful implementation, a QoS analysis was carried out on the LEO satellite network and cellular network based on TIPHON.

3.1 Throughput

In the first experiment, 100 data packets were sent. The size of the first to tenth data packets was 156 bytes (equivalent to 1248 bits), while the size of the eleventh to ninety-ninth data packets was 157 bytes (equivalent to 1256 bits). The size of the hundredth data packet was 158 bytes (equivalent to 1264 bits). Thus, the total size of all data packets sent in the first experiment was 125528 bits. The calculation of throughput value and percentage uses the equations as described in Equations 1 and 2.

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

$$Throughput\ (\%) = \frac{Throughput\ (bps)}{Bandwidth\ (bps)} \times 100\% \tag{2}$$

Based on Equation 1, the throughput value is obtained from the total size of data packets successfully sent and received in a certain time interval, divided by the duration of that time. In the first experiment, all 100 data packets from the sensor device were successfully received by the actuator device. The first packet was sent at 14:02:21.340 (UTC+7), and the 100^{th} packet was received at 14:04:01.888 (UTC+7), with a total duration of 101 seconds (00:01:40.548). The throughput value of the first experiment, calculated based on this data, is 1,242.9 bps.

In the first experiment, the throughput value obtained was 1,242.9 bps (rounded to 1,243 bps). The second experiment used the same number and size of data packets as the first experiment. The first packet was sent at 14:37:54.931 (UTC+7), and the 100^{th} packet was received at 14:39:35.581 (UTC+7), with a transmission duration of 101 seconds (00:01:40.650). Because the size and duration of data packet transmission in both experiments were identical, the calculated throughput value was also the same, which was 1242.9 bps. This throughput value is relatively small because the size of the IoT device data used is relatively small. The results of throughput measurements on the LEO Starlink satellite network and the by.U cellular network are described in Table 3.

Table 3. LEO Satellite and Cellular Throughput Values

Experiment	Time (s)	Throughput (bps)	Throughput (%)	Category	Index
1^{st} LEO	101.548	1,243	0.001243	Bad	1
2^{nd} LEO	101.650	1,243	0.001243	Bad	1
1^{st} Cellular	101.690	1,243	0.001243	Bad	1
2^{nd} Cellular	101.491	1,243	0.001243	Bad	1

Based on the calculation in Table 3 using Equation 2 and Equation 3, the throughput percentage value of the LEO Starlink satellite network and the by.U cellular network is below 1% for the IoT use case with very small data and a bandwidth of 100 Mbps, so it is categorized as bad based on TIPHON. Both networks show equivalent QoS values for the throughput parameters in the developed IoT Smart Farming.

3.2 Packet Loss

The packet loss parameter is used to assess the network QoS based on the number of data packets lost during the transmission process. In the first and second experiments of this study, 100 data packets were successfully transmitted from the sensor device to the actuator using the MQTT protocol via the LEO Starlink satellite internet network and by.U cellular. Data packet loss reflects the condition of the network experiencing disruption. The calculation of packet loss is explained in Equation 3.

$$Packet\ loss\ (\%) = \frac{\sum\ data\ packet\ sent - \sum\ data\ packet\ received}{\sum\ data\ packet\ sent} \times 100\% \quad (3)$$

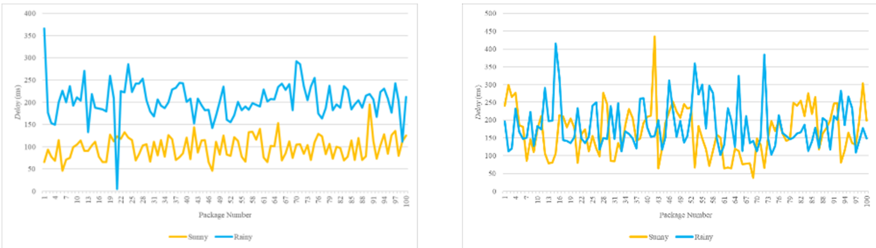
Based on the calculation results of Equation 3, the packet loss value on the LEO Starlink satellite internet network and by.U cellular is the same, which is 0%. Referring to the TIPHON category, this value is included in the very good category. These results demonstrate that the Starlink and by.U networks can transmit IoT Smart Farming data packets reliably without packet loss, enabling accurate and precise decision-making in the automatic irrigation system in this research, regardless of sunny or rainy weather.

3.3 Delay

The delay parameter is used to measure the time required to send each data packet from the sensor device to the actuator device by calculating the difference between the arrival time and the sending time of the data packet. In this study, delay measurements were carried out using the Arduino IDE serial monitor, referring to the same NTP server. The average delay value is used as one of the QoS indicators using Equation 4.

$$Average\ delay\ (ms) = \frac{\sum\ Delay\ (ms)}{\sum\ data\ packet\ sent} \quad (4)$$

Based on the calculation of Equation 4, the average delay values in the first and second experiments of the LEO Starlink satellite network were 98 ms and 95 ms, respectively, with an overall average of 97 ms in the very good category according to TIPHON when the weather is sunny. In the first experiment during rainy weather, the LEO satellite network delay value was 205 ms, and 199 ms in the second experiment, with an overall average value of 202 ms, which is in the good category. For the by.U cellular network, the average delay of the first experiment was 175 ms and the second experiment was 168 ms, with an overall average of 171 ms, which is in the good category according to TIPHON when the weather is sunny. In the first experiment during rainy weather, the delay value of the cellular network was 194 ms and 187 ms in the second experiment, with an overall average value of 191 ms, which is in the good category. The graph of the delay values from the experimental results is presented in Figure 3.



(a) The LEO Starlink satellite network (b) The by.U cellular network

Figure 3. Experimental Result Graph for the Delay Parameter

Based on the graph in Figure 3, the size of the data packet does not have a significant effect on the delay value because the variation is very small. It is hypothesized that the delay value of an LEO satellite network will be large if data communications are conducted during rainy weather. Therefore, this research also includes data and QoS analysis of delay parameters during rainy weather. Based on the delay value graphic visualization presented in Figure 3, it can be seen that the LEO Starlink satellite network delay value is greater during rainy weather conditions than during sunny weather conditions. Meanwhile, the delay value of the by.U cellular network remains relatively consistent during both rainy and sunny weather conditions. The experimental results of this study indicate that the LEO Starlink satellite network delay value will be greater during rainy weather conditions, while the delay value of the by.U cellular network is relatively the same as during sunny weather conditions.

3.4 Jitter

Jitter is a variation in the arrival time of data packets at the receiving device in a network, which occurs due to the difference in time between packet arrivals (Sabila et al., 2022). The smaller the jitter value, the better the network quality (Hafiz & Susianto, 2019). To calculate jitter, the delay variation value is used, which is the difference between the delay of a packet and the previous delay. The jitter value is obtained by dividing the total delay variation by the number of packets received minus one (Agustin et al., 2023). The jitter calculation is shown in Equation 5.

$$Jitter\ (ms) = \frac{\sum_{i=1}^{n} \quad Delay_i - Delay_{i-1}}{n - 1} \tag{5}$$

Based on the test results and jitter calculations in Table 4 using Equation 5, both the LEO Starlink satellite network and by.U cellular networks show jitter values that are included in the very good category according to the QoS assessment. This low jitter value reflects good network quality on both types of infrastructure tested.

Table 4. LEO Satellite and Cellular Jitter Values

Experiment	Sunny Weather			Rainy Weather		
	Jitter (ms)	Category	Index	Jitter (ms)	Category	Index
1st LEO	29	Very Good	4	35	Very Good	4
2nd LEO	26	Very Good	4	80	Very Good	4
1st Cellular	59	Very Good	4	49	Very Good	4
2nd Cellular	52	Very Good	4	69	Very Good	4

After analyzing each QoS parameter of the LEO satellite and cellular networks, a comparison was made using the TIPHON category and index to assess the technical quality of each network as described in Table 5 for sunny weather and in Table 6 for rainy weather. The average QoS index of the Starlink LEO satellite network is 3.25, while the by.U cellular network is 3, both in the good category in sunny weather. The average QoS index of the LOE Starlink satellite network and the by.U cellular network during rainy weather conditions is 3, which is in the good category. This shows that the QoS of both networks in this research is relatively equivalent.

Table 5. QoS Comparison Between LEO Satellite and Cellular in Sunny Weather

QoS parameters	Starlink LEO Satellite Network			by.U Cellular Network		
	Value	Category	Index	Value	Category	Index
Throughput	0.001243%	Bad	1	0.001243%	Bad	1
Packet Loss	0%	Very Good	4	0%	Very Good	4
Delay	97 ms	Very Good	4	171 ms	Good	3
Jitter	27 ms	Very Good	4	56 ms	Very Good	4

Table 6. QoS Comparison Between LEO Satellite and Cellular in Rainy Weather

QoS parameters	Starlink LEO Satellite Network			by.U Cellular Network		
	Value	Category	Index	Value	Category	Index
Throughput	0.001032%	Bad	1	0.001033%	Bad	1
Packet Loss	0%	Very Good	4	0%	Very Good	4
Delay	202 ms	Good	3	191 ms	Good	3
Jitter	58 ms	Very Good	4	64 ms	Very Good	4

4 Conclusion

This study has successfully implemented and analyzed the QoS of the LEO Starlink satellite-based internet network and by.U cellular for the IoT Smart Farming prototype of an automatic irrigation system on lettuce farming land at BBPP Lembang. The results of the comparative QoS analysis based on TIPHON show that the LEO Starlink satellite network falls into the category of good QoS assessment in both sunny and rainy weather, while the by.U cellular network falls into the category of equally good QoS assessment in both sunny and rainy weather. The quality of the LEO Starlink satellite network decreases during rainy weather conditions, particularly in terms of delay, where its value is higher compared to the relatively stable by.U cellular network.

5 Future Work

The results of this research can serve as a reference for further research with various use cases, including IoT Smart Farming scenarios in different locations, as well as other applications such as Smart Fisheries, etc. Further research is recommended to be conducted in hard-to-reach areas such as mountains, forests, deserts, or islands, considering various weather conditions, such as sunny to heavy rain. Comparative QoS analysis can also be expanded by comparing other terrestrial or satellite networks. In further research, LoRa technology can be compared in terms of quality, including cost and power, which was not feasible in this research due to time constraints.

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