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IJIE

Journal homepage: http://penerbit.uthm.edu.my/ojs/index.php/ijie
ISSN : 2229-838X e-ISSN : 2600-7916

The International Journal of Integrated Engineering

Design and Investigation of RGB-type LED Visible Light Communication System

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DOI: https://doi.org/10.30880/ijie.2021.13.02.016
Received 27 May 2020; Accepted 2 December 2020; Available online 28 February 2021

Abstract: This paper examines the feasibility of a Red Green Blue (RGB)-type Light Emitting Diode (LED) Visible Light Communication (VLC) system based on wavelength division multiplexing (WDM). Each color in the RGB-LED is individually modulated to increase the data rate by three times as compared to the single channel modulation approach used in conventional VLC system. Color filters are employed to detect separately the RGB signals at the receiver side. The proposed system utilized a reflector to improve the performance and the system is lens-free. In this work, an approach of approximated WDM testing is adopted due to the incapability of multiplexing by the microcontroller at higher data rate. The proposed system is demonstrated to transmit and receive data at a maximum distance of 1.4m, with total data transmission speed of 345.6 kbps using standard WDM, while a total speed of 1.5 Mbps up to maximum distance of 1.2m and 3 Mbps up to maximum distance of 0.7m is achieved by the approach of approximated WDM testing.

Keywords: Visible Light Communication, RGB-Type Light Emitting Diode, OOK-NRZ, WDM

1. Introduction

Spectral deficiency due to exponential increase in mobile data traffic [1] and limited bandwidth offered by the radio-wave spectrum, electromagnetic interferences, security problems and health problems are some of the issues faced by current wireless technology utilizing radio frequencies [2].

Visible light communication (VLC) provides a solid solution to the problems [3] above especially bandwidth limitation [4]. Much interest in VLC after the invention of LED as fast modulation characteristics is not supported by traditional light sources [5].

However, much problem arises in the process of exploring this new technology. One of the issues is choosing between two types of white Light Emitting Diode (LED). The first type is using Phosphor White LED, which uses blue LED chip and phosphor layer to convert blue light to white light. These LEDs are preferred for low cost-efficient installations because of relatively simple design. Another type is Red, Green and Blue LEDs (RGB-LEDs), which uses the respective colors to produce white light through color mixing. RGB-LEDs provide the possibility of increasing data rate with Wavelength Division Multiplexing (WDM), meaning to use different colors to transmit data through multiplexing techniques [2].

White LED has lower bandwidth which can be improved by employing pre-emphasis techniques [5-8] and blue filtering, where bandwidth is improved from 3 MHz to 325 MHz [8]. Utilization of the visible light spectrum is not efficient as only blue light is received by the receiver.

A high-speed VLC system on the simplest on-off keying-non-return-to-zero (OOK-NRZ) based transmission which makes use of pre-emphasis technique was proposed for the optical transmitter [6]. RGB-type white LED was used, but only one color was modulated with data, thus not employing wavelength division multiplexing.

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A bi-directional transmission system based on commercial RGB-LEDs was proposed and experimentally demonstrated [9]. Color filters were employed to perform wavelength division multiplexing. The proposed full-duplex SCM-WDM VLC system has high complexity in terms of spectrally efficient modulation formats (QAM-OFDM), advanced signal processing, pre- and post-equalizations techniques used. This setup involved the use of lenses and the transmission distance is up to 0.7m.

In another research [10], a CSK-CDMA system is proposed, where two spatially separated LED transmitters are used along with optical filters. It is seen that the system has does not produce white light from the red and green filters, with absence of blue light in the system, and that the LEDs are far apart instead of 2 LEDs in a single package.

A visible light communication system for location information employing optical filters and secondary lenses was proposed [11], where the optical filters allow specific wavelengths and cancelling out interference of unwanted light sources. OOK is used, where Red and Blue acts as downlink while green acts as uplink from for the central device. White light is not produced from the light source, thus not allowing it to be used as normal lighting source.

Simple VLC systems were designed [12-14], where Arduino UNO is used as the microcontroller to process the data input to the transmitter and to process the received data. The data rates are not high due to the use of the digital pins of the microcontroller, which does not have fast data rates.

This project will demonstrate the implementation of a simple VLC system using commercially available Red, Green and Blue single packaged LEDs to transmit data wirelessly, while employing OOK-NRZ and WDM. OOK-NRZ is chosen from the IEEE 802.15.7 [15] due to its high spectral efficiency and low system complexity [16]. Driver circuits were designed accordingly. For the receiver, color filter is added to distinguish the different color. Other than that, trans-impedance amplifier (TIA) and comparator circuit is designed to convert the current back to voltage and improve the detected signal. Arduino Mega microcontroller is used on both side of the system to transmit data and convert the signal back to character format through the serial port pins which has much higher data rates compared to the digital or analog pins.

This study is limited to indoor testing, where surrounding light is turned off with assumptions that the system will replace all fluorescent lights in an indoor environment, providing illuminance and data transmission. The range of communication from the transmitter to the receiver only starts at 0.5m instead of 0.1m where assumptions were made where transmission distance of less than 0.5m is not practical. Even though the microcontroller used has 3 serial ports which can be readily used to supply 3 different data to each color channel, the asynchronous function of write operation is still sequential to a certain extent, where at baud rate of higher than 115.2 kbps, the delay between the data packets sent at different color channel becomes too great until there is no overlapping of data packet between the color channels, not utilizing the ability of wavelength division multiplexing, leading to the use of approximated WDM testing.

2. Design Methodology

The block diagram of the overall system for the RGB-type white LED system is as shown in Fig. 1. Input data from the user will be converted into binary data, which is called carrier-less OOK-NRZ data. This data will then be fed into a MOSFET driver circuit to drive the LEDs at its rated power. The data is separated into three parts before being transmitted, using Arduino IDE software with Arduino Mega. The colour filter distinguishes the different data based on the colour and the separated data is combined and printed on the Serial Monitor.

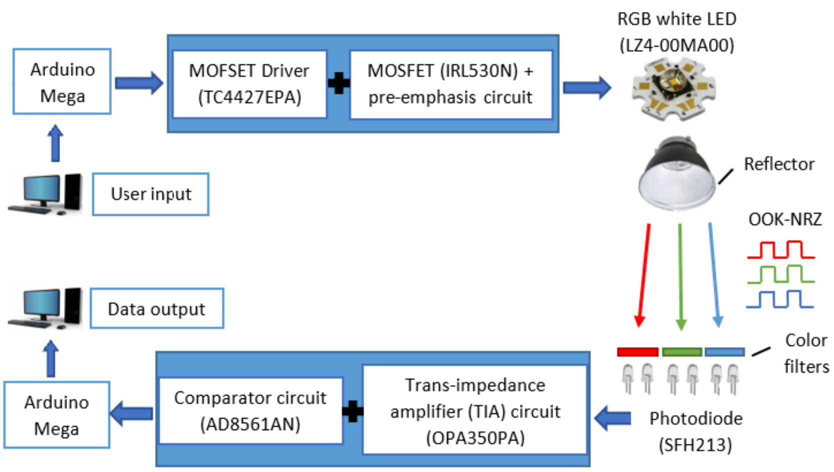


Fig. 1 - Overall system

2.1 Transmitter

Fig. 2 shows the transmitter circuit design. TC4427EPA acts as a link between the serial port of the Arduino MEGA because if the serial port is connected directly to the gate of the power MOSFET, the frequency response of the system will become poor. The MOSFET driver is also capable of providing maximum gate current of 1.5A at supply voltage of 18V. The output resistance is as low as 9Ω, where a lower value of output resistance is better for higher frequency response.

The power MOSFET chosen is IRL530N where it can achieve a maximum drain current of 17A. The gate voltage provided by the MOSFET driver allows this MOSFET to operate at saturation region, which is the ideal condition for OOK-NRZ signal.

The LED chosen is LZ4-20MA00, where it has individually addressable red, green, blue and amber die, though only red, green and blue will be used. It is a high-power LED with luminous flux of 85lm, 120lm and 30lm for red, green and blue respectively according to the data sheet. The drive current for each different color is adjusted accordingly to uniformize the signal to noise ratio of all the three color channels with best effort. Heatsinks are used to reduce effects of rising temperature on the color spectrum of the LED [17-18].

Pre-emphasis is also introduced in the transmitter circuit by a simple RC circuit in parallel with the load resistors showing that it can improve frequency responses [6]. A by-pass capacitor of value 47µF is used to absorb voltage transients of the supply, thus increasing integrity of the incoming voltage to the electronic components.

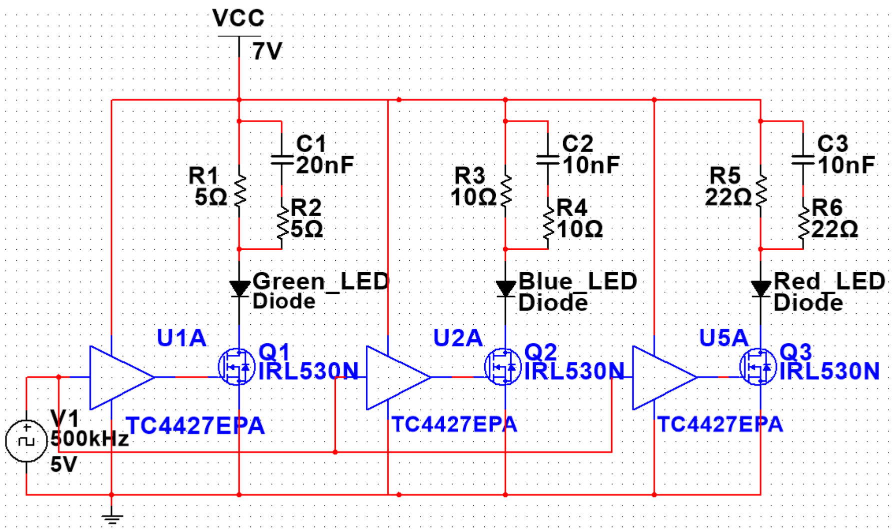


Fig. 2 - Transmitter circuit

2.2 Receiver

Fig. 3 shows the TIA and comparator circuit for the receiver. For the photodiode, the received signal is always in current. As such, trans-impedance amplifier circuit will be needed to convert the current to voltage. OPA350PA type Op-amp is used for the circuit. Other than that, the circuit consist of 510kΩ resistor. The large feedback resistor is used to allow the receiver to draw enough photocurrent for longer distance communication.

The comparator circuit consist of a 2kΩ potentiometer that is connected to the inverting input of the comparator. The main reason of using this setup is because as the transmission distance increase, the voltage of the input signal dropped significantly. The reference voltage can be adjusted using the potentiometer to reshape the signal into a near perfect square wave. A 10nF capacitor is added next to the potentiometer to smoothen the current.

SFH213 PIN type photodiode is chosen for the system as PIN is preferred application in VLC [19]. PIN photodiode is designed to overcome the deficiencies of the PN photodiode by providing a large depletion region for the absorption of the photon by lowering capacitance to create higher speed system [20].

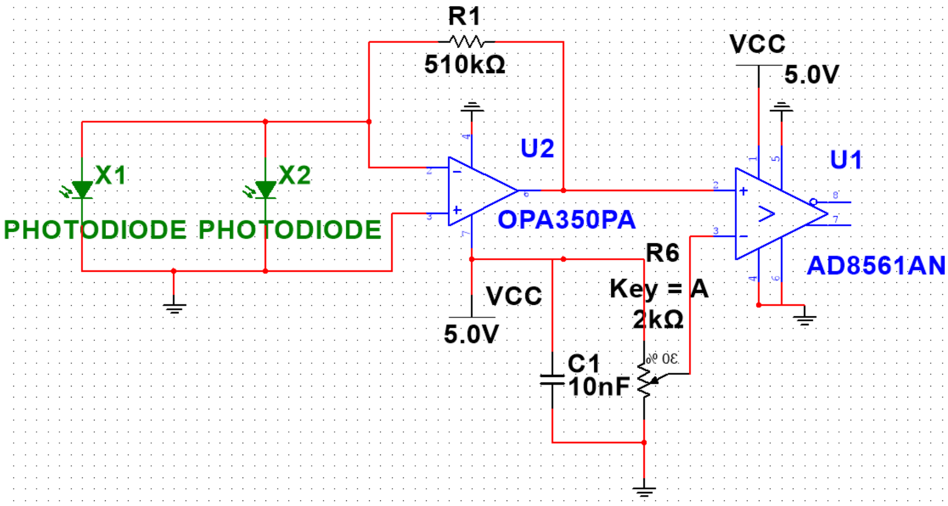


Fig. 3 - The TIA and comparator circuit for one color channel

2.3 Data Collection

- The intensity of each individual color of the RGB LED is adjusted by adjusting the load resistance of each individual color channel to give uniform voltage level received by the receiver.
- The output waveforms were observed and the FFT function of the DSO (TDS1002B) is used to measure the SNR of the signal received by the receiver after the TIA for each individual channel using formula number 1 below [21], where FFT is equal to 2048 according to the TDS1002B manual sheet. Only one channel is supplied with square waves while the other two channels were supplied with constant current to maintain white light illumination.

$$SNR = Signal - Floor - 10\log(FFT) \quad (1)$$

- The efficiency of each individual color filter is recorded by measuring the intensity of light received by the receiver when the desired color light is turned on and when the undesired color light is turned on, where efficiency is the ratio of the intensity of the reflected output light to the intensity of the input light at a wavelength [22].
- The effect of using the reflective cup is evaluated by comparing the SNR of each individual color channel before and after use of reflective cup.
- The Bit Error Ratio (BER) of the system is estimated by sending multiple characters in a single line, where each character represents a series of binary data. Each character sent is compared with the actual character sent, and the ratio of number of errors and total characters sent is calculated to estimate the BER of the system under different conditions. This estimation is considering the worst-case scenario where when one character is wrong, all the 8 bits in one packet representing one character is considered wrong. The reason for using this estimation is due to limitations in terms of hardware of controlling each individual bit in serial communication of the microcontroller.
- The working distance of the system is determined by finding distances where the BER of the system is zero.

2.4 Testing

The input reference voltage of the comparator is adjusted accordingly at best effort where the approximate reference voltage is adjusted by observing 50% duty cycle from the output from the comparator, then fine-tuned again by running a few rounds of BER testing to obtain the best reference voltage and this reference voltage is recorded.

The group conducted continuous transmission of data up to around 10,000 characters sent as a total number of samples to estimate the BER for each channel, and 30 thousand characters for overall system.

The BER of each channel is estimated by supplying the investigated color channel with data from the microcontroller, while the other color channels supplied with square wave at the respective frequencies investigated, which is half the operating baud rate of the data from the microcontroller. This method is used at higher frequency testing due to limitations of the microcontroller. This method is closest model for demonstrating WDM for current situation. This method is hereafter referred as approximated WDM testing.

The BER of the whole system is estimated by supplying all three channels with data at baud rate of 115.2 kbps from the microcontroller as the microcontroller can support asynchronous serial writing functions only up to data rate of 115.2 kbps.

3. Results and Discussions

Different tests were done to achieve the study's objectives. Testing of the LED lights, filters and reflectors were done and presented. TABLE I. shows the efficiency of each color filter used, where efficiency is ratio of the color of interest to the total input light. Total input light is the sum of intensity of color of interest and unwanted color. It is shown that the red filter has the highest efficiency while green has the lowest efficiency. The difference in these efficiencies is mainly due to the imperfect color spectrum matching of the respective LEDs and the off-the-shelf color filters used. A more specific color filters could be used to improve the efficiency.

However, in this experiment, the performance of the least efficient color filter is sufficient for the system as it is tested that the comparator is able to differentiate between the targeted signal and the unwanted signals from other channels. The square waveform observed on the oscilloscope under two different situations, with unwanted signal turned on and with unwanted signal turned off are found out to be similar with duty cycle very close to 50%.

Table 1 - Efficiency of color filters used

Color Filter	Efficiency		
	Color of Interest (*V*)	**Unwanted Color (*V*)**	**Efficiency**
Red	1.13	0.23	0.83
Green	0.75	0.33	0.69
Blue	0.78	0.24	0.76

The signal to noise ratio testing is performed under the condition where only one channel is supplied with data, while other channels are supplied with constant current. The frequencies of 125 kHz, 250 kHz and 500 kHz are chosen as the standard common operating baud rates of the microcontroller is 115.2 kbps, 230.4 kbps, 250 kbps and 500 kbps. 230.4 kbps testing is omitted as it is relatively close to 250 kbps. Therefore, the signal to noise ratio testing will be at frequencies of 57.6 kHz, 125 kHz, 250 kHz and 500 kHz because OOK-NRZ baud rate value is twice the signal frequency.

The improvement provided by the reflector designed is evaluated as shown in Fig. 4. It is estimated that the improvement introduced by the reflector is around 7 dB for red channel and 5 dB for both green and blue channel. The minimum operating distance is also shifted from 0.3m to 0.5m, while increasing the maximum operating distance. Similar effect of improvement was observed for the frequencies of 57.6 kHz, 125 kHz and 500 kHz. Optically, the use of reflector allowed more light energy of all spectrums to be concentrated and delivered onto a focused region at the receiver side for a better signal to noise ratio performance.

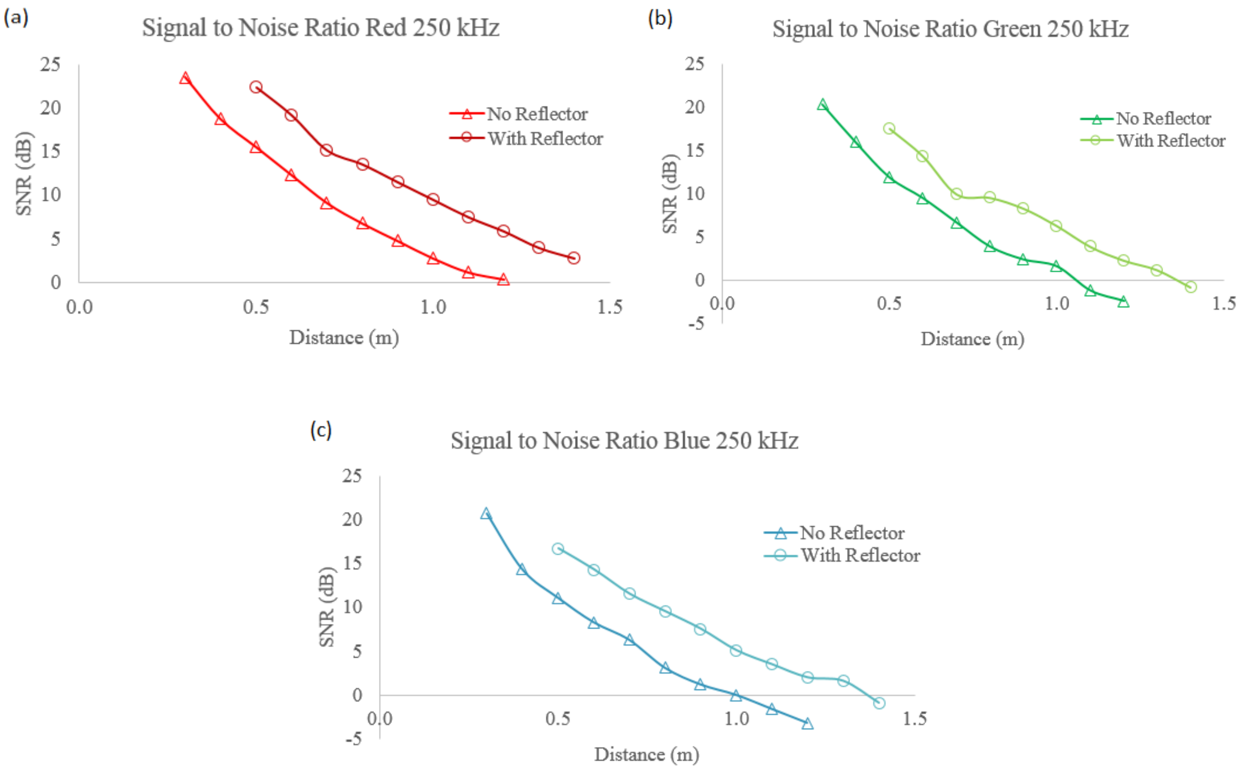


Fig. 4 - Improvement in SNR after using reflector for three different channels: (a) red; (b) green; (c) blue

The SNR of the system at different frequencies is presented as shown below in Fig. 5. The channel to be investigated is supplied with data while other channels are supplied with constant current. Similar results were obtained for 54.6 kHz as with 125 kHz.

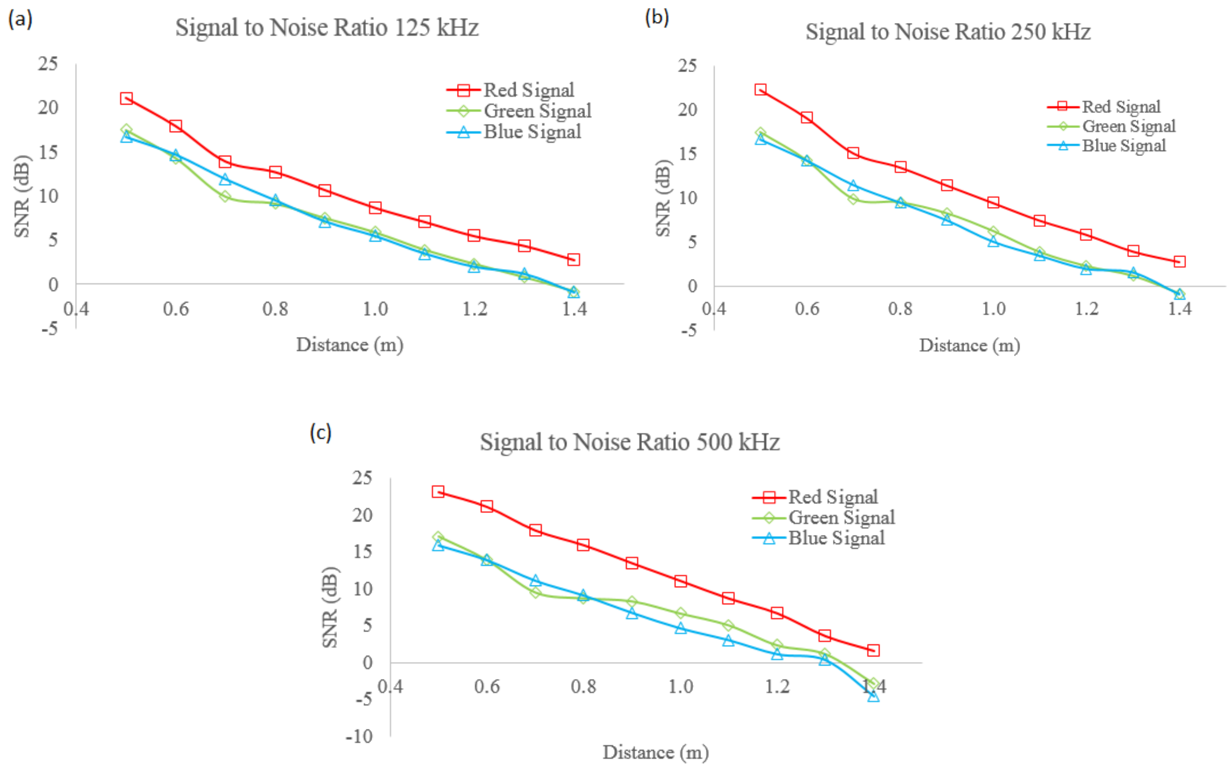


Fig. 5 - SNR of the system at (a) 100kHz; (b) 250kHz; (c) 500kHz

The calibrations of the load resistances of each color channel has been done, resulting in almost equal SNR at the receiver for green and blue channels. However, due to extra high sensitivity of the photodiode to red color spectrum, the SNR for red channel will always be higher as compared to green and blue channel. It is also observed that at higher frequencies, the SNR becomes less uniform and tends to fluctuate as seen from Fig. 5 (b) and Fig. 5 (c). This is because the system is unstable at higher frequencies as PCB board and circuit designs does not take into consideration for much higher frequency operations. It is also estimated that the maximum operating distance of the system should be around 1.4m as the signal to noise ratio values start to drop to negative values for green and blue channels. Therefore, the bit error ratio testing will extend to 1.5m.

The comparator reference voltage recorded is as shown below in Fig. 6. At lower frequency, the comparator reference voltage is easier to set while at higher frequencies, the reference voltage becomes harder to predict. Similar results were obtained for baud rate testing of 115.2 kbps and 250 kbps as compared with results for 500 kbps.

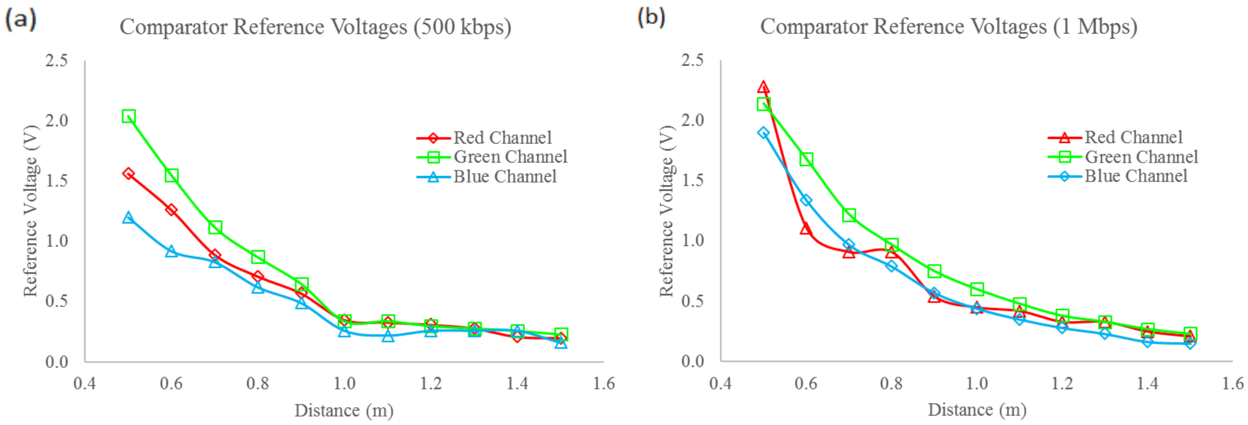
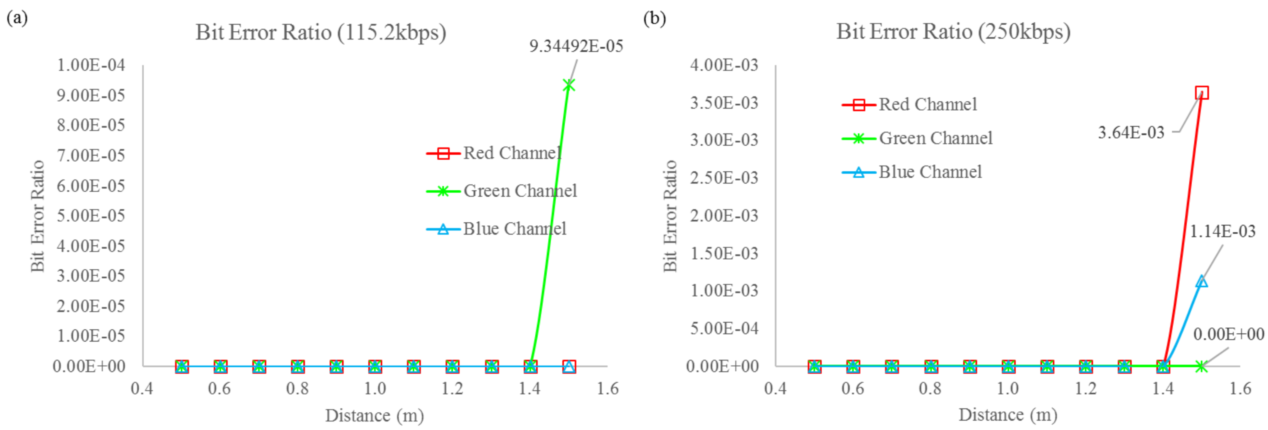


Fig. 6 - Comparator reference voltage obtained for (a) 500 kbps; (b) 1 Mbps

Finally, the BER of each channel is as shown in Fig. 7 for approximated WDM testing. Data rates of 115.2 kbps, 250 kbps, 500 kbps and 1 Mbps are tested as these data rates are the standard common operating baud rates of the microcontroller.



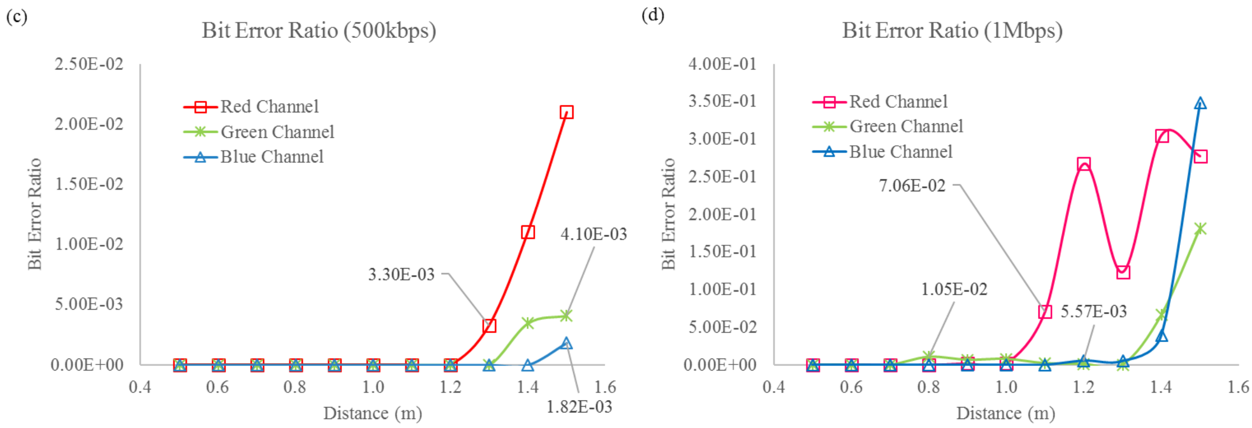


Fig. 7 - BER of the system at (a) 115.2 kbps; (b) 250 kbps; (c) 500 kbps; (d) 1 Mbps

At transmission data rate of 115.2 kbps and 250 kbps, the BER of the system is zero at transmission distance of between 0.5m to 1.4m. At 1.5m, at data rate of 115.2 kbps, green channel has BER of 9.34×10^{-5} while BERs for other channels are zero as shown in Fig. 7 (a). At transmission data rate of 250 kbps and 1.5m, the BER is 3.6×10^{-3} for red channel and 1.1×10^{-3} for blue channel, while green channel has BER of zero as shown in Fig. 7 (b).

However, for transmission data rate of 500 kbps, the BER of the system is zero at transmission distance of between 0.5m to 1.2m. At 1.3m, the BER is 3.3×10^{-3} for red channel, while BERs for other channels are zero as shown in Fig. 7 (c).

Finally, for transmission data rate of 1 Mbps, at 0.7m, the BER for all 3 channels are zero, but at 0.8m, green channel had BER of 10.5×10^{-3}, while the BER of the other color channels are zero. It is also observed that at high frequency, the BER of the system becomes highly unpredictable as shown in Fig. 7 (d).

Therefore, the working distance can be evaluated to be from 0.5m to 1.4m for data rates below 250 kbps per channel (Total: 345.6 kbps and 750 kbps), 0.5m to 1.2m for data rate of 500 kbps per channel (Total: 1.5 Mbps) and 0.5m to 0.7m for data rate of 1 Mbps per channel (Total: 3 Mbps). It is important to note that the testing done is under approximated WDM testing, and this method is used due to limitations of the microcontroller.

Fig. 8 shows the performance evaluation of the whole system with combination of all three channels. Due to the limit of the maximum data rate supported by the microcontroller for asynchronous serial writing functions, all three channels are supplied with data at baud rate of 115.2 kbps individually from the microcontroller. The combination provides a total baud rate of 345.6 kbps for the system.

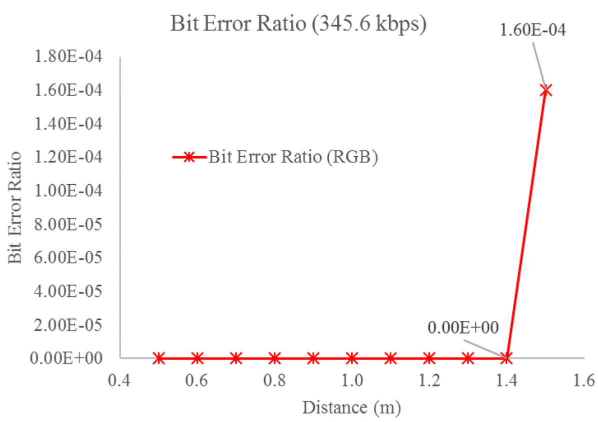


Fig. 8 - Overall BER of the system at 345.6 kbps (115.2 kbps per channel)

At the transmission rate of 345.6 kbps, the BER of the system is zero at transmission distance of between 0.5m to 1.4m, while small BER of 1.6×10-4 is recorded at 1.5m. This testing of the system is working under WDM situations and has working distance from 0.5m to 1.4m. The non-zero BER at 1.5m using actual WDM in Fig. 8 is consistent with that of the case of approximated WDM testing for the per channel data rate of 115.2 kbps as shown in Fig. 7 (a), where green channel is the source of the overall error present in Fig. 8 at 1.5m. These results show the feasibility of an RGB-type LED VLC system based on wavelength division multiplexing.

4. Conclusion

The RGB VLC system has been experimentally implemented by employing wavelength division multiplexing using commercially available high brightness LED at total data rate of 345.6 kbps (115.2 kbps per channel) with maximum distance of 1.4m. A total data rate of 1.5 Mbps (500 kbps per channel) with maximum distance of 1.2m and 3 Mbps (1 Mbps per channel) with maximum distance of 0.7m is achieved using the approximated WDM testing approach.

Acknowledgement

This work was supported by the Final Year Research Project Funding from Swinburne University of Technology Sarawak.

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