Comparative Performance Study of ESP-NOW, Wi-Fi, Bluetooth Protocols based on Range, Transmission Speed, Latency, Energy Usage and Barrier Resistance

Dania Eridani
Department of Computer Engineering
Diponegoro University
Semarang, Indonesia
dania@ce.undip.ac.id

Adian Fatchur Rochim
Department of Computer Engineering
Diponegoro University
Semarang, Indonesia
adian@ce.undip.ac.id

Faiz Noerdiyan Cesara
Department of Computer Engineering
Diponegoro University
Semarang, Indonesia
faiznc@student.ce.undip.ac.id

***Abstract*—This paper discusses and provides comparison results of ESP-NOW, Wi-Fi, and Bluetooth as wireless local area network protocols. These protocols have been widely implemented on IoT devices. Inconsequential use of these protocols in areas that are not appropriate according to the characteristics of the protocols will cause problems such as fast battery drain, transmission speed is too wide with small data sent, and so on. For this reason, it is important to conduct a comparative study, to obtain information on the performance comparison of each protocol. We hope that IoT system designers can make it as a reference in the selection of these protocols. This paper will compare each protocol from the point of view of point-to-point transmission using key performance indicators such as maximum range, transmission speed, latency, power consumption, and resistance to obstructions using built-in and external antennas. Experiments were done with an equivalent testing method using the same components or tools. The data obtained were used to compare each protocol using a descriptive quantitative method by presenting the data in numerical, graphical, or descriptive form. The results of this paper are expected to be used as a consideration for which protocol is suitable for its implementation by providing an overview of the advantages and disadvantages of each protocol. A brief analysis of suitable applications for each protocol is provided.**

Keywords—Comparison; Internet of Things; ESP-NOW; Wi-Fi; Bluetooth

I. Introduction

The development of IoT (Internet of Things) devices is growing rapidly. IoT devices are known as small devices that do many things. With the combination of IoT devices and various sensors, it is estimated that more than 360 Exabytes of data will be obtained by the end of 2020 [1]. Recent forecasts suggest that this number will grow to 1.6 trillion devices by the end of 2025 [2].

IoT is formed from connectivity between objects or things. IoT devices need to be smart to collect data, process it, and send it safely with minimum possible use of space and maximum operational time [1]. Various data transmission protocols for IoT are expected to provide good performance, which can be seen from factors such as latency, power usage, transmission capacity, reliability, and security in transmitting data [3]. The need for good connectivity and energy usage is a determining factor for the future development of IoT technology.

Several protocols are currently used for IoT development. Some are intended for WLAN (Wireless Local Area Network) such as Wi-Fi and Bluetooth, Wide-Area Wireless Communication such as LoRa, and short-range technologies such as RFID [1]. Recently, there is a new protocol that allows multiple devices to communicate with each other without the use of Wi-Fi, with low power consumption [4] called ESP-NOW. This statement needs to be tested by comparing ESP-NOW with similar protocols such as Wi-Fi and Bluetooth. All of these protocols fall within the scope of local area communication protocols and are suitable for IoT devices that require both point-to-point and point-to-multipoint transmission. Conceptually, all point-to-multipoint communication is a point-to-point communication that sends data from one node to another. The ability of a communication protocol can be seen from factors such as transmission speed and latency, which can be seen directly from its performance when transmitting data between two things or nodes. From the perspective of IoT devices, factors such as maximum range between two nodes, power usage, and signal resistance to obstructions are directly related to how good a protocol is.

This study will compare these protocols with an equivalent testing method using the same tools and equipment from the point of view of point-to-point communication, with an analysis using the quantitative descriptive method by describing or visualizing the data based on the data as it is. Key factors tested are the maximum distance, data transmission capability, transmission latency, power usage, and the effect of obstacles using both the built-in and external antenna between two devices. Data from this paper is expected to be used as consideration for determining the appropriate implementation of each protocol and some examples of its matching usage by looking at the advantages and disadvantages of each protocol.

This paper contains an explanation of the equipment and tools used to perform the test in Section III. The conditions when performing the tests in Section IV. Analysis and comparison results are presented with graphical and numerical data with a quick explanation in Section IV too. A brief analysis of suitable applications for each protocol is also provided in this section. The paper is concluded in Section V.

II. Literature Review

A. ESP-NOW

ESP-NOW is a communication protocol from Espressif, which allows two or more devices to communicate without using Wi-Fi that is safe, energy-efficient, and supports peer-to-peer without a handshake after pairing [4]. ESP-NOW supports encrypted communication with the ability to send data in a short time of up to 250-bytes per payload [5] and is available to ESP8266 and ESP32 that produced by Espressif.

B. Wi-Fi

Wi-Fi or Wireless Fidelity is a set of wireless local network communication standards, which uses the 2.4 GHz or 5 GHz frequency band [6]. Wi-Fi is a wireless communication solution for local areas at a relatively affordable cost by providing fast data transfer speeds and ease of use. Wi-Fi can be found in cafes, office environments to residential areas.

C. Bluetooth

Bluetooth is a protocol for the communications industry specification that is applied to wire-free PAN (Personal Area Network) and operates in ISM license-free 2.4 GHz band frequency using a frequency hopping technique to send data [7]. Currently, Bluetooth has 2 versions, BLE (Bluetooth Low Energy) and Bluetooth Classic [8]. The latest version of Bluetooth is Bluetooth 5.2 [9].

D. ESP32

ESP32 is a microcontroller board designed by Espressif System. It is a 32-bit microcontroller that runs on the Xtensa LX16 instruction [10]. This microcontroller was first introduced on September 6, 2016. Various versions of ESP32 were developed to meets various functions. There are versions of ESP32 which are packaged on a development board and in bare chip form. Examples of versions of ESP32 are the ESP32 Development Board, ESP32-CAM, and ESP32U with their respective features and intended use.

Fig. 1. The ESP32 Development Board

E. Previous Research

Several studies are using one of the three protocols discussed, and it was from previous studies that the tested factors were determined. However, no study has compared these protocols under the same condition. Some of the previous research is comparing wireless data exchange technologies in Line-of-Sight conditions by A. Denisov and A. Saveliev in 2018 [11]. The maximum range will be tested in this condition. Then the effort to make WiFi-friendly buildings by S. Suherman in 2018 [12] uses different types of barriers to testing Wi-Fi penetration capability, therefore testing is carried out on various types of barriers. Then an attempt to compare existing Bluetooth versions and the effect of distance and obstructions in 2017 by M. B. Yaakop and his team [13]. Next is the study of Bluetooth's maximum range in a health infrastructure by J. Pancham and his team in 2018 [14], which uses glass as a barrier and RSSI as a signal strength indicator. Then the use of ESP32 as an implementation for IoT by Alexander Maier and his team in 2017 [15]. This study will also use ESP32 to test each protocol. Next is a study of using ESP-NOW for low-cost voice transmission in 2019 by T. N. Hoang and his team [16], which examined key factors of a communication protocol such as latency, power, data transmission, and external antennas usage. The last one is a study of Wi-Fi strength by T. Istanto and F. X. Manggau in 2018 [17], which uses dBm units as an indicator in signal strength reception.

To properly compare it, this study aims to discuss and compare these protocols with the same testing condition and analyze collected data using quantitative descriptive analysis method based on the data as it is. Each protocol can be used to be a suitable protocol for particular conditions, but the information obtained from this study can be used as a reference for future IoT-based devices.

III. Testing Methodology

This study will compare several key factors such as maximum range, transmission speed, latency, power usage, barrier disruption effect, and external antenna usage.

A. Testing Requirement Analysis

Before testing can be done, supported hardware is needed to test each protocol. Suitable hardware is also needed to test each parameter. The following table lists the protocols and devices that support them.

TABLE I. PROTOCOL SUPPORT ON VARIOUS DEVICES

Protocol	Devices
Wi-Fi	Smartphones, Tablets, Laptops, Smart TVs, Printers, Game Consoles, ESP8266, ESP32, Arduino Uno Wi-Fi Rev.2, and others.
Bluetooth	Smartphones, Tablets, Laptops, Speakers, Headsets, Hearing aids, Smart Watches, Game Console, ESP32, Arduino Uno Wi-Fi Rev.2, and others.
ESP-NOW	ESP8266, ESP32.

From various devices, only ESP32 supports each protocol tested. Therefore, this paper will use ESP32 as a testing media. Because ESP32 only supports Wi-Fi version b/g/n [18], this paper will compare it using the b/g/n version of Wi-Fi currently supported by ESP32. This paper also uses Bluetooth v.4.2 BR/EDR supported by current ESP32 [18] and does not use BLE (Bluetooth Low Energy), because of Bluetooth Classic's design to transmit data continuously [19], similar to Wi-Fi.

From various versions of ESP32, this paper will use ESP32 Development Board, ESP32-CAM, and ESP32U because of their compatibility with test parameters (especially with external area port and power usage testing in ESP32U). An antenna module is also needed to perform external antenna testing. This paper uses a 2.4 GHz with U.FL to SMA connector antenna to test each protocol on the receiver side to match the ESP32U antenna socket.

Fig. 2. 2.4 GHz External Antenna with 3 dBi gain

B. Devices and Testing Circuitry

This study uses both internal and external antennas to measure each protocol's maximum transmission range in the Line-of-Sight condition.

To measure data transmission speed, the internal antennas of the ESP Development Board and ESP32-CAM are used to transmit data with a 1-meter separation between boards.

In latency measurement, we use an additional button to trigger the exact timing needed. Then a series of processes will be executed to measure latency. The full circuit used can be seen in Figure 3. Then a flowchart on how the system works can be seen in Figure 4.

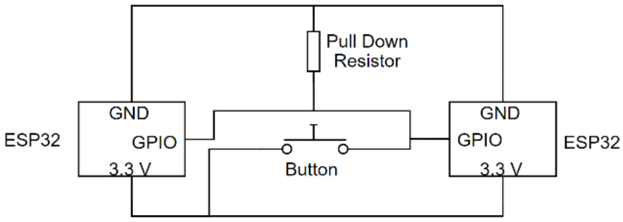

Fig. 3. Component Arrangement of Latency Measurement Circuit

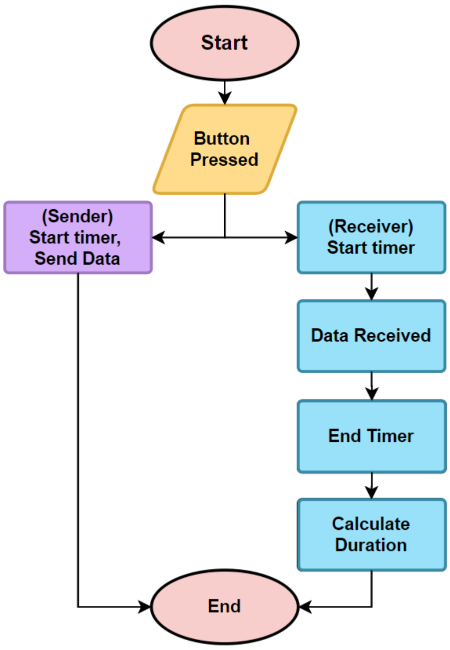

Fig. 4. Data Processing Flow on Sender and Receiver side

To measure power usage, we are using the Ohm principle where voltage is the result of multiplication between resistance and current. If the resistance is exactly 1 Ohm, the voltage is the same as the passed current. We can know the current by measuring the voltage level between two points at each end of the resistor. The described circuit can be seen in [20, Fig. 5]. Then to know the power usage, multiplication of working voltage of ESP32 at 3.3 Volt and average current draw is conducted.

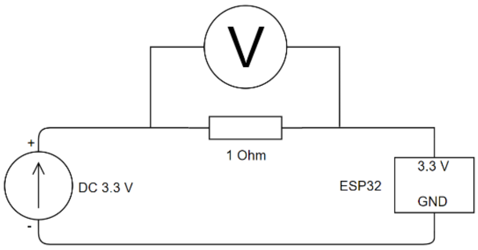

Fig. 5. Power Testing Schematic

In barrier testing, this study seeks to determine the effect of different types of material. Barrier materials tested were 19.2 cm walls, 1 mm metal plates, wood material that was represented by plywood with a thickness of 3 mm, and 2-way glass with a thickness of 3 mm. Tests were carried out using internal and external antennas, with the configuration below.

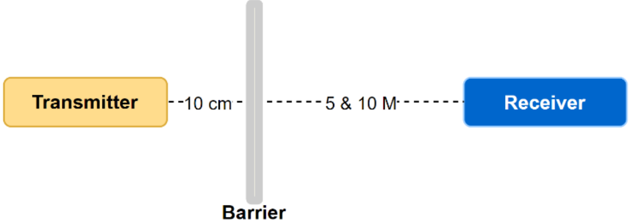

Fig. 6. Barrier Testing Setup

Lastly, in every external antenna testing, this study measures RSSI (Received Signal Strength Indicator) and transmission success rate from a receiver standpoint.

IV. Testing Results and Analysis

To perform an equivalent test, it is necessary to know that each protocol tested has its characteristics. The general characteristics of each protocol can be seen in Table II.

TABLE II. PROTOCOL CHARACTERISTICS

Variable	Wi-Fi [21]	Bluetooth (4.2) [21]	ESP-NOW [5]
IEEE Specification	802.11 (a/b/g)	802.15.1	802.11
Frequency	2.4 GHz & 5 GHz	2.4 GHz	2.4 GHz
Data Rate	54 Mbps	~784 Kbps **[22]**	1 Mbps **[23]**
Maximum Range	100 meters	60 meters **[22]**	~220 meters **[24, 25]**
Maximum Payload	2312 Bytes **[26]**	251 Bytes **[27]**	250 Bytes **[5]**

Characteristics of the parameters tested are carried out on various devices, especially Wi-Fi and Bluetooth protocols used in mobile devices. ESP-NOW itself was developed for IoT devices, therefore we need a test that compares these protocols from the point of view of IoT devices.

A. Test Conditions and Results

1) Maximum Range

Maximum range test is conducted in a Line-of-Sight condition inside a residential area. Maximum range is obtained if the pairing process is done and data is transmitted successfully. One byte of data is sent to confirm a successful data transmission, then 10 consecutive readings of RSSI value are recorded if packet loss were <10%. Maximum distance is obtained using the assistance of a GPS sensor on the Smartphone.

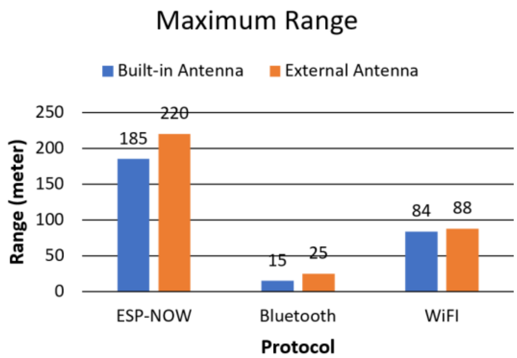

Fig. 7. Maximum Range Test Results

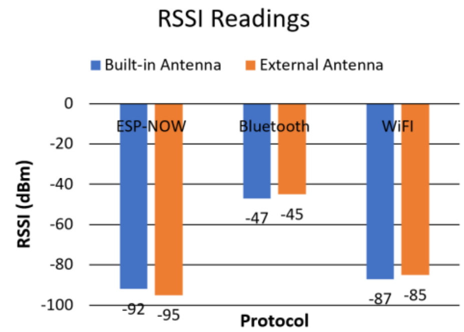

Fig. 8. RSSI Readings from Test Results

Using the built-in antenna, the maximum range is 15 meters on Bluetooth, 84 meters on Wi-Fi, and 185 meters on ESP-NOW. Whereas if an external antenna is used, the range is significantly increased on Bluetooth to 25 meters and 220 meters on ESP-NOW. The range on Wi-Fi also increased to 88 meters. With Bluetooth, the distance increased by 10 meters or 66.6%, 35 meters or 18.9% on ESP-NOW, and 4 meters or 4.7% on Wi-Fi. This slight increase in Wi-Fi may occur due to nearby interference, further study is needed.

Testing results show that the use of an external antenna with correct antenna orientation and specification on the receiving side can increase the strength of the received signal, which also impacts increasing the maximum range. It can be concluded that the use of an external antenna can increase the maximum transmission range by each protocol, provided that the antenna orientation is pointing at the correct position.

2) Data Transmission Capability

Data transmission testing is carried out using ESP-NOW, Bluetooth Serial, and Wi-Fi UDP in Arduino IDE. Experiments are conducted with 200 Bytes of packet size and MTU (Maximum Transmission Unit) of each protocol. Specific transmission delay between packets is applied to ensure <1% packet loss when transmitting data.

TABLE III. MAXIMUM TRANSMISSION UNIT OF EACH PROTOCOL

Protocol	**MTU (Byte)**
Wi-Fi	1460 Bytes **[28]**
Bluetooth (4.2)	251 Bytes **[27]**
ESP-NOW	250 Bytes **[5]**

The amount of data sent is divided by the required transmission time to determine transmission speed. There is a fixed time delay before and after the packet delivery sequence, with a total of 20 ms to synchronize it. A total of 30 tests were carried out. The average test results on the 200 Bytes payload can be seen in Figure 9.

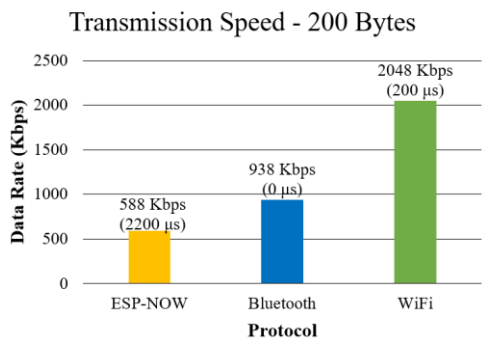

Fig. 9. Transmission Speed at 200 Bytes of Packet Size

Wi-Fi has the best transmission speed of 2048 Kbps, then Bluetooth at 938 Kbps and ESP-NOW at 588 Kbps. ESP-NOW requires a delivery delay between packets of 2.2 ms to prevent transmission failure. On Wi-Fi, transmission speed can reach its maximum speed with a 0.2 ms delay between packet delivery. This delay is required to ensure a good connection and avoid packet loss. The test results at the MTU can be seen in Figure 10.

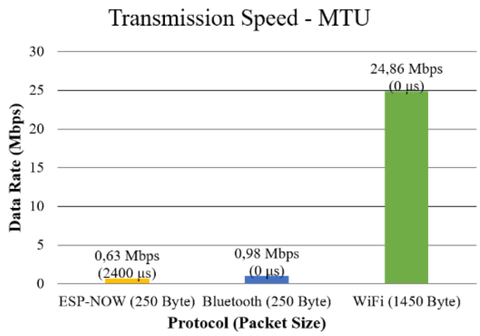

Fig. 10. Transmission Speed at MTU

By using MTU, Wi-Fi also has the best ability to transmit data at 24.86 Mbps, followed by Bluetooth at 0.98 Mbps and ESP-NOW at 0.63 Mbps with a transmission delay of 2.4 ms to ensure a good quality connection.

It can be concluded that Wi-Fi is suitable for high transmission speed usage. But ESP-NOW and Bluetooth can be good alternatives too, with Bluetooth works on various mobile devices, and ESP-NOW on ESP32 or ESP8266 only.

3) Latency

In latency testing, there is 4 kind of trials with variable data size. There are 1, 10, 50, and 100 Bytes. Latency measured is from sender to receiver using the built-in antenna at a distance of 1 meter. Testing is done by two ESP32 modules and connecting them according to the schematic in Figure 3. As many as 30 consecutive readings were taken and calculations were done to find the average latency.

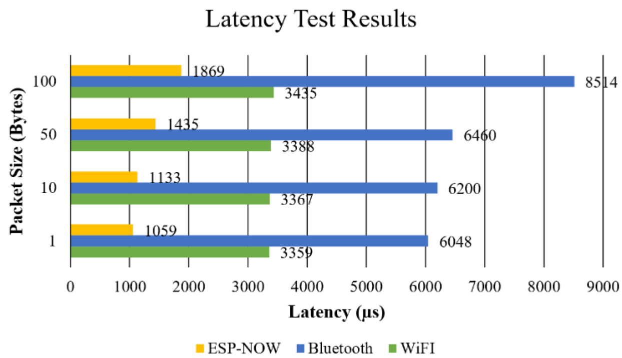

Fig. 11. Latency Test Results

For 1 Byte of data, the lowest latency is achieved by ESP-NOW which only takes 1 ms. Wi-Fi follows at 3.3 ms and Bluetooth at 6 ms. From the data, the size of the packet is directly proportional to the time it takes to transmit data. The size of the payload does not have much effect on the latency of Wi-Fi. Whereas in ESP-NOW and Bluetooth, latency increases as the packet size increases.

If a low latency transmission is required, ESP-NOW can be the primary option. However, if the device does not support this protocol, Wi-Fi can be the next option. Then the final option is to use Bluetooth with minimized data size minimized to prevent excessive sending delays.

4) Power Usage

An additional circuit is used to measure power usage, and it can be seen in Figure 5. The test was carried out 2 times when sending 200 Bytes of data and only connected without data transmission. A total of 30 tests were carried out to find the average power consumption. A voltmeter is used to take readings.

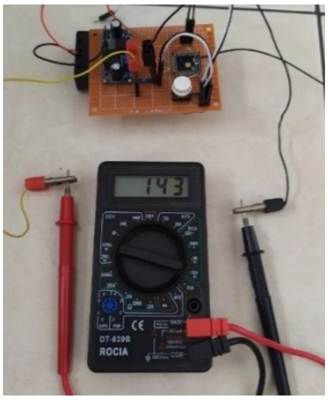

Fig. 12. Circuit Used and a Voltmeter for Current Measurements

The calculation of power usage is done by multiplying the current with 3.3 Volt (ESP32's working voltage). Average power usage in different configurations can be seen below.

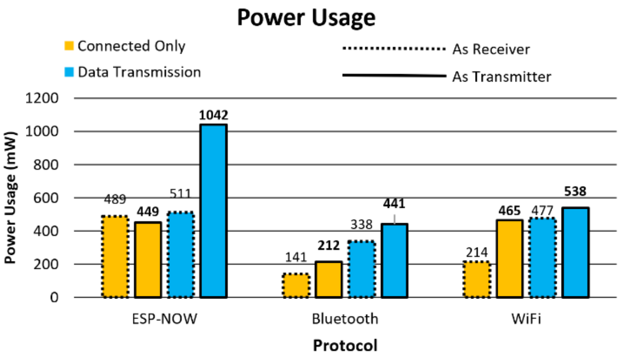

Fig. 13. Power Usage on Various Protocols

When only connected as a receiver, Bluetooth power usage is only 141 mW, followed by Wi-Fi which only uses 214 mW of power as a receiver. On the other hand, ESP-NOW consumes 489 mW. When only connected as a transmitter, Wi-Fi and ESP-NOW are within the same power usage range, but Bluetooth only consumes 212 mW. The same thing happens when transmitting as a receiver, where Bluetooth power consumption is slightly below Wi-Fi and ESP-NOW at 338 mW. It is clear that when transmitting data, ESP-NOW consumes the most at 1042 mW, followed by Wi-Fi with 538 mW and Bluetooth which only uses 441 mW.

From the data collected, it is known that Bluetooth excels in its power consumption. ESP-NOW has the most power consumption, and Wi-Fi is in between. On ESP32, ESP-NOW needs to enable Wi-Fi to work, which indicates that ESP-NOW is built on top of Wi-Fi. This addition can be the cause of its large power consumption. ESP-NOW is a relatively new protocol, and each protocol has its architecture. A patch update from the manufacturer may reduce power usage when transmitting data.

If power sources are limited and devices need to always be online, Bluetooth can be the right solution. The next option is Wi-Fi followed by ESP-NOW. However, there are many ways to reduce power consumption like turning off the radio module or entering sleep mode.

5) Barrier Effect

In testing the barrier effect, this study tests the connectivity between two ESP32 modules if there is a barrier. However, each material has its characteristics that could absorb, block, and even reflect signals. The characteristics of the material can be estimated by its conductivity and permittivity level. Conductivity is a property that determines how well a material conducts electricity [30]. Permittivity is the ability of a material to store electric potential energy when influenced by an electric field [31], also known as relative permittivity. The higher the conductivity, the greater its ability to reflect signals, the higher the permittivity, the more it will absorb signals [12]. Characteristics of the tested material can be seen in [32, Tab. IV].

TABLE IV. CHARACTERISTICS OF TESTED MATERIALS

Material	Relative Permittivity	Conductivity (S/m)	Frequency (GHz)
Concrete	5.31	0.0326	1 – 100
Wood	1.99	0.0047	0.001 – 100
Glass	6.27	0.0043	0.1 – 100
Metal	1	10	1 – 100

Testing was conducted using both built-in and external antennas using the configuration in Figure 6. The data collection process is similar to distance testing, with the RSSI value collected when there are 10 RSSI readings with the same value in a row and is the value that occurs most often.

TABLE V. RSSI READINGS USING BUILT-IN ANTENNA (IN DBM)

Protocol	Barrier (at 5 m / 10 m)				
	LoS	*Plywood*	*Glass*	*Metal*	*Wall*
Wi-Fi	-54/-61	-57/-62	-54/-62	-62/-67	-67/-74
Bluetooth	-28/-29	-30/-31	-29/-30	-35/-40	-46/(Fail)
ESP-NOW	-55/-60	-56/-61	-56/-62	-65/-71	-79/-87

The signal attenuation from a distance of 5 meters and 10 meters using the built-in antenna is obtained from this data.

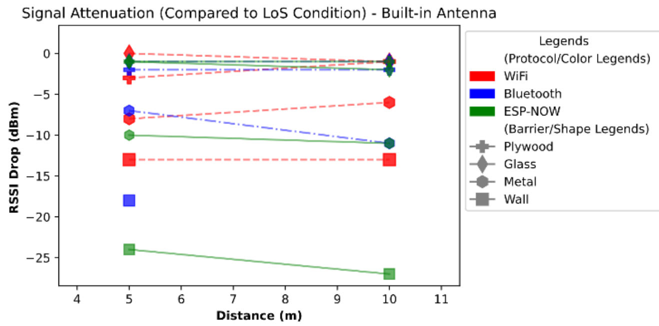

Fig. 14. Signal Attenuation of Various Materials using Built-in Antenna

Plywood and glass did not affect the received signal much at 1-2 dBm. But there is a significant signal attenuation between 6-11 dBm from metal and 13-27 dBm from the wall. When using the built-in antenna, the signal attenuation from Wi-Fi is not very significant compared to the other protocols.

TABLE VI. RSSI READINGS USING EXTERNAL ANTENNA (IN DBM)

Protocol	Barrier (at 5 m / 10 m)				
	LoS	***Plywood***	***Glass***	***Metal***	***Wall***
Wi-Fi	-45/-52	-47/-55	-45/-52	-55/-61	-60/-66
Bluetooth	-22/-28	-23/-29	-22/-28	-29/-33	-35/-43
ESP-NOW	-48/-55	-49/-54	-50/-56	-58/-64	-64/-69

The signal attenuation from a distance of 5 meters and 10 meters using the external antenna is obtained from this data.

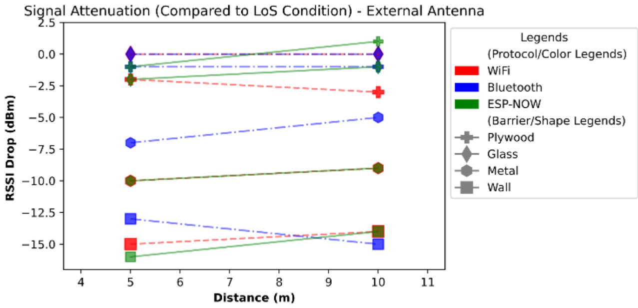

Fig. 15. Signal Attenuation of Various Materials using External Antenna

Similar to the previous test, plywood and glass materials do not have much effect. In ESP-NOW, the signal reception on plywood is better than at LoS (Line-of-Sight), and it is within reasonable measurement error. However, metal and wall still cause a significant signal reduction. The reduction ranges from 5-7 dBm in metallic materials in Bluetooth. On Wi-Fi and ESP-NOW, the RSSI is reduced by 9-10 dBm. The Wall reduces the signal reception by 13-16 dBm in each protocol.

Therefore, walls followed by metal significantly affect signal reception. Plywood and glass do not have a significant impact. Wi-Fi has the best resistance to the presence of obstructions, followed by Bluetooth and ESP-NOW. Keep in mind that Bluetooth failed to transmit data at 10 meters on the wall test using the built-in antenna. The three protocols tested have comparable performance in terms of resistance to obstructions.

B. *Optimum Usage*

After various testing, it can be seen the advantages and disadvantages of each protocol. ESP-NOW can transmit data at a distance of 165.47 meters [33]. Test using built-in antenna showed similar results. Test using Wi-Fi and Bluetooth are also within the supported range and transmission capabilities [34]. Data shows that Wi-Fi has the best data transmission speed. The lowest latency is achieved by ESP-NOW, which can transmit data with a latency of ±1 ms, which is not much different from a similar study [20]. In terms of transmission speed, ESP-NOW is tested when the payload sent is large (200 and 250 Bytes). When the payload is 32 Bytes, the transmission speed is 217 Kbps [20]. This proves that a larger packet size increases overall transmission speed. In terms of power usage, Bluetooth is the best protocol. Similar experiments measuring the power consumption of ESP32 show that it consumes about 650 mW of power using Wi-Fi and Bluetooth [35]. This is a similar result because this study uses ESP32U. Power usage testing of ESP-NOW is not very far from a similar study where the ESP32 consumes 280 mA - 330 mA (1W) when transmitting data [16].

Bluetooth has minimal power consumption and good resistance to obstructions but has a bad transmission latency. Bluetooth is suitable for devices that need to save energy at close range but do not require high urgency. An example is a smart home device that uses a battery, where it is always connected to a smartphone at various points in the house. In addition, Bluetooth is also suitable for wearables that must be connected and only have a limited power source.

On the other hand, Wi-Fi has the fastest transmission speed with good resistance to obstructions. Wi-Fi can be used to send data between devices connected to an access point quickly, regardless of obstacles. Wi-Fi maximum range is also quite good, allowing mass use in open areas that require a fast connection. However, because of its power usage, it is not suitable for devices that have to always be active. An example of Wi-Fi is a gateway that collects data from various sensors. Wi-Fi can also be used if there is a big bandwidth requirement. For example, a robot that sends data from a camera sensor. Overall, Wi-Fi is between Bluetooth and ESP-NOW, which offers good transmission quality, good range support, and power consumption between the two.

ESP-NOW protocol has exceptional distance support in LoS (Line-of-Sight) conditions with low latency. However, it consumes more power, and obstructions quickly weaken the signal strength. If a responsive device, long-range communication, and a minimal amount of data transmission are desired, ESP-NOW is suitable. An example of this scenario is to control a robot from distance. Its low latency allowing it to be used on quite critical systems. To overcome its power usage, the ESP32 radio module can be activated only in specific situations and disabled whenever data transmission is not needed. Another example is when a dispersed application is needed to collect temperature or other physical data, where a good range is needed with only low data transmission.

A brief summary of the performance of each protocol can be seen in Figure 16.

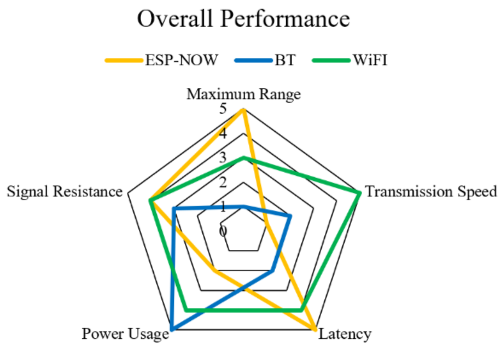

Fig. 16. Overall Performance of each Protocol

In addition, the three protocols tested can be connected to several devices simultaneously. The thing that can distinguish it can be several factors that are tested in this paper. Therefore, collected data from this paper can be used as a reference when determining the appropriate protocol for this kind of distributed system scenario.

V. CONCLUSION

Based on the data obtained, each protocol has its advantages and disadvantages. The best protocols are those that are able to meet the required specifications, which can be seen by key performance indicators such as maximum range, power usage, transmission speed, response time, and its ability to transmit signals and penetrate various barriers. Broadly speaking, Wi-Fi has good interconnectivity support and overall performance. ESP-NOW supports maximum distances with low transmission latency. Bluetooth has low power consumption and is suitable for various devices designed for long-term applications.

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