Design and Implementation of Visible Light Communication System Using Pulse Width Modulation

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***Abstract*—Visible Light Communication (VLC) is a relatively new technology which could potentially be complementary to the existing radio frequency communication system. VLC allows lamp or other kinds of light source not only used as illumination, but also as a data transmission at the same time. Single carrier modulation technique is suitable to be applied on VLC that does not require high-speed data transfer. In this paper, we proposed a visible light communication scheme using pulse width modulation (PWM) technique in transmitting data for running text application. To evaluate the PWM accuracy, experiments were conducted based on different parameters such as PWM frequency, transmitter-receiver distance, and the receiver's angle of view. Furthermore, we also measured the point-to-point communication system performance which resulted in 920 bps data transfer rate and 10^{-4} bit error rate (BER) without affecting the lighting function.**

Keywords*—*visible light communication, pulse width modulation, single carrier modulation, bit error rate.

I. INTRODUCTION

Visible Light Communication (VLC) is one of new technologies that attracts many researchers and scientists around the world. The advanced development of LED technology enables LED to be switched at high-speed and used not only for illumination, but also for wireless communication [1]. LEDs have several advantages over fluorescent and incandescent lamp, such as more efficient, better durability, lower price, smaller sizer, cooler operation, and more eco-friendly [2] [3]. VLC utilizes visible light which has spectral wavelength between 390 to 780 nm. Since visible light is totally harmless to humans and the environment, the use of visible light is considered as a step forward to create the concept of "Green Communication".

The transmission using LED can be performed by using Intensity Modulation (IM), while the reception is done by using Direct Detection (DD) method. In general, based on the modulation technique, there are two trends of modulation technique widely used in various studies, which are single-carrier and multi-carrier modulation [4]. Several examples of single carrier modulation techniques commonly applied to VLC are On-Off Keying (OOK) [5] and Pulse Position Modulation (PPM) [6]. Eunbyeol et al. employed OOK modulation technique to get 10 kbps data transfer rate [7]. Multi-carrier modulation technique based on Orthogonal Frequency Division Multiplexing (OFDM) was reported to be able to provide communication with data transfer rate up to 100 Mbps [8].

Despite the superiority in terms of data transfer speed, OFDM has a downside of high Peak to Average Power Ratio (PAPR). The nature of high PAPR in OFDM will cause a dimming effect on LED which disrupts the lighting system. In addition, the hardware implementation of OFDM is very complex and expensive. Thus, it is too wasteful resources when OFDM is used for low data rate application (e.g. running text or streaming characters). Even with OOK modulation, beside it has low data transfer rate, OOK modulation scheme is also vulnerable to the effects of dimming and even blinking on the LED for on-off conditions. In OOK, the on-off duration ratio is very dependent on the data to be transmitted.

Some VLC potential applications do not require high-speed data transfer such as running text or digital signage and shopping assistant via text delivery [9]. In this paper, we propose an alternative single-carrier modulation technique, which is called pulse width modulation (PWM). PWM technique is implemented using a microcontroller to send data in the form of text. The purpose of this research is to design and implement a PWM scheme to provide efficiently and accurately low-speed data transfer for running text application without disturbing the illumination system.

The steps undertaken in this study starts from the design of the analog front end (AFE) for the transmitter and receiver. The AFE on the transmitter side consists of high power white phosporus LEDs and LED driver. While the AFE at the receiver side comprises a photodiode (PD) and signal conditioning circuit. The PWM modulator/demodulator, synchronizer, data framing and data flow control software are designed and implemented on the microcontroller.

The remainder of this paper is organized as follows. Section II describes pulse width modulation (PWM) technique. Section III presents the detail of proposed system design. The test results and performance analysis are provided in Section IV. Finally, the conclusions are drawn in Section V.

II. PULSE WIDTH MODULATION

Pulse Width Modulation (PWM) is a type of pulse time modulations that allows digitally modulated analog data. Thus, by using PWM technique is also possible to obtain more bits/symbol compared to the OOK modulation.

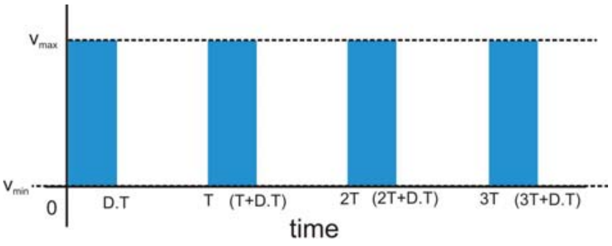


Fig. 1. PWM waveform

PWM uses rectangular wave pulse and varies the pulse width for data modulating both analog and digital. If we have a rectangular pulse wave voltage $V(t)$ with period T, where V_{min} is the minimum amplitude, V_{max} is the maximum amplitude, and duty cycle D (where $0 < D < 1$) as shown in Figure 1, the average value of the pulse wave is

$$\bar{V} = \frac{1}{T}\int_0^T V(t)dt \tag{1}$$

where $V(t)$ is a digital pulse which has a maximum value V_{max} when $0 < t < D \cdot T$ and the minimum value V_{min} when $D \cdot T < t < T$. The Equation (1) then becomes as follows

$$\begin{aligned}\bar{V} &= \frac{1}{T}\left(\int_0^{D\cdot T} V_{max}dt + \int_{D\cdot T}^{T} V_{min}dt\right) \\ &= \frac{D\cdot T\cdot V_{max} + T(1-D)V_{min}}{T} \\ &= D\cdot V_{max} + (1-D)V_{min}\end{aligned} \tag{2}$$

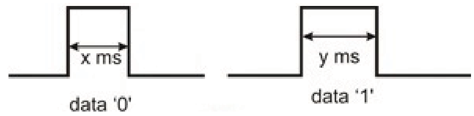
Since this VLC uses Intensity Modulation (IM) and Direct Detection mechanisms, the LED power can be calculated by

$$P_{LED} = V_{LED} \cdot I_{LED} \tag{3}$$

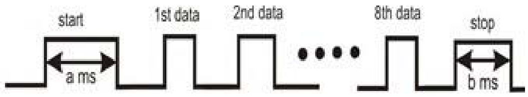
where V_{LED} is the LED voltage and I_{LED} is the LED current. And as we know, the LED intensity will be heavily influenced by the LED power (Intensity $\approx$ Power). In other words, the output voltage V will greatly affect the intensity of the LEDs. The higher the value of V, the higher the intensity of the LED (the light) and vice versa. Based on (2), the value of V is very dependent on D (duty cycle). When PWM is used to modulate the 1-bit digital data, distinguishing '0' and '1' can be performed by varying the value of D. Therefore, when the PWM is used in VLC, the value of D should be chosen wide enough to make the noise margin high but narrow enough, hence it does not cause a dimming effects on the lighting functions.

One bit data modulation scheme using PWM technique in this experiment is illustrated in Figure 2a. Bit '0' has a pulse width x ms and bit '1' has pulse width y ms. In this experiment, we also tested the multibit PWM namely 2 bits and 3 bits. In 2-bit PWM, there are 4 different pulse widths to represent bits "00", "01", "10", and "11". Likewise for 3-bit PWM modulation, there are 8 different pulse widths.

The output data at the transmitter will have a data format as illustrated in Figure 2b. Each one packet of data consists of 8 bits of data and each packet begins with the start bit of a ms pulse width as headers, and stop bits of b ms pulse width. The Start bit and stop bit are used to synchronize the data at the receiver.



(a) 1 bit PWM modulation

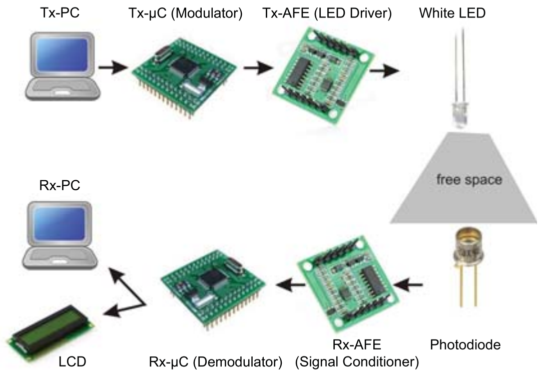


(b) Transmitted data format

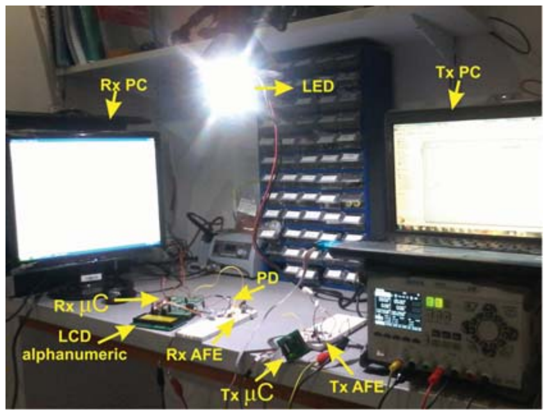
Fig. 2. PWM modulation scheme

III. System Design

The overall block diagram of proposed system design is shown in Figure 3. The communication system is designed to support point-to-point in one direction. Tx-PC is used to transmit data stream in the form of text in ASCII format. The data stream is then sent to Tx microcontroller (Tx-μC). The communication between Tx-PC and Tx-μC is performed using a USB to UART converter. Tx-μC will modulate the data received from the Tx-PC and perform data framing. The modulated data will be fed to the analog front end transmitter



(a) Illustration



(b) Implementation

Fig. 3. Proposed system design

circuit (Tx-AFE) which consists of LED driver. The LED driver circuit will switch on and off the LED based on the modulated data so that the data will propagate through free space (optical channel).

The data will be received by the photodiode in the receiver. The information contained in the light is converted into electricity. The output signal from the photodiode has suffered from both attenuation and distortion caused by the channel as well as the influence of photodiode optical nonlinearities characteristic. The analog front end receiver circuit (Rx-AFE) will condition the received signal so that Rx microcontroller (Rx-μC) can demodulate the data correctly. The data stream is then displayed on the LCD as a running text and also sent to the Rx-PC for analysis.

A. Hardware Design

The hardware part in the proposed system design is the analog front end (AFE) at both transmitter and receiver. At the transmitter, Tx-AFE comprises LED driver, while at the reciver Rx-AFE consists of trans impedance amplifier (TIA) and comparator serving as signal conditioner. The technical specifications of the white LED and photodiode used in our experiment are shown in Table I.

TABLE I. TECHNICAL SPECIFICATIONS OF LED AND PHOTODIODE

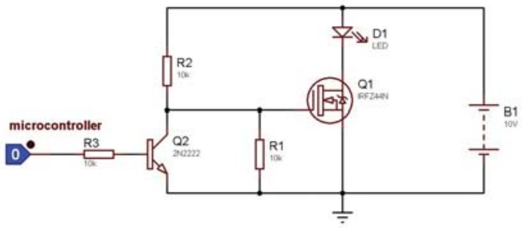
Component	Specification
LED	Voltage rating: 8-12 V Power: 5 W View angle: 120 o Luminuous intensity: 180-300 lx Wavelength: 380-760 nm
Photodiode	Spectral response: 400-1000 nm Rise/fall time: 50 μs Cutoff frequency: 100 kHz

At the transmitter side, the LED driver is used to control the LEDs for on off switching by a microcontroller. The LED driver circuit used in this experiment is shown in Figure 4a. Transistor Q2 is used to amplify the voltage as the output of the microcontroller only 3.3 V while the LED voltage rating of at least 8 V, whereas transistor Q1 is used to amplify the current.

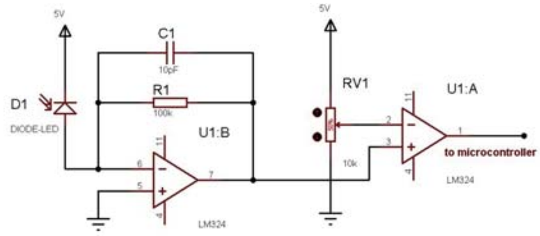
The analog circuit at the receiver side is used to condition the output signal from the photodiode since the output signal of the photodiode will experience attenuation and distortion. For the output of the photodiode is electrical current, TIA is necessary to convert the current into a voltage. Current to voltage converter is made by the op-amp U1:B as shown in Figure 4b. Once converted into a voltage, this signal is fed to the comparator to overcome the distortion in the signal. Potentiometer RV1 can be tuned manually to set the comparator threshold. The output of the comparator is then connected to the Rx-μC.

B. Software Design

The software part is designed for PC (as GUI) and microcontroller. The software designed for Tx-PC serves as an interface with the user so that the user can enter the data in form of text paragraph up to 1000 characters. In addition, it also serves as a data flow controller so that the data stream to be transmitted does not accumulate on the microcontroller.



(a) LED driver on the transmitter



(b) TIA and comparator on the receiver

Fig. 4. Analog front end schematic

The software designed on Tx-μC consists of data buffer (from Tx-PC), data covertion from ASCII into the bit stream, data framing for synchronization, and data modulation. The modulated data is then connected to the LED driver. The Flowchart on Tx-μC software design is depicted in Figure 5.

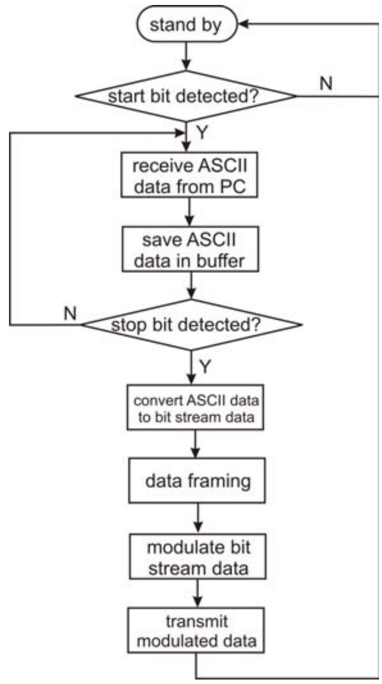


Fig. 5. Flowchart of software on Tx-μC

The flowchart for receiving data on the microcontroller is shown in Figure 6. The data packet is received when the header (start bit) has been detected and data reception process is terminated when the stop bit is detected. The data packet is then demodulated and converted into ASCII characters and displayed on the LCD for running text application. For data analysis purpose, the converted data is also sent to Rx-PC.

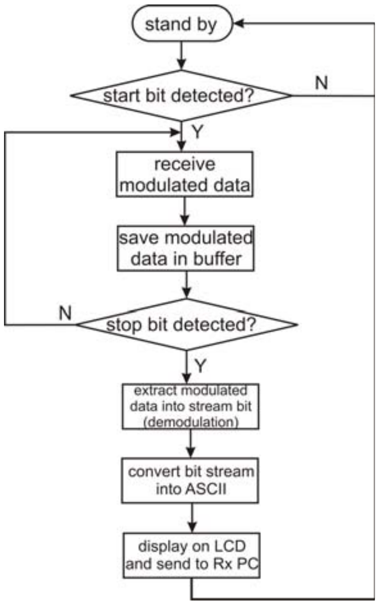


Fig. 6. Flowchart of software on Rx-μC

IV. Test and Analysis

Several tests are performed in this experiment. The first test is functional test of AFE. To ensure that AFE works properly, we observe the pulse shape at the Tx-AFE and Rx-AFE. This test is important to examine whether the signal from the transmitter can be received by receiver so that the following process is feasible to be performed. Other testing parameters such as PWM frequency, distance of LED-photodiode, and the angle of receivers position is varied to determine the effect to the modulation accuracy. Bit error rate (BER) is calculated to measure the performance quality of data streaming test.

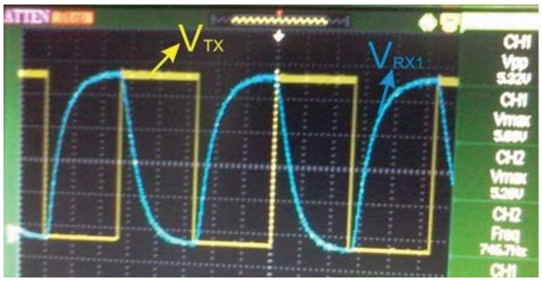
A. Hardware Test

The AFE is tested by passing rectangular pulses with a frequency of about 750 Hz at the transmitter and observing the shape of the pulse at the transmitter and receiver. Figure 7 shows the shape of the waveform in the transmitter and receiver.

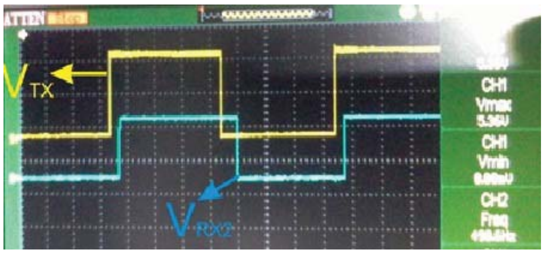
Figure 7a shows the pulses at the transmitter (yellow) and the output of the TIA (blue). The TIA circuit is able to amplify the signal to be 5 V (PP) but the signal becomes distorted resembling shark fin shape. This distorted signal can be corrected by the comparator into a rectangular pulse with the compensation on delay effect between the transmitted and received pulses, as shown in Figure 7b. However, the delay size is only 100-500 μs hence can be accepted or ignored.

B. The Effect of PWM Frequency

This test aims to determine how fast modulation can be obtained with a high degree of accuracy. The level of accuracy meant here is a measure of how well the receiver is able to distinguish the data '0' and '1' when using a 1-bit PWM, and '00', '01', '10', and '11' when using 2-bit PWM, and eight different pulse level widths when using a 3-bit PWM as well.



(a) The pulse at the transmitter (yellow) and distorted pulse at the receiver (blue)



(b) The pulse at the transmitter (yellow) and corrected pulse at the receiver (blue)

Fig. 7. The waveform shape at the transmitter and receiver

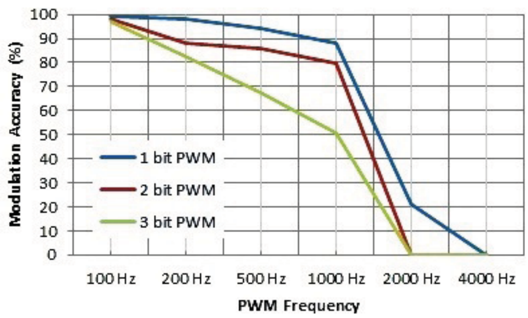


Fig. 8. The effect of PWM frequency to the PWM accuracy

The test results on the effect of frequency to the modulation accuracy is shown in Figure 8. The PWM frequency is varied ranging from 100 Hz to 4 kHz for 1-bit, 2-bit, and 3-bit PWM. From Figure 8, it can be concluded that the higher frequency modulation used and the more bits PWM used, it will degrade the PWM accuracy. For 1-bit and 2-bit PWM, the system still works fine (the accuracy is more than 50%) when using 1 kHz frequency. Nevertheless, for a 3-bit PWM, the frequency is only 500 Hz to obtain an accuracy above 50%.

C. The Effect of Distance

Obviously, as one kind of wireless communication, VLC must also be able to provide data communication with high mobility to the user. One of the parameters that determines the mobility is the distance variable between the LED and a photodiode. Figure 9 shows the PWM modulation accuracy measurement affected by the distance variable.

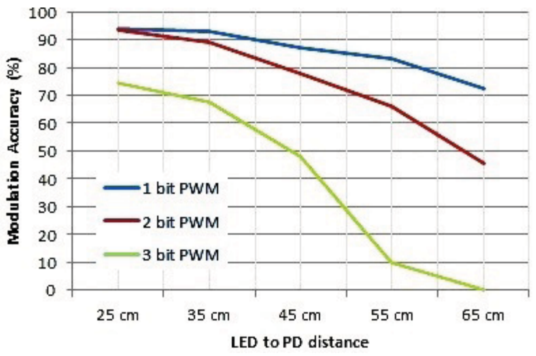


Fig. 9. The effect of LED-PD distance to the PWM accuracy

In general, we can conclude that the longer the distance between LED and PD, the modulation accuracy gets worse. This is due to the fact that longer distance will make PD receive diminishing light intensity. Thus, the obtained pulse width is changed which reduces the level of modulation accuracy. The three types of modulation still work fine within 25-45 cm rage. Moreover, 1-bit PWM is still able to reach 70% level of accuracy within 65 cm distance.

D. The Effect of Receiver's Angle of View

Another parameter to support high mobility is the varying angle (position) of the light reception. In the two previous tests, the position of the LED and PD are in a straight line LOS with $0°$ angle. In current case, the angle of photodetector reception is changed from $0°$ to $45°$. The test results are depicted in Figure 10.

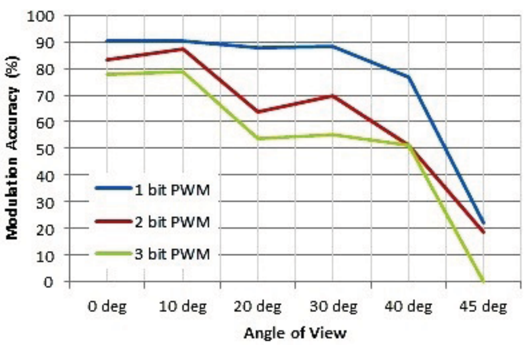
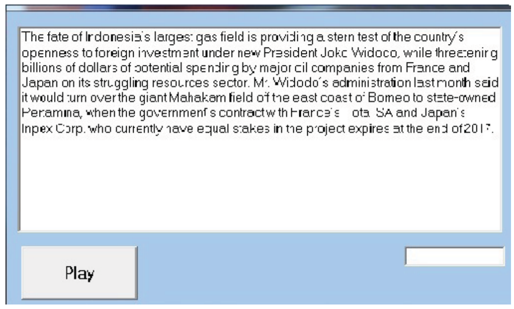


Fig. 10. The effect of receiver's angle of view to the PWM accuracy

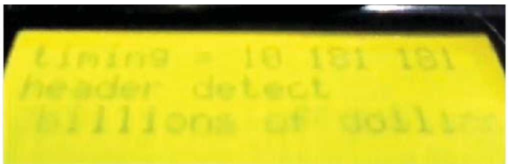
From the test results shown in Figure 10, the rising in the reception angle does not always lead to a decrease in accuracy. This is due to the fact that the multipath effect is not only influenced by this configuration (compared to LOS configuration), but also the environmental conditions. However, in general, increasing the angle of view will worsen the modulation accuracy.

E. Measurement of BER Performance

Based on Subsection IV-B, IV-C, and IV-D, the obtained parameter settings with a high degree of accuracy is 1 kHz PWM frequency for 1-bit and 2-bit PWM, and 500 Hz for 3-bit PWM at a distance of about 40 cm and the reception angle of $0°$. In this performance test, the data stream comprising 1000 characters sent from the transmitter to the receiver. The data received in the receiver is then displayed on the LCD alphanumeric as running text and also transmitted to Rx-PC for BER calculation. Figure 11a shows the graphical user interface (GUI) used in the Tx-PC, while Figure 11b shows the running text displayed on the LCD alphanumeric.



(a) GUI on Tx PC



(b) Running text display on the alphanumeric LCD

Fig. 11. Testing the overall communication system

TABLE II. PERFORMANCE OF THE OVERALL COMMUNICATION SYSTEM WITH MULTI-LEVEL BIT PWM FOR DATA STREAMING

Modulation	Data Transfer Rate	BER
1 bit PWM	920 bps	10^{-4}
2 bit PWM	1.5 kbps	5×10^{-2}
3 bit PWM	1.5 kbps	3×10^{-2}

Based on the data in Table II, the highest data transfer speed is achieved by modulating the 2-bit PWM. However, for BER performance, 1-bit PWM modulation is far superior to the others. The BER value of 1 bit PWM is 10^{-4}, or in other words, there is only 1 bit error out of 10,000 transferred bits. 1-bit PWM modulation offers best accuracy (indicated by lowest BER value) since its dynamic range of pulse width is highest among others.

V. CONCLUSION

PWM can be used as an alternative modulation technique for visible light communication, especially for low data rate application. The superiority of PWM tecnique over OOK is that PWM offers less dependent on-off ratio to the transmitted data, a simple synchronization method, and can be applied to multi-level bit modulation enabling higher speed data transfer. The transfers data at speeds up to 920 bps with a very low BER (only 10^{-4}) has been successfully obtained using our proposed inexpensive components and simple system. 1-bit PWM is shown to have the best accuracy (lowest BER) and still reaches 70% level of accuracy within 65 cm distance.

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