



A Cost-Efficient RGB Laser-Based Visible Light Communication System by Incorporating Hybrid Wavelength and Polarization Division Multiplexing Schemes

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Visible light communication (VLC) has been proven a promising technology to counter the limitations of radio frequency (RF) communication technology such as high interference and high latency issues. VLC offers high bandwidth as well as immunity to interference from other electromagnetic spectrums. Due to these features, VLC can be an excellent solution for biomedical and healthcare applications for transmission of body sensor signals and other crucial patient information. In this work, a highly efficient VLC system is designed to transmit six channels, with each one carrying 10 Gbps of data, over a 500 m optical fiber link and a 200 cm VLC link. To make the VLC system cost effective, simple and efficient on-off keying (OOK) (non-return to zero) is used as the encoding scheme. Moreover, to further enhance the capacity and bandwidth of the proposed VLC system, hybrid wavelength division multiplexing (WDM) and polarization division multiplexing (PDM) schemes are incorporated by using red, green, and blue lasers. The reported results show the successful transmission of all channels (6×10 Gbps) over 500 m optical fiber and 200 cm of VLC link.

Keywords: visible light communication, wavelength-division multiplexing (WDM), polarization division multiplexing (PDM), on off keying, biomedical application

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INTRODUCTION

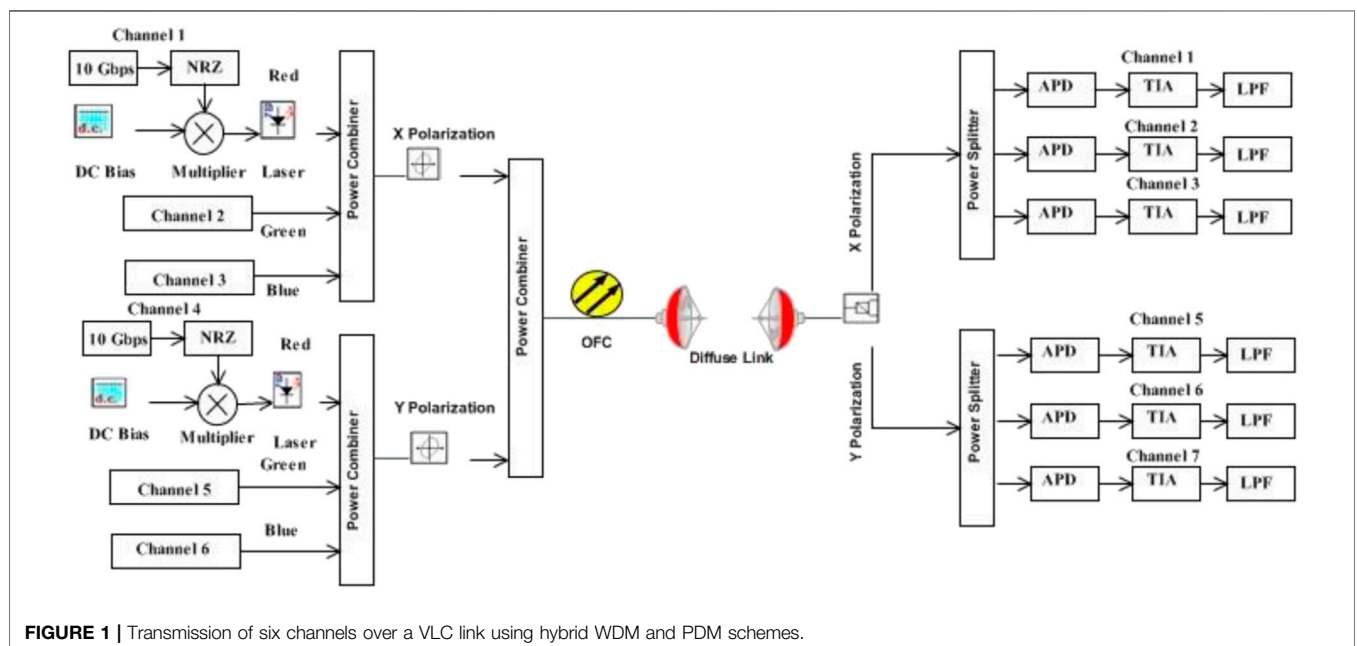
Incessant demand of higher data rates and multifold user support in existing networks has forced researchers to look beyond radio frequencies (RF), which are bandwidth-limited, toward optical wireless systems (OWC) that offer nearly unlimited bandwidth (>400 THz) via mounting an infrared and ultraviolet region of the electromagnetic spectrum [1]. Among different employed OWC systems, the visible light communication (VLC) system stands out as an apt future solution for terrestrial communication due to its ubiquitous influence and as light-emitting diodes (LEDs) are readily engaged in innumerable commercial applications ranging from lighting systems to multimedia display units in offices as well as homes, vehicles, and mobile phones. The VLC system offers innumerable features that consist of energy-efficient operation, higher data rates, zero RF or electromagnetic interference, and a physical layer of data security [2, 3]. Even with so many advantages, LEDs have a limited data rate due to strong internal polarization fields in common c-plane LEDs and hence are not considered suitable for higher speeds (in the gigabit range) [4–6]. Newly developed micro-LEDs offer a higher data rate in the order of 3 Gbps, but due to low illumination levels their use as light sources is not appropriate [7, 8]. On the other hand, laser diodes (LDs) have a high modulation bandwidth and high output power that allow them

to be better candidates for proposing an optimum solution in a high-speed and long-reach VLC system [9]. Hu et al. displayed a VLC link with the link range of 300 m by using a 650-nm laser diode and data rate of 10 Mbps [10]. Another group of researchers reported construction of a WDM-VLC system over a link range of 10 m using red and green lasers with a 500 Mbps data rate [11]. Another work reported using a 450-nm laser diode and QAM-OFDM-based VLC over a range of 5 m for a data rate of 9 Gbps [12]. Wei et al. [13] demonstrated a RGB laser diode-based VLC system over a bidirectional 1 m. Yeh et al. [14] demonstrated a 1,250 Mbps VLC system using a yellow phosphorous LD over a range of 1 m. Advanced modulation formats such as OFDM or QAM used with VLC systems are proved to be better in terms of high data rate but with increased cost and complexity of the system. In order to keep the system at minimal cost, on-off keying (OOK) is proved to be efficient in terms of low complexity and cost effectiveness. In 2016, researchers demonstrated a 2-m VLC link with a data rate of 266 Kbps using OOK [15]. In 2017, Lu et al. reported a GaN-based VLC system employing NRZ-OOK with a 600 Mbps data rate over a transmission range of 0.6 m [16]. For harnessing VLC with indoor white lightning, a new type of red, green, and blue (RGB) LDs are employed. In 2011, researchers reported highly bright white light generated from LDs by mixing red, green blue, and yellow light components [17]. To enhance data rate, researchers have employed various multiplexing techniques namely wavelength division multiplexing (WDM), multiple input multiple output (MIMO), and polarization division multiplexing (PDM). In 2015 [18], Tsonev et al. proposed a 100 Gbps system using an RGB LD-based WDM-VLC system by using 36 parallel data streams. Chi et al. [19] in 2016 proposed and demonstrated an RGB LED-based VLC system with a PS-Manchester and WDM scheme with a data rate of 3.35 Gbps and a 1 m indoor transmission range. Another study in 2017 [20] proposed a WDM-based VLC system over a 1 m span with a data rate of 4.05 Gbps. Recently in 2020 [21], Messa et al.

experimentally demonstrated detection of a WDM-VLC signal via a single photodiode with the use of MIMO signal processing. These studies conclude that implementation of RGB-LD-based WDM-VLC can significantly enhance system performance. For further enhancement of the capacity of the proposed system, another multiplexing technique is proposed such as the PDM technique. In 2015 [22], Kwoon et al. experimentally demonstrated enhancement of data rate up to 2.04 Gbps by employing the PDM scheme in the VLC system. Hsu et al. in 2018 [23] demonstrated an OFDM-PDM based VLC system with a data rate of 1.4 Gbps. Recently in 2020 [24], authors have demonstrated the transmission of 1.2 Gbps and 1.12 Gbps of data over a 3 and 4 m free space link by using dual polarized green and blue LED-based light streams. On the other hand, hybrid multiplexing schemes are used by many researchers to increase the bandwidth and capacity of optical communication systems [25–35]. In this work, the OOK modulation technique is used for realization of a low-cost VLC system. Further to increase the capacity of the system, hybrid WDM and PDM multiplexing schemes are proposed using RGB LDs. The remainder of this paper is described as follows: *Hybrid WDM-PDM-VLC Modeling* shows the modeling of the proposed WDM-PDM VLC system, *Results and Discussion* represents the results and discussion, and *Conclusion* shows the overall conclusion of this work.

HYBRID WAVELENGTH DIVISION MULTIPLEXING-POLARIZATION DIVISION MULTIPLEXING-VISIBLE LIGHT COMMUNICATION MODELING

The schematic diagram of the proposed 6×10 Gbps hybrid WDM-PDM-based VLC system, modelled in OptiSystem software, is shown **Figure 1**.



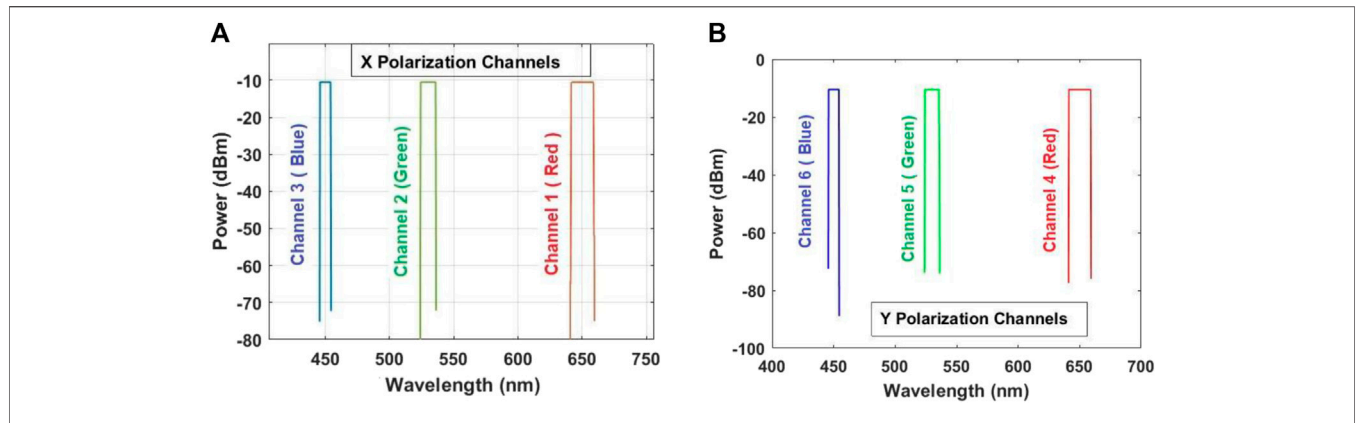


FIGURE 2 | Measured optical spectrum, (A) X polarization channels, (B) Y polarization channels.

TABLE 1 | Modeling parameters for the proposed WDM-PDM-VLC link.

| Component | Parameters | Value |
|-----------------------|------------------------------|----------------------------|
| Laser diode | Wavelengths | 650 nm, 530 nm, and 450 nm |
| | Extension ratio | 10 dB |
| | Power | 0 dB |
| | Linewidth | 10 MHz |
| | DC bias generator | Amplitude |
| Diffuse link | Transmitter half angle | 60 deg |
| | Irradiance half angle | 0 deg |
| | Incidence half angle | 0 deg |
| | Detection surface area | 1 cm ² |
| | Optical concentration factor | 1 deg |
| | Index concentration factor | 1.5 |
| | Propagation delay | 0 ps/m |
| Avalanche photo diode | Gain | 3 |
| | Responsivity | 1A/W |
| | Ionization ration | 0.9 |
| | Dark current | 10 nA |
| | Thermal noise | 100e-024 W/Hz |
| TIA | Voltage gain | 600 Ω |
| | Input capacitance | 3 pF |
| | Feedback resistance | 0.01e+009 |
| Simulation window | Sequence length | 1,024 |
| | Samples per bit | 64 |
| | No. of samples | 65,536 |

As shown in **Figure 1**, six channels are transmitted by using hybrid WDM and PDM schemes. A red laser (650 nm), green laser (530 nm), and blue laser (450 nm) are used for the WDM scheme whereas X polarization with a 0° phase shift in azimuthal and Y polarization with a 90° phase shift in azimuthal are used for the PDM scheme. Each channel generates a pseudo random bit stream of 10 Gbps which is encoded using the NRZ modulation format and then the signal is fed to the directly modulated (DM) laser. To ensure the laser diode (LD) operates above threshold, a direct current (D.C.) bias is fed into it. The output of the first three

channels are combined together and subjected to a 0° azimuthal phase (X polarization) whereas the output of the remaining three channels are combined and fed to the 90° phase shift in azimuthal (Y polarization). **Figure 2** represents the measured optical spectrum of three channels for each state (X and Y polarizations).

These outputs from each polarization state are combined and transmitted over 500 m optical fiber and diffuser. For the modeling of the diffuse link, the transmitter source is assumed as a Lambertian disk which is irradiating a detector surface located at an axial distance h from the source. The Lambertian order which is based on transmitter half angle can be expressed mathematically as follows [36]:

$$m = \frac{-\log 2}{\log [\cos(\text{Transmitter half angle})]} \tag{1}$$

whereas optical concentrator gain can be mathematically expressed as:

$$\text{Gain} = \frac{I^2}{\sin(CR)^2} \tag{2}$$

where I is defined as the internal refractive index of the lens and CR is defined as the field of view.

At the receiver side, a polarization splitter is used to de-multiplex the polarized signal for each state (X and Y polarizations). For each receiving channel, an avalanche photo diode (APD) is used to detect the light from the diffuser. The down-sampling frequency of APD is set to corresponding wavelengths transmitted at the transmitter side. The output of APD is amplified by using a *trans*-impedance amplifier followed by the low pass filter (LPF). At the output of LPF, bit error rate (BER) is measured by using a bit error tester. The received signal at the receiver is expressed as [37, 38]:

$$y(t) = x(t) \otimes h(t) + n(t) \tag{3}$$

where $y(t)$ represents the received signal, $x(t)$ represents the transmitted signal, $h(t)$ represents the impulse response of the transmitted signal, and $n(t)$ represents the additive noise which is composed of shot noise, thermal noise, and dark current noise. However, in this work, background noise is assumed to be negligible. The other modeling parameters considered for the proposed WDM-PDM-VLC link are mentioned in **Table 1**.

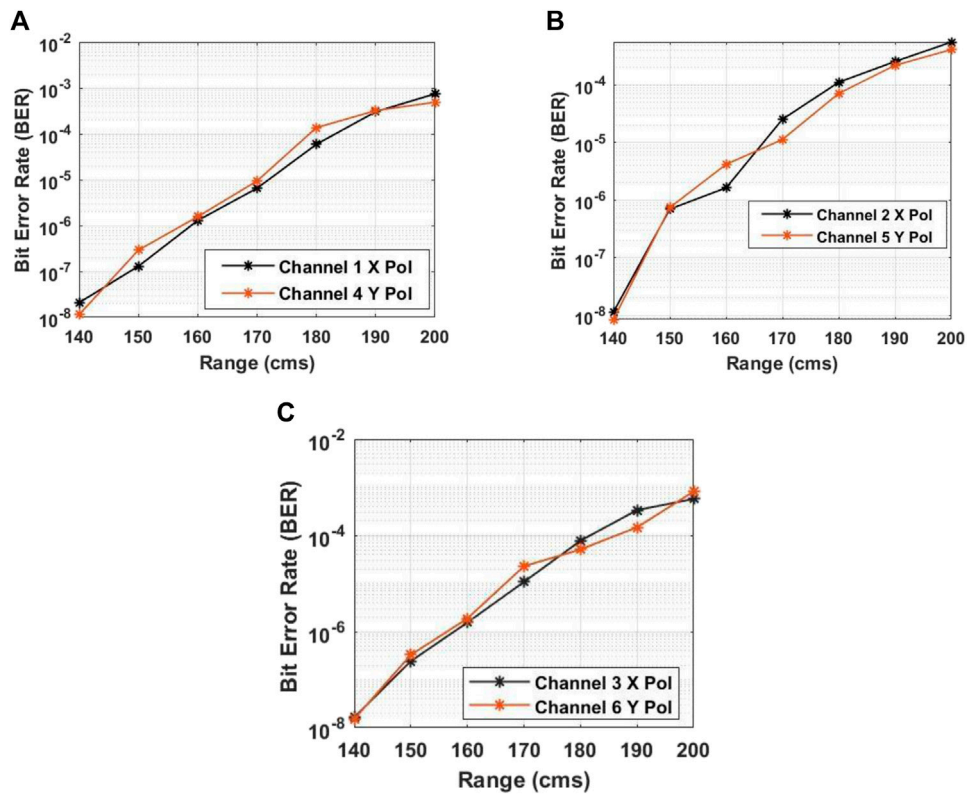


FIGURE 3 | Measured BER for each polarization channel, (A) channels 1 and 4, (B) channels 2 and 5, and (C) channels 3 and 6.

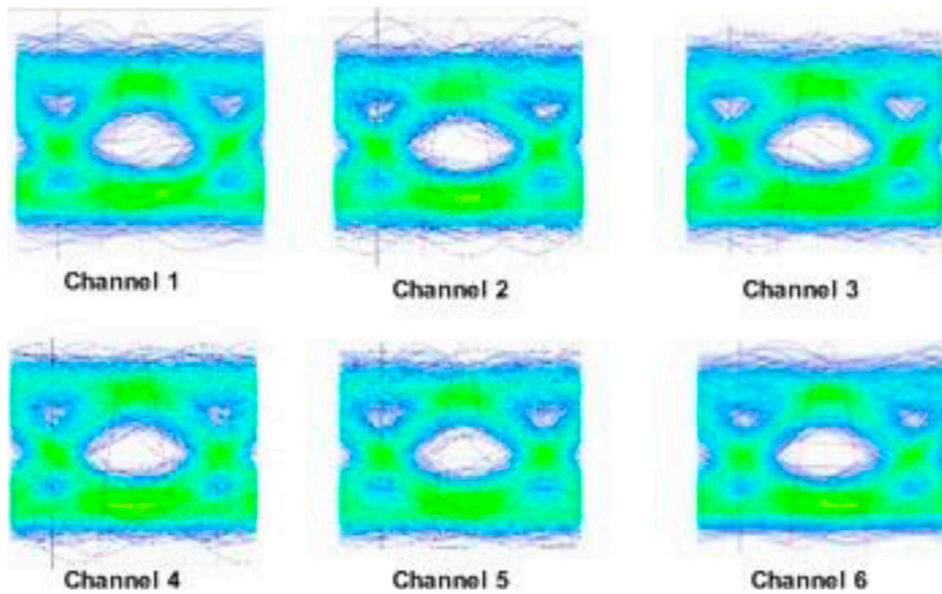


FIGURE 4 | Computed eye diagrams for all channels at the diffuse link of 200 cm.

RESULTS AND DISCUSSION

This section comprises the results from the modeling of the proposed WDM-PDM-VLC link. BER is used to evaluate the performance of the proposed WDM-PDM-VLC link. **Figure 3** shows the computed BER for all the channels with respect to diffuse link range. It shows that channel 1 which is transmitted over 640 nm with X polarization and channel 4 which is transmitted over 650 nm with Y polarization achieved a BER of less than 10^{-3} at a diffuse link range of 200 cm. For channel 1 and channel 4, the BER is measured as 10^{-8} at the diffuse link range of 140 cm. As the diffuse link ranges increase further, BER also increases for both channels. Similarly, channel 2 (transmitted over 530 nm with X polarization) and channel 5 (transmitted over 530 nm with Y polarization) have also achieved a BER less than 10^{-3} .

Channels 2 and 4 have also measured a BER of 10^{-8} at the diffuse link range of 140 cm. The values of BER for channel 3 which is transmitted over 430 nm with X polarization and channel 6 which is transmitted over 430 nm with Y polarization are also measured as less than 10^{-3} . This satisfies the acceptable BER threshold of $\approx 10^{-3}$ as per FCC limits. The measured eye diagrams for all the channels at the diffuse link range of 200 cm are shown in **Figure 4**. It shows that eye diagrams are open enough to receive the 10 Gbps of data over a diffuse link up to 200 cm with an acceptable BER.

CONCLUSION

In this work, six channels each carrying 10 Gbps of NRZ-encoded data are transmitted over a 500 m optical fiber and diffuse link range

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up to 200 cm by incorporating WDM and PDM schemes. RGB lasers are used for the WDM scheme whereas X and Y polarization states are used for the PDM scheme. For X polarization, an azimuthal phase shift of 0^0 is used whereas for Y polarization, an azimuthal phase shift of 90^0 is used. The performance of the proposed WDM-PDM-VLC link is evaluated in terms of BER and eye diagrams. The reported results show the successful transmission of all channels over a 500 m optical fiber link and 200 cm diffuse link with an acceptable BER $\approx 10^{-3}$. This work can be extended by considering real-time test beds to transmit high-speed data over a VLC link.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

CX-P has conceived of the presented idea, designed the model and performed the computations and wrote the original draft.

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