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The Influence of Kalman Filtering on the Received Signal Strength Indicator in Multi-node Bluetooth Low Energy Communications

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Abstract – *Bluetooth Low Energy (BLE) is one of low power Wireless Personal Area Network (WPAN) Technology. BLE has high data transfer rate at a low range, but implementation of BLE is easier than other WPANs. Distance conversion in wireless communication is a challenge in itself for the accuracy of distance estimation, one of them is the RSSI parameter. The RSSI fluctuating value generated by BLE caused by multipath fading and noise phenomena in observation environment. This article aims to apply the Kalman Filter to fine-tune the RSSI value so that the distance estimation to be precise. Testing was carried out in environment with many obstacles, on a BLE multi-node systems. The test results prove that the Kalman filter can correct the distance estimation error by 27.48%. In addition, the results of this distance conversion are sent by LoRa communication to be displayed on the website page.*

Keywords – *Bluetooth Low Energy; Filter Kalman; Log Normal Path Loss; RSSI; WPAN.*

I. INTRODUCTION

WIRELESS Personal Area Network (WPAN) is a wireless technology encompassing small, portable, easy-to-use information and telecommunication devices that can easily connect to public or personal networks for rapid and efficient data transfer [1]. Examples include Infrared, Bluetooth, Zigbee, and WiFi connections. Bluetooth operates on the ISM 2.4GHz frequency and adheres to the international standard IEEE 802.15.1. Currently, Bluetooth is more popular than other WPAN technologies because it can handle various data formats such as images, videos, and audio within a computer network. Bluetooth also offers a data transfer speed of 1Mbps over short distances.

One development from the Bluetooth version is Bluetooth Low Energy (BLE). BLE is considered low power, thus it has a longer lifetime compared to conventional Bluetooth. BLE can support multi-communications from eight devices, hence it is referred to as Smart Bluetooth. The throughput of BLE is considered good for the implementation of Wireless Sensor Networks (WSN) [2]. Currently, BLE is one of the communication standards for Internet of Things (IoT) technology, due to beacon communications that can connect with nearby smart gadgets [3].

Localization is one of the trending research topics in the field of WSN, aimed at estimating a position or distance using low-power communication media. Localization systems for ultrawideband technology include Radio Frequency Identification (RFID), Global Positioning System (GPS), and BLE. Research that has developed BLE for indoor localization has been conducted by [4] and [5]. This research analyzes the BLE RSSI values for distance conversion using the log-normal distance path loss model. In [6], a fingerprinting method is applied for localization on BLE, which is considered suitable in industrial environments with metal obstacles. BLE can cover weak WiFi signals as in [7], with trilateration localization.

Recent studies have found that BLE is highly susceptible to fast fading interference [8]. However, BLE can provide the best accuracy in localization with the right scenarios and algorithms [9]. Additionally, BLE maintains a stable connection indoors [10]. BLE is highly suitable for Indoor Positioning Systems (IPS) [11]- [12]. This article focuses on the method of determining distance estimation accuracy with the RSSI parameter from inter-node BLE communications, without applying localization techniques in distance

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determination.

Radio frequency signal transmission is modeled with log-normal path loss, which shows the relationship of RSSI to distance. Multipath fading phenomena such as reflection, diffraction, and shadow fading cause fluctuating RSSI values, thereby affecting the accuracy of distance determination. Therefore, additional methods are needed to stabilize these RSSI values, one of which is the Kalman filter [13].

The Kalman filter has the advantage of predicting future events and analyzing the correlation of various types of data. This filter is also known as the Linear Least Mean Squares Estimator (LLSME), which can filter out noise, is computationally light, does not consume much memory, and can operate at all frequencies [14]. This type of filter includes the Discrete Kalman Filter (DKF), Extended Kalman Filter (EKF), and Unscented Kalman Filter (UKF) [15]. Kalman filter applications for tracking object accuracy such as in [16] and image processing as in [17]. The error in distance conversion with the Kalman filter is lower compared to without the filter [18].

The results of BLE RSSI measurements fluctuate, thus affecting the distance results, hence there is a need for additional methods to minimize these fluctuations. One such method is filtering. Research in [12] applied BLE for social distancing in COVID patients, implementing filtering at a ten-meter distance resulting in 80% accuracy. Research conducted in [19] applies the Kalman filter in BLE communications to track Alzheimer's patients. The Kalman filter can improve the accuracy of estimating the position of Alzheimer's patients by 69.7%.

Distance estimation is determined by the RSSI from BLE, which is an output of the Kalman filter process, then this distance data is transmitted to the cloud system using the Long Range (LoRa) protocol. LoRa communication is one of the WPAN technologies with a longer range than BLE. LoRa operates at the 920 MHz frequency in Indonesia. A LoRa connected with an internet connection is referred to as a gateway node. LoRa includes low-power, low-bit-rate wireless communication technology [20]. The contributions of this research are described as follows:

1. Distance conversion with the Kalman filter in multinode BLE communication.
2. The communication system consists of BLE and LoRa (Long Range) devices, three client nodes communicating with beacons from BLE, and one gateway node communicating with LoRa to the client nodes.
3. The communication algorithm between the gateway node and the multi-node clients that aids the data transmission process to the cloud and is displayed on a web dashboard.

II. RESEARCH METHODS

The research methods used in this article are illustrated in Figure 1, which consists of three client nodes hereafter referred to as N1, N2, and N3, as well as a gateway node. Communication between client nodes utilizes BLE beacons to obtain data such as MAC addresses and RSSI values from each node. This data is then converted into distances by implementing a Kalman filter at each client node. Subsequently, LoRa at the client node will transmit the distance data to the gateway node which then forwards the data to the cloud system for display on a web dashboard.

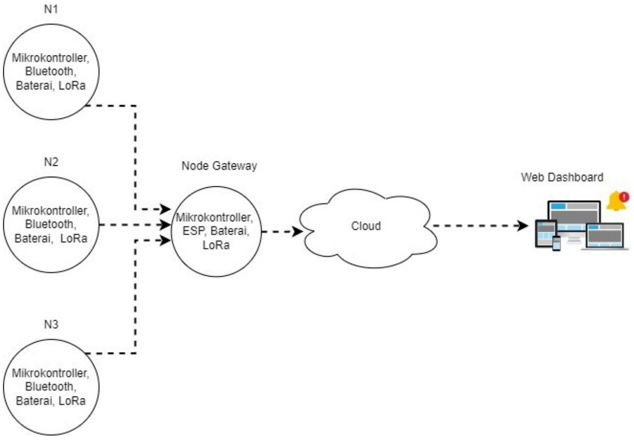
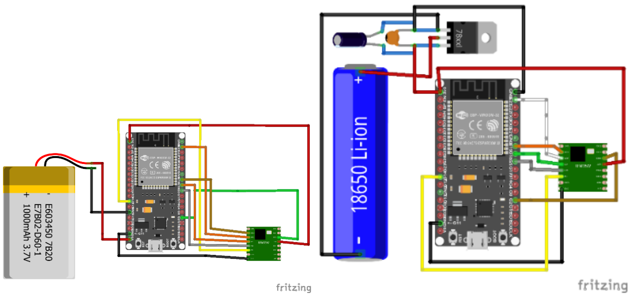


Figure 1: Multinode communication system

Each client node comprises a microcontroller, BLE, LoRa, and a battery. A single gateway node consists of an ESP, LoRa, and a battery. LoRa on the client node activates once BLE communication is complete, and the gateway node is ready to receive data from the client node. Further explanation regarding this research method includes the hardware design of the client and gateway nodes, measurement scenarios for multinode BLE, communication algorithms, and the application of the Kalman Filter for distance conversion.

i. Hardware Design

The communication system in this article involves client nodes and a gateway node. The three client nodes communicate using BLE to obtain RSSI values. The schematic diagrams of these nodes are shown in Figure 2. The prototype of the node is presented in Figure 3. One gateway node receives data from the client nodes using LoRa transmission media, then sends and displays the table data on the web 1.



(a) **(b)**

Figure 2: Node Circuitry (a) schematic of the gateway node (b) schematic of the client node

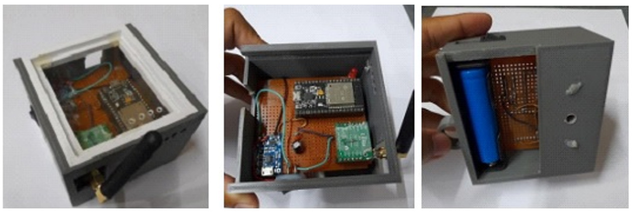


Figure 3: Appearance of the client and gateway nodes

Table 1: Hardware Component Input/Output Pins

Component Type	Component Pin		Connected Component
	Start	Destination	
18650 Battery	V+	VIN	3.3V Regulator
	GND	GND	
3.3V Regulator	VOUT	Ceramic Capacitor (VOUT)	Ceramic Capacitor
	GND	Ceramic Capacitor (GND)	
Ceramic Capacitor	Ceramic Capacitor (VOUT)	Polarity (+)	Electrolytic Capacitor
	Ceramic Capacitor (GND)	Polarity (-)	
ESP32	3.3V	VOUT	3.3V Regulator
	GND	GND	
LoRa	3.3V	3.3V	ESP32
	GND	GND	
	DIO0	GPIO 2	
	RESET	GPIO 14	
	NSS	GPIO 5	
	SCK	GPIO 18 / VSPI CLK	
	MOSI	GPIO 23 / VSPI MOSI	
	MISO	GPIO 19 / VSPI MISO	

ii. Measurement Scenario

Data collection was conducted in a semi-outdoor indoor area as shown in Figure 4. This environment is the 12th-floor balcony of Universitas Dinamika, surrounded by walls, stairs, and adjacent to a high-rise building. This setting represents an urban environment with multiple obstacles.

The positioning of the client nodes for RSSI data collection is as depicted in Figure 5. The distance between client nodes is 2 meters, with each node positioned one meter high. RSSI data is then converted into distance using the log-normal path loss model, formulated in Equation (1). The reason for maintaining a 2-meter distance between client nodes is that the prototype in this study is used as a physical distancing detector.

$$d_i = 10^{\left(\frac{RSSI_{d0} - RSSI_i}{10n}\right)} \tag{1}$$

where in Equation (1): Distance conversion from the i-th measurement, d_i - Distance conversion from the i-th measurement, $RSSI_i$ - RSSI value from the i-th measurement, n - Path loss coefficient value, and $RSSI_{d0}$ - RSSI value from the initial distance measurement.

Figure 4: Observation Environment

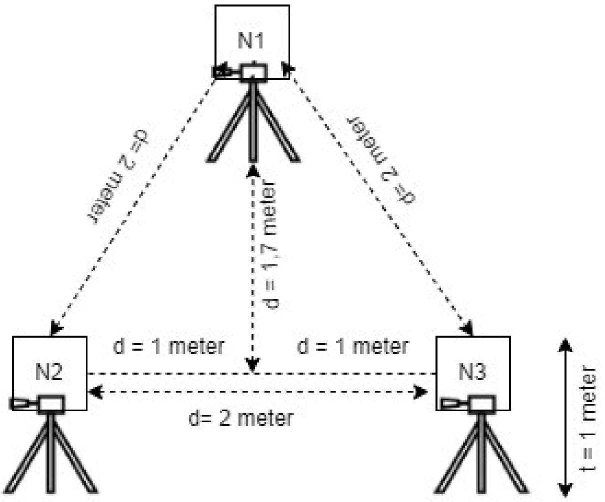


Figure 5: Measurement scenario among nodes

Based on Equation (1), it is necessary to first determine the value of parameter n, which is obtained from the RSSI value at a 1-meter distance ($RSSI_{(1m)}$) of -65.79 dBm and the RSSI at a 2-meter distance ($RSSI_{(2m)}$) of -74.74 dBm. Equation n is written in Equation (2). From this equation, a value of $n = 2.97$ is obtained.

$$n = \frac{RSSI_{(1m)} - RSSI_{(2m)}}{10\log_{10}(d)} \tag{2}$$

where in Equation (2) - Calculation of the path loss coefficient.

iii. Communication Algorithm

The communication algorithm of this research involves two communication protocols on BLE and LoRa devices. Both are low-power communication media operating at different frequencies. BLE operates at 2.4

GHz, and its implementation must be carefully managed to avoid interference with WiFi networks. BLE is applied to the client node to estimate a 2-meter distance. LoRa operates at a 920 MHz frequency, capable of long-range communication. LoRa is implemented on the gateway node and client node to forward data to the web. The implementation of the communication algorithm is divided into two algorithms: the communication algorithm between client nodes and the communication algorithm between the client node and the gateway node.

Communication between client nodes utilizes BLE beacons, which are performed through periodic advertising and scanning. One client node will share its information with other client nodes, allowing these nodes to be recognized and located via their MAC addresses and RSSI values.

The gateway node connects to the client nodes via LoRa communication. The gateway node makes a call to all client nodes once every second. If there is no response from the call, it is assumed that each client node is performing advertising or scanning. Additionally, the gateway divides the data it receives into two parts according to the pilot shown in Figure 6. The gateway node will be ready to receive data again after 3 seconds, followed by calling back the client nodes.

iv. *Data Transmission Format*

Data transmission is carried out according to the data format shown in Figure 6. The pilot is a symbol located at the beginning and end of the data received by the gateway node. ID RX is an identity containing the MAC address of the receiver, ID TX is an identity containing the MAC address of the sender. The distance is the result of RSSI conversion using the log-normal distance path loss model, between the sender and receiver. The total overall data transmitted is 42 bytes.

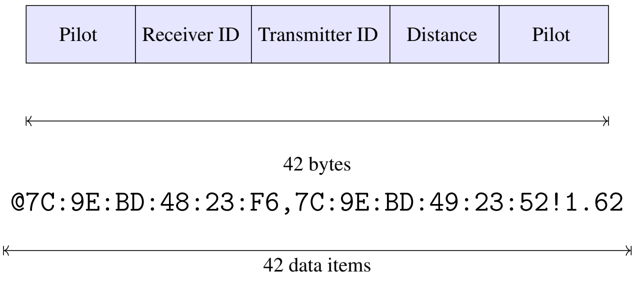


Figure 6: Data transmission format

v. *Kalman Filter*

RSSI is one of the distance conversion parameters. RSSI is influenced by environmental conditions such as obstacles or noise. The fluctuating RSSI values lead to errors in distance estimation, necessitating the application of the Kalman filter method. The Kalman filter is one method for solving non-linear problems. This filter does not consume memory, making it easy to implement on Arduino. The process in the Kalman filter consists of Predict and Update phases. The Kalman filter equations are seen in Equations (3)-(7).

Predict:

$$X_{t|t-1} = X_{t-1|t-1} \tag{3}$$

$$P_{t|t-1} = P_{t-1|t-1} + Q_t \tag{4}$$

Update:

$$X_{t|t} = X_{t|t-1} + K_t(y_t - X_{t|t-1}) \tag{5}$$

$$K_t = \frac{P_{t|t-1}}{(P_{t|t-1} + R_t)} \tag{6}$$

$$P_{t|t} = (1 - K_t)P_{t|t-1} \tag{7}$$

where: the Equations (3)-(7) - Kalman filter process. X - Estimated state, P - State variance matrix, Q - Process variance matrix, valued at 0.01, y - Measurement variable, RSSI value from the measurement, K - Kalman gain, R - Measurement matrix, valued at 1, $t|t$ - Current time period, $t-1|t-1$ - Previous time period, and $t|t-1$ - Intermediate steps.

The application of the Kalman filter to obtain estimated RSSI (RSSI') and estimated distance (d') using the log normal path loss model. Then, d' is compared with the actual distance value (d) of 2 meters. The application of the Kalman filter is shown in Figure 7. After obtaining d', the next step is to compare it with the actual distance according to the error equation shown in (8).

$$\text{error }(\%) = \left|\frac{(d' - d)}{d}\right| \times 100\% \tag{8}$$

where in Equation (8) - Error percentage of d' compared to d.

vi. *Web Display*

After the application of the Kalman filter by each client node, the next step is to send this distance data to the gateway node. The gateway node will separate the data received from the client nodes and forward this distance data to the Web. The web dashboard displays the distance between the two clients which is less than two meters. The appearance of the web dashboard is shown in Figure 8. Based on the web dashboard display, the history section explains that the distance between one client node and another client node, named Nama1 and Nama2, includes a distance conversion column and time recording.

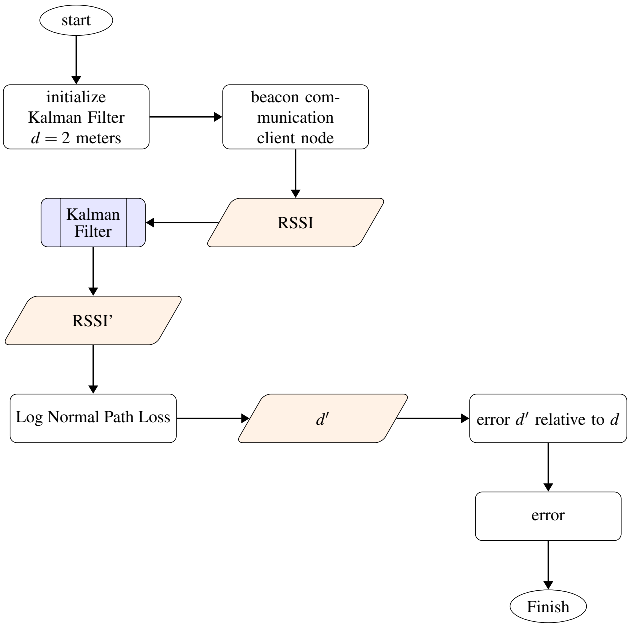
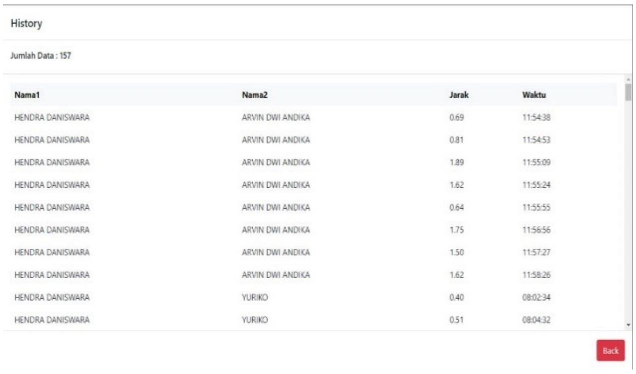


Figure 7: Flowchart of Kalman Filter Application



History

Jumlah Data : 157

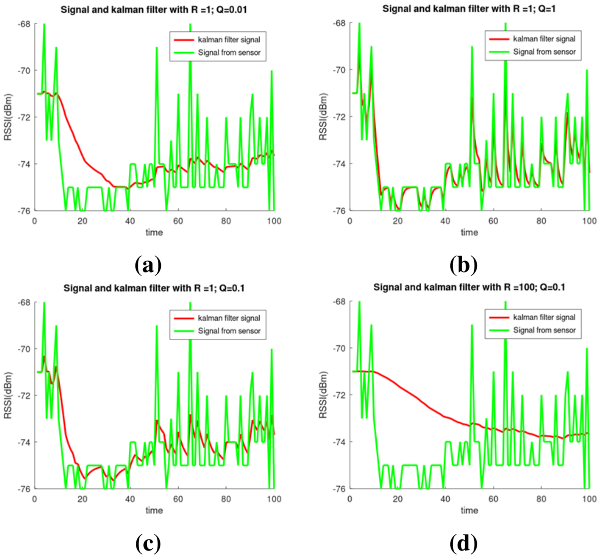
Nama1	Nama2	Jarak	Waktu
HENDRA DANISWARA	ARVIN DWI ANDIKA	0.69	11:54:38
HENDRA DANISWARA	ARVIN DWI ANDIKA	0.81	11:54:53
HENDRA DANISWARA	ARVIN DWI ANDIKA	1.89	11:55:09
HENDRA DANISWARA	ARVIN DWI ANDIKA	1.62	11:55:24
HENDRA DANISWARA	ARVIN DWI ANDIKA	0.64	11:55:55
HENDRA DANISWARA	ARVIN DWI ANDIKA	1.75	11:56:56
HENDRA DANISWARA	ARVIN DWI ANDIKA	1.50	11:57:27
HENDRA DANISWARA	ARVIN DWI ANDIKA	1.62	11:58:26
HENDRA DANISWARA	YURIKO	0.40	08:02:34
HENDRA DANISWARA	YURIKO	0.51	08:04:32

Figure 8: Web dashboard display

III. RESULTS AND DISCUSSION

The performance of the Received Signal Strength Indicator (RSSI) from the BLE devices used is shown in Figure 9. The further the distance, the more attenuated the RSSI becomes. The performance of BLE for RSSI is only readable up to a distance of 8 meters with many obstacles present in the environment. This 8-meter distance represents the maximum range of the measurement space or observation environment.

The input to the Kalman filter in this study is the RSSI from communication between client nodes. RSSI is one of the communication parameters that can change due to multipath fading in the observation environment. RSSI obtained is more stable with the Kalman filter. The smoothness level of the Kalman filter is influenced by the variables Q and R in Equations (5)-(7). As shown in Figure 10, the RSSI data from measurements and the output of the Kalman filter process can smooth the RSSI values better, obtained for $R = 1$ and $Q = 0.01$.



(a) (b) (c) (d)

Figure 9: Changes in Parameters R and Q in the Kalman Filter (a) $R = 1$ and $Q = 0.01$ (b) $R = 1$ and $Q = 1$ (c) $R = 1$ and $Q = 0.1$ (d) $R = 100$ and $Q = 0.1$

i. Testing the Kalman Filter Between Client Nodes

Distance conversion using the log-normal path loss model is a simple method to predict distance from the RSSI value of the communication process. However, this model cannot eliminate noise or reflections that affect the RSSI, making its values unstable and thus resulting in high distance conversion errors. Multinode RSSI measurements with BLE are presented in Table 2. Measurements were conducted six times for each client node over 10 minutes.

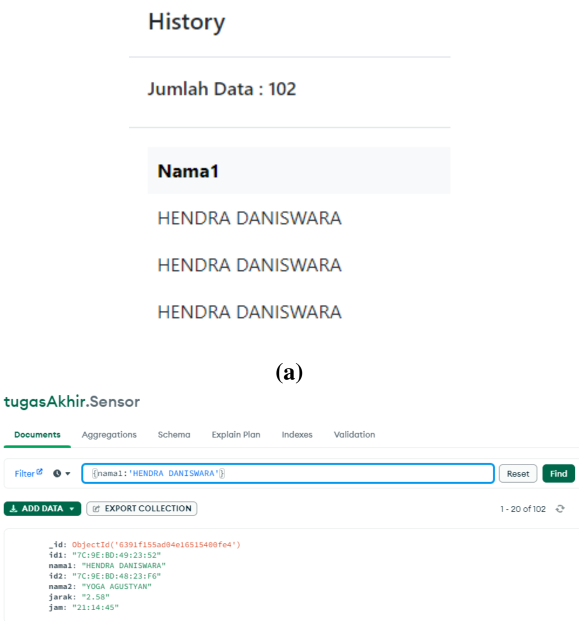
The results of RSSI testing and the Kalman filter are shown in Table 2, where the RSSI data from communication between N3 and N1 encountered a large error or what is called an outlier, possibly caused by multipath fading or human error during data collection. These results show that the average error of distance conversion without the Kalman filter is 63.72% and with the Kalman filter is 36.24%. The Kalman filter can reduce the error by 27.48%.

ii. Testing Data Transmission to the Cloud System

Data transmission testing to the cloud system was conducted at a distance of less than 1 meter for 19 minutes. The purpose of the test is to analyze communication between LoRa at close range, which is 1 meter. The data sent by the client node was successfully received by the gateway node. Subsequently, this data was forwarded by the gateway node to the web server by ESP 32 using a WiFi or internet connection. Figure 10 shows that the data received and sent with LoRa was successful 100% at close range of less than one meter. The data was successfully forwarded and displayed on the web

Table 2: Comparison of Distance Conversion with and Without the Kalman Filter

Node Client	RSSI dBm	RSSI’ dBm	d m	d’ m	Error d (%)	Error_d’ (%)
N1N2	-76	-74.51	2.21	1.97	10.34	1.70
N2N1	-75	-74.35	2.04	1.94	2.11	2.91
N2N3	-78	-77.28	2.58	2.44	28.85	21.85
N3N2	-78	-77.63	2.58	2.50	28.85	25.21
N3N1	-92	-87.19	7.63	5.25	281.47	162.73
N1N3	-70	-75.12	1.39	2.06	30.70	3.07
Average Error (%)	63.72 without filter, 36.24 with filter					


History

Jumlah Data : 102

Nama1

HENDRA DANISWARA

HENDRA DANISWARA

HENDRA DANISWARA

(a)

tugasAkhir.Sensor

```
{namal:'HENDRA DANISWARA'}
```

```
_id: ObjectId('6391f155ad04e16515400fe4')
id1: "7C:9E:BD:49:23:52"
nama1: "HENDRA DANISWARA"
id2: "7C:9E:BD:48:23:F6"
nama2: "YOGA AGUSTYAN"
jarak: "2.58"
jam: "21:14:45"
```

(b)

Figure 10: Display of Data Received by the Web (a) web history (b) data from the client node

using WiFi communication.

IV. CONCLUSION

Based on the testing results with the application of the Kalman filter to dampen the noise from BLE RSSI, it can be concluded that distance conversion with the Kalman filter with variables $R = 1$ and $Q = 0.01$ is effective. The Kalman filter can improve the error rate by 27.48% in the multinode BLE communication system. The results of the distance conversion are displayed on the web. The communication system between client nodes and the gateway node is regulated using the BLE algorithm between client nodes and the LoRa algorithm from the client node to the gateway.

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