Visible Light Communication System Design Using Raspberry Pi4B, LED Array, and MQTT Synchronization Protocol

Teuku Alif Rafi, Catur Apriono
Department of Electrical Engineering, Faculty of Engineering, Universitas Indonesia, Depok, 16424, Indonesia

ARTICLE INFO

Article history:

Received December 17, 2022
Revised February 01, 2023
Published February 06, 2023

Keywords:

Visible Light Communication;
LED;
Photodiode;
Raspberry Pi;
2×2 LED Array;
On-Off Keying;
Synchronization Method;
BER

ABSTRACT

Visible light communication emerged as the solution to overcome limitations exist in RF-based communication system. Although many research has been done on VLC, there are still a lot room for improvements, especially in the design of the VLC itself. This study discusses a simple visible light communication system design that transmits temperature and humidity information. The system uses Array 2×2 LED configuration to transmit data and photodiode to receive the optical signal. Raspberry Pi is used as the signal processor. The research carried out variations in the color of LED used, variations in the method of synchronization, and variations in the data rate transmission with BER value as the main parameter to be analyzed. The research contribution is to propose a simple visible light communication design that transmit and receive information in reference to room temperature and humidity using Raspberry Pi and DHT-11 sensor, while also implementing two synchronization methods to maximize synchronization in transmission thus minimizing the BER value in higher bit rate. The LED used is blue with an average voltage of 0.0423 V for bit ‘1’ and 0.00448 V for bit ‘0’. The throughput can be achieved are within range 1bps to 10 kbps with BER 0.5 as a threshold. The implementation of the synchronization method decreases the average BER value by 0.0945 with the implementation of transmission calibration synchronization and decreases the average BER value by 0.1221 using the MQTT communication protocol. In conclusion, the design has limitations through the component used in the transmitting and receiving end with BER values relatively high. Further research for system development can be done by implementing Forward Error Correction to minimize errors that occur in the transmission and collaborating with vendors with same research field for the latest components for VLC system design.

Corresponding Author:

Teuku Alif Rafi Akbar, Department of Electrical Engineering, Faculty of Engineering, Universitas Indonesia, Depok, 16424, Indonesia
Email: teuku.alif@ui.ac.id

1. INTRODUCTION

The development of wireless communication media driven by the Industrial Revolution 4.0 has led to many innovations related to communication methods. Generally, radio frequency (RF) is used as a wireless communication medium, just like existing wireless technologies (Wi-Fi, Bluetooth, etc.) [1]–[3]. As we all know that the communication system has several limitations, including the main problem of radio frequency communication media is the limited frequency spectrum available, besides that there are several external factors that cause the use of radio frequencies for communication to have certain limitations, especially in rooms [4], [5]. One of the changes that occur due to this problem is the use of spectrum as a communication medium, humans can use visible spectrum for wireless communication called VLC [6].

VLC is a communication concept that can overcome the limitations of the radio frequency spectrum and will become a wireless communication medium in the future [7]–[9]. The visible light communication system proposed uses LED as an information transmitter, a photodiode as an information receiver, and a microcontroller for further processing of information in the process of transmitting and receiving, to realize the use of VLC. Visible light communication has advantages over other types of wireless communication, including the security of data transmission has a higher security feature because LED lights do not penetrate the surface. VLC can be used as an alternative to the current Internet of Things technology, the communication properties of wireless communication systems (such as optical communication) seem to be suitable and can be used as indoor lights at the same time [2], [5], [10]–[12].

According to [6], [8], [13], while VLC uses LED, it encompasses numerous advantages such as a longer lifespan, LED only emits low temperature because it has a low heat generation, dan it has an improved color rendering without using any harmful chemicals. VLC is standardized by the VLCA (*Visible Light Communications Association*) and IEEE (such as IEEE 802.15.7 for Physical and MAC Layers of the VLC).

VLC still has so much room for improvement, VLC is a disruptive technology that has the potential to serve as a complementary technology to the radio frequency standards [14]–[17]. There are terms such as Internet of Light that can be known as the *Li-Fi* (*Light Fidelity*), which can transmit the internet through LED bulbs as an innovation facing the spectrum crunch on Wi-Fi with two-way multi-user communication and a high-speed internet provider with less radiation [18]–[24]. Although there are several challenges such as light perspective distortion, blurring, shadowing effect, ambient light, etc. that disrupt the efficiency of VLC according to [6], [8], [11], [25], [26].

Based on the research conducted in [1], VLC uses modulation categories such as dimming and flickering also as standard concepts to manipulate the light intensity in a way VLC communicates. VLC uses CSK (Color Shift Keying), OOK (On-Off Keying), and OFDM (Orthogonal Frequency Division Multiplexing) and implemented these modulation techniques in the physical layer. VLC uses topologies such as Peer-to-Peer, star, and broadcast [12], [26], [27].

Research on visible light communication has been running since 2010, and development has been carried out to date. One of them is research conducted in [28]. Using the Arduino Mega 2560 as the processing part of the communication system. The results show that the parametric observation of BER shows that the average value of BER using white LEDs is smaller than that of red, green, and blue LEDs, which are 0.377, 0.412, and 0.387, respectively. Another research was conducted in [29], where this research proposed a visible light communication system based on an Arduino microcontroller and using a 1×2 LED Array architecture for transmitting room temperature data. The results obtained have several limitations where the transmission speed resulting from the design has not reached the standard of the VLC transmission speed on PHY I, PHY II, and PHY III, where the transmission speed of the design reaches the maximum throughput of 1kbps.

Research in [30] proposed a toy-based VLC system design that offers two-way communication for educational purposes using Arduino Mega. The proposed design transmitted a binary code where the transmitter reads in ASCII code that is converted into binary code, and the laser module will dim to be received by the transmitter. The functionality of the proposed design can be much more improved to account for greater use of the design such as in child education

Research on visible light communication has been done using Raspberry Pi, and one was conducted in [31], [32]. This research presented a visible communication system design based on LED, PD, and Raspberry Pi version 3s. This research uses a portable hybrid RF/VLC and RF/FSO transceivers, with the integration of a 4×4 LED Array configuration for wireless data broadcasting use. The result was summarized in a maximum transmission rate of 1kbps at 4cm.

According to [32] A low-cost VLC system was designed using Raspberry Pi with the implementation of controlled dimming with multi-header-hybrid pulse position modulation (MH-HPPM) under dimming levels of 0.25, 0.5, and 0.75. The results showed that the proposed design works at 3 m for 0.25 dimming levels with a peak throughput of 130 Kbps, and it works at 3.5 m for 0.5 and 0.75 dimming levels with a peak throughput of 110 Kbps.

Research in [33] proposed an indoor positioning system for the VLC system. This study conducts the positioning of lights causes light strength to vary through different sources and light strength at day is stable at different times. This study state that RGB-LED offers more bandwidth modulation, higher data rates, and lower response time. CSK is suggested to be used as the modulation technique. Mainly there are three methods available to use in the positioning of the VLC including, the mathematical method, the sensor-assisted method, and the optimization method. This study conducts the challenges of multipath reflection and the long delay to VLC. In addition, the VLC system requires an advanced microcontroller and computer to maximize the processing part of the signal.

Research in [34] proposed an enhancement for an Indoor VLC communication system using optical path design and adding some FEC code (such as Reed-Solomon Code and Low-Density Parity Check). The result shows that adding FEC code in the system can enhance the distance reached by the VLC communication system while also maintaining the BER value at 10^{-3}. Optical performance can be enhanced by using a proper reflection cup and adjusting the optical source with a suitable convex lens that can lengthen the maximum transmission distance covered by the VLC communication system. The proposed design reaches a transmission distance of 7 m with a peak throughput of 5 Mbps.

In this study, a visible light communication system prototype was designed using the OOK ASK modulation technique and 2×2 LED Array configuration with the implementation of the synchronization method for synchronization of data transmission. The proposed design is intended to be low in cost, and simple to use [35], [36]. The prototype design is used to transmit room temperature and humidity data. BER value is used as the main parameter to be studied to analyze how the performance of the designed visible light communication system. This research aims to maximize the design of VLC system by using the peak transmission or bit rate with the BER value as the parameter to analyze. The design is intended to be low cost and applicable to daily usage information such as temperature and humidity.

From previous research, several obstacles were found which became important points for the optimization of the design to be carried out in this study, where the first obstacle was the microcontroller used previously in the form of the Arduino UNO and Arduino Mega 2560 which has a read and write speed that can be said to be small and less capable of processing transmissions according to VLC standardization for PHY I, PHY II, and PHY III [37]–[40]. The goal of the desired bit rate is around 1kbps to 1mbps with BER value less than 0.5 based on previous research done in [28], [29], [31]. One of the suggestions for a more suitable and stronger microcontroller to process data transmission requirements [33] is using the Raspberry Pi 4B, where Raspberry Pi is a single-board computer with specifications such as processor, RAM, and memory. Better read & write speed compared to the previous board used. The Raspberry Pi uses the Python programming language which has a wider library than the C++ language itself used by Arduino. This research contribution is to propose a simple visible light communication design that transmit and receive information in reference of room temperature and humidity using raspberry pi and DHT-11 sensor. This research also contributes by implementing communications protocol for IoT devices such as raspberry pi to maximize synchronization in transmission thus minimizing the BER value in higher bit rate.

2. METHODS

This research has a structured approach to design the VLC system based on the previous research done in [28], [29], [31] as the evaluation. Hence, the process of the research requires literature study from multiple sources included, the design of the transmitter and receiver using the components needed, program the transmitter and receiver one-by-one, testing the system design, comparing the LED colors used, analyze how the system works, evaluate with the transmission problems occurred, implemented few methods to synch the transmission and readings of LED signal, compare each method, evaluate the overall design of the VLC system, propose the conclusion and further work to be done. Fig. 1 shows the flow of research done in this study.

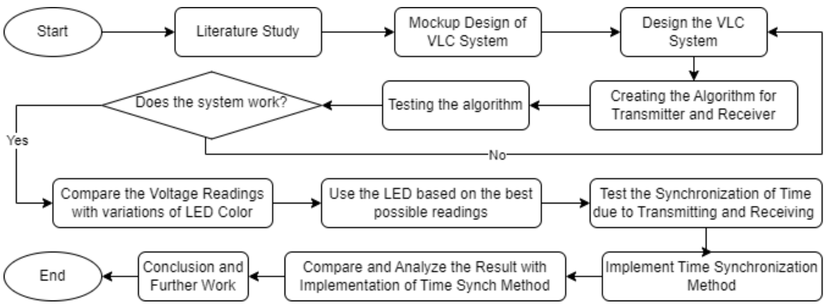

Fig. 1. Proposed VLC Design Flowchart

The proposed research flow (methodology) designed to be step-by-step to make sure that every steps in designing the proposed design to be detailed and can be analyzed before further actions in this research. There are many probable error that can occur and there are also maybe limitations related to the components used. BER values are used as the main parameter to determine the overall efficiency of transmitting and receiving end with the maximum threshold of 0.5. In order to determine the exact problems or limitations the system has and take conclusions and further work recommendations to future researchers.

The proposed design consists of two main parts, the transmitter and the receiver using an air channel. Fig. 2 shows the flowchart of the proposed design of the visible light communication system. The main components are Raspberry Pi 4B single-board computer, a Red & Blue Laser Emitting Diode (LED) as an optical source that transmits information, and a PIN photodiode as an optical sensor that reads the light.

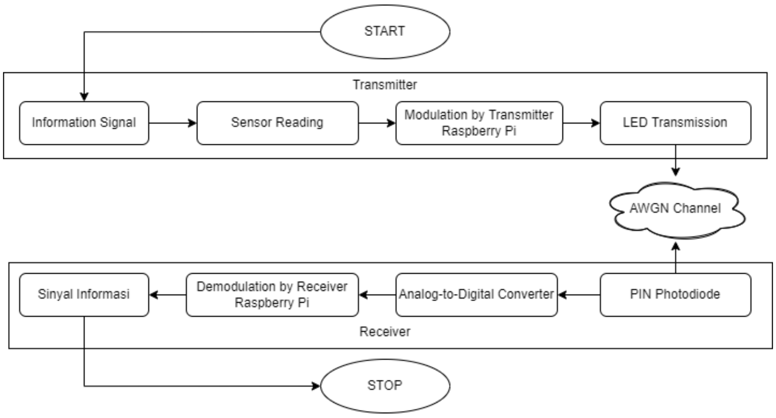

Fig. 2. Proposed VLC System Design Flowchart

Visible light communication system is a form of wireless communication that can transmit information signals which can be in the form of analog signals and digital signals. On the single-board computer used, namely: Raspberry Pi 4B, there are only digital signals that can be processed and processed, so to process and process analog signals, a unit is needed that can convert from analog signals to digital signals, in the form of an Integrated Circuit (Analog -to-Digital Converter), for example, MCP3008 which is an ADC from Adafruit. If the signal to be processed on a single-board computer is a digital signal, then no additional components are needed to process the signal. After the information signal to be processed is in the form of a digital signal, a modulation technique will be carried out that has been adjusted to the form of the digital signal and which is in accordance with the desired technique. The addition of modulation techniques is also carried out to adjust the carrier signal to the information signal so that it can be transmitted properly on the propagation channel media. The results of the information signal from the two processes will be forwarded using a sender and transmitted in the form of an optical signal (light) to be sent on a propagation channel in the form of air (generally in wireless communication).

The optical signal that is sent will experience propagation in the media in the form of air until it reaches the receiving side. On the receiving side, a photodiode component is used which can receive optical signals in the form of light. However, the photodiode component used (in the form of a PIN photodiode) will only receive light signals and the output that will be generated from the photodiode is in the form of an electric current which has several different potential values. Therefore, additional components are needed to convert analog signals in the form of electric potentials into digital signals (binary numbers) before being forwarded to the single-board computer used, namely the Raspberry Pi 4B. On single-board computer components, a process will be carried out which is the opposite of what has happened on the sending side, namely, there is a demodulation process. The results obtained from the two processes will be forwarded to the operator on the receiving side, if the desired signal is in the form of an analog signal, a conversion function is needed in the signal conversion component. If the desired signal is a digital signal, the results received will be displayed on the screen connected to the single-board computer on the receiving side.

The proposed design is carried within few procedures, the first one is to test a single LED configuration on the transmitting end and the receiver side will read the voltage value. The LED will be varied between red and blue LED to transmit optical signal. The result of the readings will be analyzed to determine which LED perform better on the system, hence moving forward with the best resulting LED. The second procedure is to test the overall system performance using the 2×2 Array LED configuration based on the research (referensi khalfan) with the variations of bit rate from 1 bps to 1 kbps. The result of the readings will be analyzed using BER value calculations based on the transmitted bit value sent and the readings of bit value on the receiving side. The third procedure is to improve the overall performance of the system, based on the first and second procedure results by implementing time synchronization into the system using semi-manual transmission calibration and automatic synchronization of IoT devices using the MQTT communication protocol. The result of the transmission will be carried out and to be compared to each other (second and third procedure), and the overall conclusion can be carried out. The overall result and conclusion will be compared to previous research related to the visible light communication design by comparing the BER value achieved and the overall maximum transmission rate based on each distance between the transmitter and the receiver which in this research has been set on 10 cm.

2.1. Transmitter

The transmitter uses a DHT11 sensor to read the room temperature and humidity. The information is then converted in the transmitter into binary-coded decimals. Furthermore, the information presented in BCD form is encrypted and digitally modulated based on the LED characteristic of HIGH at bit '1' and LOW at bit '0' based on OOK modulation. The design will able to transmit information over the air using light as a telecommunication resource. Fig. 3 shows the proposed transmitter design

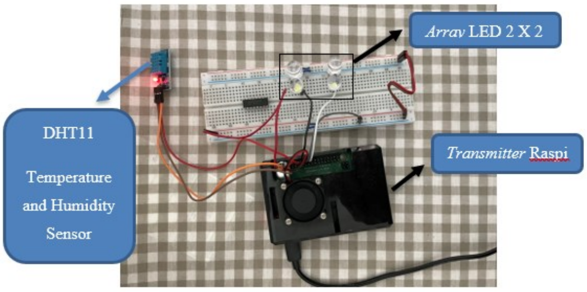

Fig. 3. Proposed Transmitter Design

2.2. Receiver

The receiver uses PIN Photodiode to capture the optical signal transmitted from the transmitter using LED. Since Raspberry Pi doesn't have an analog input pin, hence the proposed design uses an MCP3008 Analog-to-Digital Converter to convert analog signal (optical signal) into electrical pulses. The electrical pulses will be converted into BCD once more to be read and processed in the receiver using a suitable demodulation technique and the result will be translated into the original information as it was before being transmitted. Fig. 4 shows the proposed receiver design.

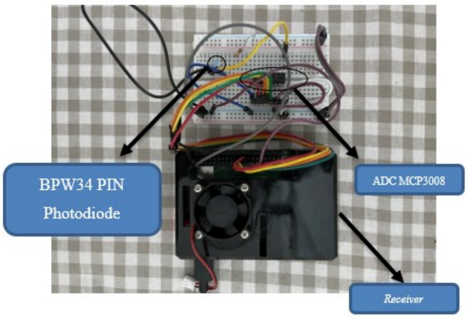

Fig. 4. Proposed Receiver Design

2.3. Bit Error Rate

Bit Error Rate (BER) is one of the parameters to see the performance and efficiency of a communication system. In digital communication technology, the bit error rate or usually abbreviated as BER. BER can be said to be the number of high-quality digital bits in the transmission network, which is interpreted as a low state and divided by that number. Bits are received, sent, or processed over a period. Bit Error Rate (bit error rate) is the number of bits received from the data stream through the communication channel path that has changed due to noise, interference, distortion, or bit synchronization errors. In this study, BER is used as a parameter to measure the performance of the visible light communication system using the On-Off Keying modulation technique, the following is an equation to find the BER value of the visible light communication system designed in (1).

Where, BER is the ratio between the damaged bits and the total number of bits transmitted, Q is a non-complementary error function, P is the optical power at the sender (Watts), N_0 is the AWGN channel power spectrum, R_b is the bit data rate (bits/second).

$$BER = Q\left(\frac{P}{\sqrt{N_0\, R_b}}\right) \tag{1}$$

Where, BER is the ratio between the damaged bits and the total number of bits transmitted, Q is a non-complementary error function, P is the optical power at the sender (Watts), N_0 is the AWGN channel power spectrum, R_b is the bit data rate (bits/second).

Equation (1) shows that the BER value of the communication system is affected by three variables, namely optical power transmission, system noise, and communication data speed. These three variables are inversely proportional to the BER value. This is due to the non-complementary error function multiplier in the equation. The multiplier of the non-complementary error function causes the BER value to have an opposite trend. For example, when the optical power value increases during transmission and the influence of the non-complementary error function is considered, it will affect the reduction of the BER value. On the other hand, the value of optical power decreases during the transmission process, considering the effect of the non-complementary error function which affects the increase in the BER value.

In the process of transmitting signals through the AWGN channel, it can be ensured that the signal gets interference that can occur. When the receiver captures the signal, it can also cause interference between signals due to the fast data rate making the pulse getting narrower to be used as a place for the desired information capacity. At this point of data collection, the signal is significantly degraded by the accumulation of random noise and ISI, resulting in an incorrect decision due to eye closure. To determine the relationship between BER and eye-opening data decisions, it is necessary to determine the statistical characteristics of the noise amplitude [41]. The signal Q factor is used to measure signal quality to determine BER. If there is no ISI distortion and the dominant amplitude noise has a Gaussian distribution, the signal Q factor is defined in (2).

$$Q = \frac{V_1 - V_0}{\sigma_1 + \sigma_0} \tag{2}$$

Where Q is a non-complementary error function, P is the optical power at the sender (Watts), V_1 represents the highest amplitude referring to bit '1' (Volt), V_0 represents the lowest amplitude referring to bit '0' (Volt), σ_1 is the root-mean-square of the Gaussian Distribution related to bit '1' (Volt), and σ_1 is the root-mean-square of the Gaussian Distribution related to bit '0' (Volt).

The mathematical equation is in the denominator position when using disruptive variables (such as noise) and data communication speed. Therefore, the value of the interference variable and data communication speed is directly proportional to the system BER value. When the interference value and data communication speed are increased by considering the effect of the non-complementary error function, it affects the increase in the BER value. On the other hand, if the interference value and data communication speed are reduced, and considering the effect of non-complementary error functions, this will result in a decrease in the BER value. The increase or decrease in the BER value is interpreted as the performance of the communication system. This is because BER can describe the amount of error information received in all messages.

The OOK modulation technique affects the performance of visible light communication systems in three ways [35], [40], [42], [43]. These are the optical signal power, the data transfer rate of the information, and the interference that occurred in the system. This study focuses on the application of data rate changes and system interference changes. The disturbance in question can be described by external light entering the reading sensors in the system. To obtain the BER value from the measurements of the designed system, the number of error information bits received is compared with the number of information bits sent [44], [45]. The BER value based on the measurement results can be expressed as (3).

$$BER = \frac{Error\ Bits\ Received}{Total\ Bits\ Received} \tag{3}$$

2.4. MQTT Synchronization

While TT in MQTT stands for Telemetry Transport, MQ refers to a product called IBM MQ. Although MQTT notation is sometimes referred to as message queue telemetry transport, there is no message queue in MQTT communication. MQTT is designed as a messaging method with a very lightweight publisher and subscriber system, ideal for connecting remote devices with a small code footprint and minimal network bandwidth, making it efficient. In the MQTT protocol, publishers and subscribers communicate through MQTT brokers. An MQTT client can be any device or application (from microcontrollers like Arduino, ESP32, Raspberry Pi, etc. to full cloud-hosted applications) that runs the MQTT library and connects to the MQTT broker over the network. The MQTT broker manages to receive messages from publishers and send messages to subscribers (also maintains a list of topics used by subscribers) [46]–[48].

2.5. Experimental Setup

The setup was done using a breadboard wired to the transmitter and receiver. The configurations of LED is based on the research (referensi Khalfan) which conducts the overall comparison and results of BER readings between a single LED configuration and Array LED configuration. Fig. 5 shows the setup conducted in this research on visible light communication using a 2×2 LED Array configuration and spacing of 10cm between the transmitter and the receiver.

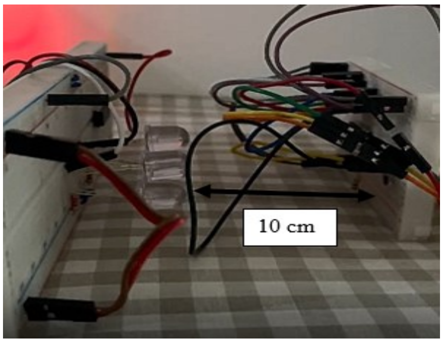

Fig. 5. The Experimental Setup

The positioning used for the 2×2 LED Array in the setup used in previous research of LED indoor positioning for VLC conducted in [49] are shown in Fig. 6. Due to light has a dualism, light can be directly classified in terms of waves. If we think of light as a wave, then when we apply the Array-LED concept, four beams of light from two light sources that are paired in series and different propagate towards a single point of photodiode receiving based on the research conducted in [50], [51]. The propagation used is direct-LOS with the matter of focusing the intensity of light captured in the photodiode readings in the receiver.

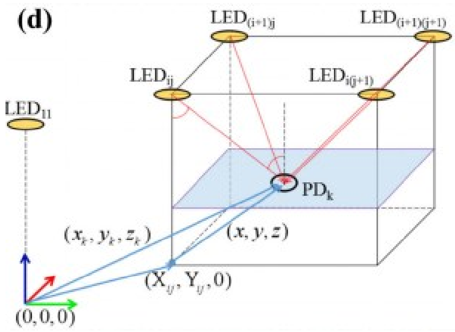

Fig. 6. Indoor Positioning System for VLC Design [49]

3. RESULTS AND DISCUSSION

This study conducts fixed variables for the limitations of the research and experiment done. The fixed variable is defined as a variable or condition that is maintained by the author to ensure that the results obtained are not directly related to this variable. The author identified three fixed variables in this study, namely:

1. Minimal Room Lighting
2. Spacing Between Transmitter and Receiver
3. 2×2 LED Array Configuration

The threshold for the maximum BER value to be tolerated in this research is 0.5. When the value of BER exceeds this threshold, the visible light communication system has a performance that indicates the probability of receiving error information bits is greater than the correct information bits will be transmitted and received. However, the desired performance target for the system is a near-zero BER value. A near-zero BER value indicates the system received fewer incorrect bits to be translated into the original information transmitted.

In this research, three main methodologies are used to carry out the experiment with BER values of the visible light communication system design as the main parameter to be analyzed. Further details are described below:

3.1. Variations of LED Color

The variation includes the types of colors in LEDs used on the transmitter (red and blue), each color has different operating wavelength characteristics to be transmitted on the transmitter. This is done to observe the effect of the LED color used on the reading performance of the photodiode used because the photodiode used has certain characteristics or tendencies to win over light with the appropriate wavelength to optimize the overall LED light reception process at the receiver, this is directly related to the performance of the overall system design.

The comparison that will be made will be related to the amount of voltage received at the photodiode, so that with variations in the voltage value obtained, it can be determined which LED color is more optimal for the next measurement. Fig. 7 shows the live simulation using blue LEDs with a 2×2 LED Array configuration with 10cm spacing.

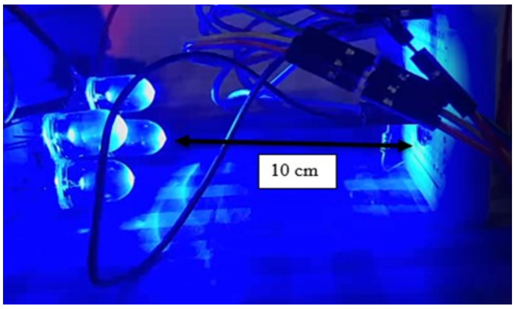

Fig. 7. Experiment Done Using 2×2 LED Array Configuration with 10 cm Spacing

Table 1 shows the voltage readings proceedings the variation of LED color used to the photodiode used in the proposed design. The deviant on the data obtained in Table 1, it is known that the blue LED has a stronger light (intensity) than the red LED, the voltage values read for binary numbers '1' and '0' can be seen clearly. This is inversely proportional to the sensitivity value contained in the datasheet, namely when the wavelength of the light beam used is close to a value of about 900 nm - 950 nm, the sensitivity value will be better for readings on the photodiode.

Table 1. Variations of LED Based on Voltage Readings

LED Color	Transmitted Bit	Voltage Readings	Received Bits
Red	0	0.0 V	0
	1	0.00322 V	0
	0	0.0 V	0
	1	0.00966 V	0
Blue	0	0.00644 V	0
	1	0.054786 V	1
	0	0.003222 V	0
	1	0.041895 V	1

This methodology used is based on the study on [28], however, there are some minor difference in direct testing that occurred, this could be due to the manufacture of the 10 mm LED used in this study, the blue LED light emitted brighter than the red LED, this can be seen in Table 1, the voltage readings and conversion values are available. the value of the voltage into a binary number when the transmitter uses red has an error in converting the value received at the receiver when compared to the bit value transmitted to the sender (the yellow color row in Table 1 shows the difference between the results of the transmitted bit and the received bit). This affects the light intensity value that will be read by the photodiode side of the receiver, so it can cause discrepancies in the test and theory on the datasheet of the components used.

3.2. Variations of Bit Rate

The author uses a variation of bit rate for the transmission of the room temperature and humidity, using the 1-bit/s mode. The purpose is to check the diode's maximum ability to read optical signals, process the received information, and analyze the overall performance of the designed transmitting and receiving components of the visible light communication system related to the parameter of BER values from each bit rate used.

Table 2 presents the performance results of the VLC design with variations in the bit rate used from 1 bps (bits per second) to 10 kbps (kilobits per second) with 10 cm spacing between the transmitter and the receiver inside a room with minimal lighting. The parameter to be reviewed is BER on the effect of bit rate variations used in this experiment.

Table 2. Measurement Results of BER vs Variations of Bit Rate

Temperature Transmission					
Distance	**Bit Rate (bps)**	**Number of Correct Bits**	**Number of Error Bits**	**Total Bit Transmitted**	**BER Value**
10 cm	1	535	466	1001	0.465534466
	10	513	488	1001	0.487512488
	100	506	495	1001	0.494505495
	1000	503	498	1001	0.497502498
	10000	542	459	1001	0.458541459
Humidity Transmission					
Distance	**Bit Rate (bps)**	**Number of Correct Bits**	**Number of Error Bits**	**Total Bit Transmitted**	**BER Value**
10 cm	1	479	522	1001	0.521478521
	10	515	486	1001	0.485514486
	100	504	497	1001	0.496503497
	1000	507	494	1001	0.493506494
	10000	586	415	1001	0.414585415

Comparing from previous research done on [29], [31], [34], the maximum bit rate that has been reached through the first procedure of this research tend to be on maximum 10 kbps with BER value is less than 0.50. Although from Table 2 there are condition when the BER value has more than the threshold that are determined with maximum BER value accepted is 0.50 which is when the transmission rate is set to be 1 bps. This condition is unusuall considering the slower the bit rate, the probability of error should be lesser than the faster bit rate.

The result of this research has a limitation in the form of bit data transmission speed that can be done, this can also be caused by the concept of transmission rather than digital data where the higher the bit data transmission speed is sent, the more pulses that will be generated and the frequency of each pulse will be even more in number but thinner in capacity, hence smaller rise time needed to. the limitations of the LEDs and photodiodes are used where at that speed the 10 mm LED used cannot perform faster switching, and the limited readings that can be done by the photodiode using the MCP3008 ADC with a clock rate that tends to be low, so the proposed visible light communication system design cannot proceed to support transmission systems with bit rate for more than 10 kbps [42], [52]–[55].

In addition, there is an effect of time synchronization on the transmitted data and the received data being different, thus causing incorrect data readings with random patterns that enter and replace the actual readings, so this causes a high BER value and a decrease in the accuracy of the transmitted transmission system. designed. This makes the design of visible light communication system tools cannot be used. Thus, it takes several techniques are used to synchronize the time between the receiving side and the transmitter to minimize reading errors due to errors in sending and reading times so that the value of BER becomes lower, and the accuracy of the tool design becomes better.

3.3. Variations of Synchronization Method

Variations of the synchronization method are used on the transmitter and receiver devices to perform a performance analysis rather than a tool designed to find out how the effect of the synchronization method on the overall performance of the visible light communication system design by comparing the BER values obtained in each synchronization method.

3.3.1. Synchronization using Calibration in Transmission

In the process of synchronizing the design of visible light communication devices on the transmitter and receiver, calibration techniques are used on the equipment. Transmission calibration technique on the device, using a separate transmission system in which the transmission from the sender to the receiver is limited from certain information on a regular basis, the sender will send an information signal related to temperature first and will continue with sending an information signal related to room humidity.

This calibration technique is used to minimize reading errors from the transmitted information related to room temperature and humidity so that it can reduce the BER value and increase the accuracy value generated to improve the performance of the visible light communication system design. Table 3 shows the performance of the VLC system design with variations in the data bit rate used from 1 bps to 10 kbps for 10 cm and minimal room lighting using the tool calibration method.

Table 3. Measurement Results of BER vs Variations of Bit Rate using Calibration in Transmission

Temperature Transmission					
Distance	**Bit Rate (bps)**	**Number of Correct Bits**	**Number of Error Bits**	**Total Bit Transmitted**	**BER Value**
10 cm	1	694	307	1001	0.306693307
	10	661	340	1001	0.33966034
	100	609	392	1001	0.391608392
	1000	566	435	1001	0.434565435
	10000	542	459	1001	0.458541459
Humidity Transmission					
Distance	**Bit Rate (bps)**	**Number of Correct Bits**	**Number of Error Bits**	**Total Bit Transmitted**	**BER Value**
10 cm	1	662	339	1001	0.33866134
	10	637	364	1001	0.36363636
	100	587	414	1001	0.41358641
	1000	554	447	1001	0.44655345
	10000	511	490	1001	0.48951049

Performance in higher bit rate using the calibration method does not have the ability to reduce the BER value and increase the accuracy of the visible light communication system design due to the limitations of the LED and photodiode used. At speeds of more than 1 kbps, the 10 mm LED used cannot perform faster switching, and the limited reading that can be done by the photodiode using the MCP3008 ADC with a clock rate that tends to be low, so the device design cannot support transmission systems with speeds of more than 10 kbps

Apart from the limitations of the device design, the use of synchronization with the transmission calibration method still has several drawbacks, such as errors that still occur in the transmission system due to synchronization in a certain time caused by the limited reading ability of the photodiode used, thus causing the BER value to be higher and the accuracy value becomes lower. There are also problems in synchronizing the exact timing between transmitting and receiving the bit since this method is a semi-manual that involves human errors probability, hence resulting the missed readings that occurred.

By using the transmission calibration method from the tool, synchronization problems can be minimized, but cannot be used for real-time transmission systems. This is because the use of the calibration method of the transmission system requires a delay between times for transmission between each information signal related to sending temperature data and room humidity data. The time lag is used to minimize the difference in the sending time made by the LED on the sending side and the reading time from the photodiode on the receiving side.

3.3.2. Synchronization using MQTT Communication Protocol

In the implementation of MQTT on the design of a visible light communication system, the transmitter side will act as a broker as well as a publisher (with the DHT11 temperature sensor used will be a supplier of information to the publisher) and the receiver will act as a subscriber, on the transmitter, it will communicate to the receiving side related to the time of sending information using the LED on the transmitter and readings from the photodiode on the receiver thus minimize the synchronization problems that occur in the synchronization method that has been done previously on the second procedure of this research. The reason to implementing MQTT is based on the research done in [56], where in this research presents that MQTT has lower latency but has a more reliable or better QOS, while also has lower power consumption vs resource requirement for this specific transmission proposed in this research.

The performance of the VLC system design with variations in the data bit rate used from 1 bps to 10 kbps for a distance of 10 cm and minimal room lighting with a synchronization method using the MQTT communication protocol are shown in Table 4. The performance of the design of the visible light communication system with MQTT produces a BER value that decreased significantly in general. The application of the MQTT communication protocol minimizes synchronization problems that may occur in the process of transmitting information using LEDs and readings made by the photodiode. There is a slightly different data that occurs in the transmission of humidity information at a data transmission speed of 10 bps, where according to the basic concept with an increase in the value of the transmission speed, the BER value should tend to increase, and the accuracy value will tend to decrease.

Table 4. Measurement Results of BER vs Variations of Bit Rate using MQTT Communication Protocol

Distance	Bit Rate (bps)	Number of Correct Bits	Number of Error Bits	Total Bit Transmitted	BER Value
Temperature Transmission					
10 cm	1	785	216	1001	0.215784216
	10	694	307	1001	0.306693307
	100	657	344	1001	0.343656344
	1000	556	445	1001	0.444555445
	10000	518	483	1001	0.482517483
Humidity Transmission					
Distance	**Bit Rate (bps)**	**Number of Correct Bits**	**Number of Error Bits**	**Total Bit Transmitted**	**BER Value**
10 cm	1	719	282	1001	0.281718282
	10	727	274	1001	0.273726274
	100	667	334	1001	0.333666334
	1000	557	444	1001	0.443556444
	10000	509	492	1001	0.491508492

However, in the test, an error still occurred and could be caused by the components used in the form of the receiving side, namely the photodiode used, and the ADC used. This may be due to a synchronization problem that has not been fully resolved by using the MQTT communication protocol. Along with the increase in data rate variations, errors or reading errors occur randomly and can lead to better or worse combinations for variations in the data rate used during testing, this can be minimized using error coding techniques after the data transmission process so that errors that occur can be corrected with the algorithm.

Other factors that can affect the performance of VLC system design are the influence of the surrounding environment such as the phenomenon of multipath propagation, and external lighting. Apart from the possibility of the propagation phenomenon, what may happen is inter-symbol interference that can occur in the process of reading the received electrical signal into binary numbers in the form of '1' and '0' on the ADC, of course, this can lead to a higher BER value. and the decreasing accuracy value of the visible light communication device design performance.

3.4. Comparison to Previous Experiment

BER values throughout the experiment done relating to the performance of VLC system design with the variation of bit rate, and the variation of synchronization method implemented in the system are illustrated in Fig. 8 and Fig. 9.

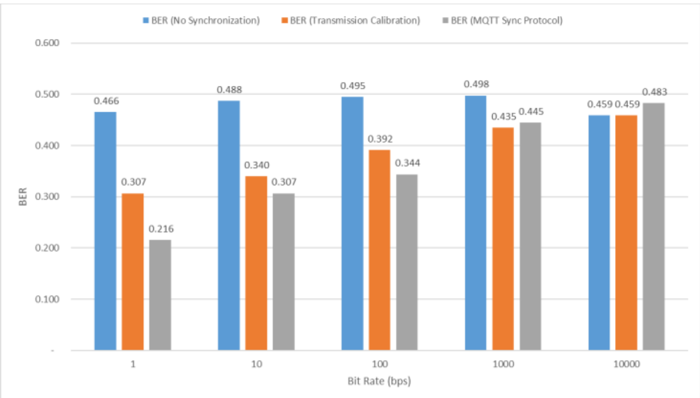

Fig. 8. Comparison of Bit Rate Variation with BER Value on Room Temperature Information Transmission with Variation of Synchronization Method used

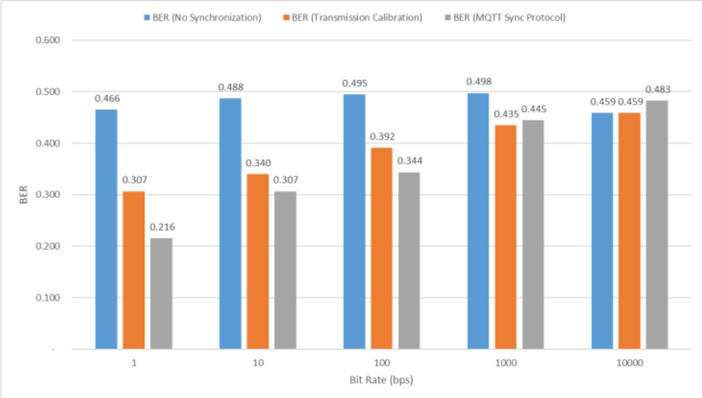

Fig. 9. Comparison of Bit Rate Variation with BER Value on Room Humidity Information Transmission with Variation of Synchronization Method used

With the increase of the bit rate used in transmitting room temperature and humidity information, the BER value will be higher, and the transmission accuracy value obtained will be lower. Using the implementation of the synchronization method used, the BER value significantly decreases linearly so that it can be concluded that the relationship between the bit data transmission speed (bit rate) and the BER value obtained has an inverse relationship, it's similar to the relationship between the bit rate and the transmission accuracy value obtained in the VLC system design.

This research has a limitation in the form of bit data transmission speed that can be done, this can also be caused by the concept of transmission rather than digital data where the higher the bit data transmission speed is sent, the more pulses that will be generated and the frequency will be than each. pulse will be even more. It is known that the LED components used cannot support the operation of emitting a light signal with such a fast frequency or pulse.

Other factors that can influence this to occur are the influence of the surrounding environment such as the phenomenon of multipath propagation, and external lighting. Apart from the possibility of this propagation phenomenon, the thing that might happen is inter-symbol interference which can occur in the process of reading the received electrical signal into binary numbers in the form of '1' and '0' on the ADC, while this can cause a higher BER value and decreasing the value of the accuracy of the design performance of visible light communication devices.

In addition, there is an effect of synchronization on the transmitted data and the received data being different, thus causing incorrect data readings with random patterns that enter and replace the actual readings, so this causes a high BER value and a decrease in the accuracy of the transmitted transmission system. designed. This makes the design of visible light communication system tools cannot be used. Thus takes several techniques are used to synchronize the receiver and the transmitter to minimize reading errors due to errors in sending and reading times so that the value of BER becomes lower, and the accuracy of the tool design becomes better.

Compared to actual common techniques used in communication between IoT devices, there are still a room for improvement where as the implementation of MQTT was one of the common protocol used based on the research done in [56], [57]. The research in [58] uses MQTT with implementation of RT-MQTT system which was proposed on the research based on SDN applications. Whereas in research [59] proposed a management system to be integrated to the transmitter and receiver, while also proposed a data transport IoT devices management for uni-directional and bi-directional VLC system.

Comparing to the identical and previous research done, including in [34], where the proposed design of indoor VLC communication system reaches a maximum covered distance of 7 m while having 5 Mbps as the peak throughput. According to [28], the proposed research proves that blue LED provides better BER results at 0.377 compared to red LED at 0.412, while the proposed design has a maximum covered distance of 3.6 cm with a peak throughput of 100 bps. Research done in [29] shows that the proposed design using a 1×2 LED Array configuration achieves the BER value at 0.4858 and reaches a maximum distance of 10 cm with a maximum throughput of 1 kbps. Research in [31] show that the proposed design of VLC using a 4×4 LED Array configuration reaches a maximum distance of 4 cm with a maximum throughput of 1 kbps. In this study, the proposed design of the VLC communication system using a 2×2 LED Array configuration achieved the average BER value of 0.4870 in average and reaches a maximum distance of 10 cm with a maximum throughput of 10 kbps. Table 5 shows the comparison for each previous research done to this research.

Table 5. Comparison Current Research to Previous Research

Research	Author	Maximum Bit Rate	Results
This Research	Teuku Alif Rafi, Catur Apriono	10 kbps with maximum distance of 10 cm	BER: 0.482517483 Implemeted synchronization method such as Transmission Calibration and MQTT Communication Protocol to minimize BER value and uses 2×2 LED Array configuration
[34]	Xiang Zhang, Min Zhang, Dahai Han Qing, Li	5 mbps with a maximum distance of 7 m	BER: 10^{-3} With the implementation of RS Code and LDPC Code
[28]	Patar Parlindungan, Catur Apriono	100 bps with a maximum distance of 3.6 cm	BER Value: ✓ 0.412 when using RED LED ✓ 0.377 when using WHITE LED Using single Array LED Configuration
[31]	Lee I. E. Chung, G. C. Pang W. L., Anas S. S., Cheong M Y	1 kbps with a maximum distance of 4 cm	No BER value available Using 4×4 LED Array Configuration
[29]	Khalfan Nadhief, Catur Apriono	1 kbps with a maximum distance of 10 cm	BER value: 0.4858 with Blue LED and 1×2 LED Array Configuration

This research has strengths and limitations that are considered throughout the research. The strength of this research compared to previous simillar research consist of the following VLC system design by using Raspberry Pi 4B and the implementation of time synchronizing method such as MQTT. Implementations of MQTT is based on the limitations of the system design with the aim to have more reliable communication and time synchronization between the transmitter and receiver. There are also limitations that are the key of the drawback from this research, mainly because of the photodiode and LED that are used in this research. Further improvement can be done by upgrading the hardwares and provide further error correction algorithms that are effective based on the VLC system design.

4. CONCLUSIONS

From the overall research conducted in this study, the conclusions are as follows. This study uses blue LEDs in a 2×2 LED Array configuration. This is due to the blue light-emitting which has a higher emission intensity than the red LED with a voltage reading value read by the photodiode with an average of 0.04834 Volts. Implementation of the synchronization method with the transmission calibration synchronization method affects the overall performance of the device design, with a decrease in the BER value of 0.0945. The implementation of the synchronization method with the synchronization method using the MQTT communication protocol affected the overall performance of the device design, with a decrease in the BER value of 0.1221. Limitations of the system lies in the component used such as LED's, Analog-to-Digital Converter, and Photodiode. In this research, there are still limitations and shortcomings that can be improved for the development of research for the next stage. The main limitations occur in the design used in designing the transmitter and receiver components, suggestions and improvements from research that can be done, as follows. Implementation of the Forward Error Correction (FEC) coding technique on the signal processing side to minimize the resulting BER value. It is necessary to develop a visible light communication system using components and devices that already have good test values Industrially, this can be done by collaborating with vendors developing visible light communication systems

Acknowledgments

This research was conducted at the author's home, Kembangan District, West Jakarta. Supported by Antenna and Microwave Research Group from the Department of Electrical Engineering, Faculty of Engineering, University of Indonesia.

REFERENCES

[1] L. Lovisolo, M. P. Tcheou, and F. R. Aacutevila, "Visible Light-Based Communication and Localization," *Handbook of Position Location*, pp. 1121–1164, 2019, https://doi.org/10.1002/9781119434610.ch31.

[2] V. v. Andreev, "Wireless Technologies of Information Transmission Based on the Using of Modulated Optical Radiation (Li-Fi Communication System): State and Prospects," *2018 Systems of Signal Synchronization, Generating and Processing in Telecommunications, SYNCHROINFO 2018*, pp. 1-4, 2018, https://doi.org/10.1109/SYNCHROINFO.2018.8457019.

[3] S. Al-Ahmadi, O. Maraqa, M. Uysal, and S. M. Sait, "Multi-user visible light communications: State-of-the-art and future directions," *IEEE Access*, vol. 6, pp. 70555–70571, 2018, https://doi.org/10.1109/ACCESS.2018.2879885.
[4] M. Z. Chowdhury, M. T. Hossan, A. Islam, and Y. M. Jang, "A Comparative Survey of Optical Wireless Technologies: Architectures and Applications," *IEEE Access*, vol. 6, pp. 9819–9840, 2018, https://doi.org/10.1109/ACCESS.2018.2792419.
[5] M. A. Jamshed, F. Heliot, and T. W. C. Brown, "A Survey on Electromagnetic Risk Assessment and Evaluation Mechanism for Future Wireless Communication Systems," *IEEE J Electromagn RF Microw Med Biol*, vol. 4, no. 1, pp. 24–36, 2020, https://doi.org/10.1109/JERM.2019.2917766.
[6] L. E. M. Matheus, A. B. Vieira, L. F. M. Vieira, M. A. M. Vieira, and O. Gnawali, "Visible Light Communication: Concepts, Applications and Challenges," *IEEE Communications Surveys and Tutorials*, vol. 21, no. 4, pp. 3204–3237, 2019, https://doi.org/10.1109/COMST.2019.2913348.
[7] H. Haas, C. Chen, and D. O'Brien, "A guide to wireless networking by light," *Prog Quantum Electron*, vol. 55, pp. 88–111, 2017, https://doi.org/10.1016/j.pquantelec.2017.06.003.
[8] M. Z. Chowdhury, M. K. Hasan, M. Shahjalal, M. T. Hossan, and Y. M. Jang, "Optical Wireless Hybrid Networks: Trends, Opportunities, Challenges, and Research Directions," *IEEE Communications Surveys and Tutorials*, vol. 22, no. 2, pp. 930–966, 2020, https://doi.org/10.1109/COMST.2020.2966855.
[9] J. Sanusi, S. Idris, A. M. Aibinu, S. Adeshina, and A. N. Obadiah, "Handover in Hybrid LiFi and WiFi Networks," *2019 15th International Conference on Electronics, Computer and Computation, ICECCO 2019*, pp. 1-6, 2019, https://doi.org/10.1109/ICECCO48375.2019.9043251.
[10] M. A. Khalighi and M. Uysal, "Survey on free space optical communication: A communication theory perspective," *IEEE Communications Surveys and Tutorials*, vol. 16, no. 4, pp. 2231–2258, 2014, https://doi.org/10.1109/COMST.2014.2329501.
[11] H. Haas and T. Cogalan, "LiFi opportunities and challenges," *Proceedings of the International Symposium on Wireless Communication Systems*, vol. 2019-August, pp. 361–366, 2019, https://doi.org/10.1109/ISWCS.2019.8877151.
[12] W. Jiang, B. Han, M. A. Habibi, and H. D. Schotten, "The road towards 6G: A comprehensive survey," *IEEE Open Journal of the Communications Society*, vol. 2, pp. 334–366, 2021, https://doi.org/10.1109/OJCOMS.2021.3057679.
[13] T. Koonen, "Indoor Optical Wireless Systems: Technology, Trends, and Applications," *Journal of Lightwave Technology*, vol. 36, no. 8, pp. 1459–1467, 2018, https://doi.org/10.1109/JLT.2017.2787614.
[14] S. S. Bawazir, P. C. Sofotasios, S. Muhaidat, Y. Al-Hammadi, and G. K. Karagiannidis, "Multiple Access for Visible Light Communications: Research Challenges and Future Trends," *IEEE Access*, vol. 6, pp. 26167–26174, 2018, https://doi.org/10.1109/ACCESS.2018.2832088.
[15] "A Review of LiFi Technology | IEEE Conference Publication | IEEE Xplore." https://remote-lib.ui.ac.id:2147/document/9358340 (accessed Dec. 13, 2022).
[16] H. Haas, C. Chen, and D. O'Brien, "A guide to wireless networking by light," *Prog Quantum Electron*, vol. 55, pp. 88–111, 2017, https://doi.org/10.1016/j.pquantelec.2017.06.003.
[17] "Indoor Optical Wireless Systems: Technology, Trends, and Applications | IEEE Journals & Magazine | IEEE Xplore." https://remote-lib.ui.ac.id:2147/document/8240590 (accessed Dec. 13, 2022).
[18] H. Haas, "LiFi is a paradigm-shifting 5G technology," *Reviews in Physics*, vol. 3, pp. 26–31, 2018, https://doi.org/10.1016/j.revip.2017.10.001.
[19] R. Badeel, S. K. Subramaniam, Z. M. Hanapi, and A. Muhammed, "A review on lifi network research: Open issues, applications and future directions," *Applied Sciences (Switzerland)*, vol. 11, no. 23, 2021, https://doi.org/10.3390/app112311118.
[20] H. Haas, L. Yin, Y. Wang, and C. Chen, "What is LiFi?," *Journal of Lightwave Technology*, vol. 34, no. 6, pp. 1533–1544, 2016, https://doi.org/10.1109/JLT.2015.2510021.
[21] M. R. Ghaderi, "LiFi and Hybrid WiFi/LiFi indoor networking: From theory to practice," *Optical Switching and Networking*, vol. 47, 2023, https://doi.org/10.1016/j.osn.2022.100699.
[22] E. Ramadhani and G. P. Mahardika, "The Technology of LiFi: A Brief Introduction," *IOP Conf Ser Mater Sci Eng*, vol. 325, no. 1, 2018, https://doi.org/10.1088/1757-899X/325/1/012013.
[23] S. Murawwat, R. Mehroze, K. Rabbi, A. Moeen, and T. Sheikh, "An Overview of LiFi: A 5G candidateTechnology," *RAEE 2018 - International Symposium on Recent Advances in Electrical Engineering*, pp. 1-6, 2018, https://doi.org/10.1109/RAEE.2018.8706906.
[24] M. Jatau, M. David, and S. Zubair, "LiFi: The Solution to Radio Frequency Saturation," *2020 International Conference in Mathematics, Computer Engineering and Computer Science, ICMCECS 2020*, pp. 1-6, 2020, https://doi.org/10.1109/ICMCECS47690.2020.240880.
[25] F. Aftab, "Potentials and Challenges of Light Fidelity Based Indoor Communication System," *International Journal of New Computer Architectures and their Applications*, vol. 6, no. 3, pp. 91–102, 2016, https://doi.org/10.17781/P002152.
[26] L. U. Khan, "Visible light communication: Applications, architecture, standardization and research challenges," *Digital Communications and Networks*, vol. 3, no. 2, pp. 78–88, 2017, https://doi.org/10.1016/j.dcan.2016.07.004.
[27] E. Zadobrischi, S. A. Avatamanitei, A. M. Cailean, M. Dimian, and M. Negru, "Toward a hybrid vehicle communication platform based on VLC and DSRC technologies," *Proceedings - 2019 IEEE 15th International*

Conference on Intelligent Computer Communication and Processing, ICCP 2019, pp. 103–107, 2019, https://doi.org/10.1109/ICCP48234.2019.8959672.

[28] P. P. Sianturi and C. Apriono, "Near Distance Digital Data Transmission of A Low-Cost Wireless Communication Optical System," in *2020 3rd International Conference on Information and Communications Technology, ICOIACT 2020*, pp. 436–440, 2020, https://doi.org/10.1109/ICOIACT50329.2020.9332039.

[29] K. N. P. Wicaksono and C. Apriono, "BER Performance Comparison on Single versus Dual LED for Visible Light Communication," in *2021 International Conference on Computer Science, Information Technology, and Electrical Engineering, ICOMITEE 2021*, pp. 209–212, 2021, https://doi.org/10.1109/ICOMITEE53461.2021.9650078.

[30] A. N. B. Baharudin, M. H. Habaebi, and F. A. Rahman, "Design and implementation of visible light communication based toys," *Bulletin of Electrical Engineering and Informatics*, vol. 8, no. 3, pp. 960–969, 2019, https://doi.org/10.11591/eei.v8i3.1506.

[31] I. E. Lee, G. C. Chung, W. L. Pang, S. S. Anas, and M. Y. Cheong, "Design of a hybrid free space optical and visible light communication system for indoor wireless data broadcasting," in *Journal of Physics: Conference Series*, vol. 1432, no. 1, 2020, https://doi.org/10.1088/1742-6596/1432/1/012065.

[32] S. Das, B. Jana, and S. K. Mandal, "Implementation of dimming controlled visible light communication using Raspberry Pi," *Opt Quantum Electron*, vol. 53, no. 12, 2021, https://doi.org/10.1007/s11082-021-03362-4.

[33] J. Luo, L. Fan, and H. Li, "Indoor Positioning Systems Based on Visible Light Communication: State of the Art," *IEEE Communications Surveys and Tutorials*, vol. 19, no. 4, pp. 2871–2893, 2017, https://doi.org/10.1109/COMST.2017.2743228.

[34] X. Zhang, M. Zhang, D. Han, and Q. Li, "Enhancement of indoor VLC communication system with optical path design and FEC code," in *2014 6th International Conference on Wireless Communications and Signal Processing, WCSP 2014*, pp. 1-5, 2014, https://doi.org/10.1109/WCSP.2014.6992113.

[35] D. F. Zhang, Y. J. Zhu, and Y. Y. Zhang, "Multi-LED phase-shifted OOK modulation based visible light communication systems," *IEEE Photonics Technology Letters*, vol. 25, no. 23, pp. 2251–2254, 2013, https://doi.org/10.1109/LPT.2013.2283583.

[36] T. Kondo, R. Kitaoka and W. Chujo, "Multiple-access and two-way visible light communication with image sensor and LED array," *2016 21st OptoElectronics and Communications Conference (OECC) held jointly with 2016 International Conference on Photonics in Switching (PS)*, pp. 1-3, 2016, https://ieeexplore.ieee.org/abstract/document/7718509.

[37] M. Bhutani, B. Lall, and M. Agrawal, "Optical Wireless Communications: Research Challenges for MAC Layer," *IEEE Access*, vol. 10, pp. 126969–126989, 2022, doi: 10.1109/ACCESS.2022.3225913.

[38] Arduino, "Arduino® UNO R3," 2022. Accessed: Dec. 13, 2022. [Online]. Available: https://store-usa.arduino.cc/products/arduino-uno-rev3.

[39] Arduino, "Arduino® MEGA 2560 Rev3," 2022. Accessed: Dec. 13, 2022. [Online]. Available: https://docs.arduino.cc/hardware/mega-2560

[40] S. K. Liaw, H. H. Chou, C. J. Wu, M. J. Chien, and C. Teng, "500 Mb/s OOK visible light communications using RGB-based LEDs," in *4th International Symposium on Next-Generation Electronics, IEEE ISNE 2015*, pp. 1-2, 2015, https://doi.org/10.1109/ISNE.2015.7131956.

[41] S. Song, V. Bhatnagar, and J. Livas, "On the gaussianly-distributed q-factor in optical communication systems," *Conference Proceedings - Lasers and Electro-Optics Society Annual Meeting-LEOS*, vol. 2, pp. 409–410, 2000, https://doi.org/10.1109/LEOS.2000.893886.

[42] H. Li *et al.*, "High Speed Visible Light Communications based on RGB Laser Diodes and OOK-NRZ Modulation," in *Asia Communications and Photonics Conference*, pp. Su2A-51, 2017, https://doi.org/10.1364/ACPC.2017.Su2A.51.

[43] N. Hao, M. Zhang, and Y. Zhang, "An OOK based visible light communication system for short distance," in *2012 7th International ICST Conference on Communications and Networking in China, CHINACOM 2012 - Proceedings*, pp. 306–308, 2012, https://doi.org/10.1109/ChinaCom.2012.6417496.

[44] B. Wang, X. T. Wang, H. Li, H. M. Gao, and Y. W. Sun, "A Method for Predicting the Bit Error Rate of Wireless Digital Communication Equipment," in *2020 IEEE 3rd International Conference on Electronics Technology, ICET 2020*, pp. 665–669, 2020, https://doi.org/10.1109/ICET49382.2020.9119708.

[45] S. J. Floris, K. A. Remley, and C. L. Holloway, "Bit error rate measurements in reverberation chambers using real-time vector receivers," *IEEE Antennas Wirel Propag Lett*, vol. 9, pp. 619–622, 2010, https://doi.org/10.1109/LAWP.2010.2053513.

[46] F. Hmissi and S. Ouni, "TD-MQTT: Transparent Distributed MQTT Brokers for Horizontal IoT Applications," in *2022 IEEE 9th International Conference on Sciences of Electronics, Technologies of Information and Telecommunications, SETIT 2022*, pp. 479–486, 2022, https://doi.org/10.1109/SETIT54465.2022.9875881.

[47] M. Alsmirat *et al.*, "2019 Sixth International Conference on Internet of Things: Systems, Management and Security (IoTSMS)," 2019, https://doi.org/10.1109/IOTSMS48152.2019.8939162.

[48] F. Chen, Y. Huo, K. Liu, W. Tang, J. Zhu, and Z. Sui, "A study on MQTT node selection," in *Proceedings - 2020 16th International Conference on Mobility, Sensing and Networking, MSN 2020*, pp. 622–623, 2020, https://doi.org/10.1109/MSN50589.2020.00101.

[49] Y. Chen, W. Guan, J. Li, and H. Song, "Indoor Real-Time 3-D Visible Light Positioning System Using Fingerprinting and Extreme Learning Machine," *IEEE Access*, vol. 8, pp. 13875–13886, 2020, https://doi.org/10.1109/ACCESS.2019.2961939.

[50] R. Zamorano-Illanes, I. Soto, E. Toledo–Mercado, J. Pereira–Mendoza and P. Adasme, "Computer Vision detection and classification of emitters for visible light communication," *2021 Third South American Colloquium on Visible Light Communications (SACVLC)*, pp. 1-6, 2021, https://doi.org/10.1109/SACVLC53127.2021.9652297.

[51] Y. Zhuang *et al.*, "A survey of positioning systems using visible LED lights," *IEEE Communications Surveys and Tutorials*, vol. 20, no. 3, pp. 1963–1988, 2018, https://doi.org/10.1109/COMST.2018.2806558.

[52] "LED, 10mm." [Online]. Available: www.element14.comwww.farnell.com

[53] P. By ALLDATASHEETCOM, "BPW34 Vishay Telefunken Silicon PIN Photodiode Description Absolute Maximum Ratings." [Online]. Available: www.vishay.de

[54] D. Tsonev, S. Videv, and H. Haas, "Towards a 100 Gb/s visible light wireless access network," *Opt Express*, vol. 23, no. 2, p. 1627, 2015, https://doi.org/10.1364/OE.23.001627.

[55] S. Dimitrov and H. Haas, "Principles of LED light communications: Towards networked Li-Fi," *Principles of LED Light Communications: Towards Networked Li-Fi*, pp. 1–207, 2015, https://doi.org/10.1017/CBO9781107278929.

[56] N. Naik, "Choice of effective messaging protocols for IoT systems: MQTT, CoAP, AMQP and HTTP," *2017 IEEE International Symposium on Systems Engineering, ISSE 2017 - Proceedings*, pp. 1-7, 2017, https://doi.org/10.1109/SysEng.2017.8088251.

[57] R. J. Pandya, R. Goyal, and R. K. Kundu, "Fault-tolerant and medium access control (FTMAC) protocol for IoT over VLC," *Proceedings of the 2019 TEQIP - III Sponsored International Conference on Microwave Integrated Circuits, Photonics and Wireless Networks, IMICPW 2019*, pp. 144–148, 2019, https://doi.org/10.1109/IMICPW.2019.8933282.

[58] E. Shahri, P. Pedreiras, and L. Almeida, "Enhancing MQTT with Real-Time and Reliable Communication Services," *IEEE International Conference on Industrial Informatics (INDIN)*, pp. 1-6, 2021, https://doi.org/10.1109/INDIN45523.2021.9557514.

[59] C. M. Kim and S. J. Koh, "Device Management and Data Transport in IoT Networks Based on Visible Light Communication," *Sensors 2018,* vol. 18, no. 8, p. 2741, 2018, https://doi.org/10.3390/s18082741.

BIOGRAPHY OF AUTHORS

Teuku Alif Rafi Akbar was born in Jakarta, Indonesia, on 14 March 2000. He entered Universitas Indonesia in 2018 and graduated in 2022 with a Bachelor's Degree of Engineering. He currently takes the Fast Track Program at Universitas Indonesia to continue his study in Magister Program, majoring in Smart Telecommunications and Wireless System Engineering, currently in his first semester. His main research interest includes visible light communication and machine learning implementation towards optical and wireless communications.

Catur Apriono (Member, IEEE) received the B.Eng. and M.Eng. degrees in telecommunication engineering from the Department of Electrical Engineering, Universitas Indonesia, Indonesia, in 2009 and 2011, respectively, and the Ph.D. degree in nano vision technology from Shizuoka University, Japan, in 2015. Since 2018, he has been an Assistant Professor of telecommunication engineering with the Universitas Indonesia, where he is currently a Lecturer with the Department of Electrical Engineering, Faculty of Engineering. His main research interests include antenna and microwave engineering, terahertz wave technology, and optical communications. He has been a member of the IEEE Antenna and Propagation Society (AP-S) and the IEEE Microwave Theory and Technique Society (MTT-S). He has had involvement in the IEEE Joint Chapter MTT/AP Indonesia Section as a Secretary and a Treasurer in 2017, 2018, and 2019, and various chapter activities, such as the First Indonesia–Japan Workshop on Antennas and Wireless Technology (IJAWT) as a Secretary and the 2019 IEEE International Conference on Antenna Measurements Applications (CAMA), Bali, in October 2019, as a Treasurer.