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Reducing the Effect of Crosstalk in WDM-VLC Systems

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ABSTRACT: Due to the rapid development of the internet and mobile communication needs, visible light communication (VLC) has become an attractive technique for indoor wireless communication. This research investigates how data rates in VLC systems are affected by the wavelength division multiplexing (WDM) technology. The WDM technique allows different data streams to be transmitted simultaneously over different wavelengths in the same optical channel. In WDM-VLC systems, the interference between channels known as crosstalk is a significant problem that may reduce the quality of communication. By optimizing the field of view (FOV) of the optical receiver and changing system parameters to reduce interference, this research resolves the crosstalk issue. With attention to the signal-to-interference-plus-noise ratio (SINR) and channel bandwidth, we use a simulated indoor environment to examine how line of sight (LOS) and non-line of sight (NLOS) elements affect the system performance. The results show that reducing the FOV leads to reducing the crosstalk and significantly enhancing data speeds and reliability in the system. Additionally, a review of practical challenges related to the implementation of different FOV lenses is presented, along with a comparative assessment of complexity, scalability, and cost in relation to present solutions. The results offer important updated knowledge on WDM's capabilities in VLC systems, enabling rapid transfer of data and efficient lighting for smart interior spaces.

1. INTRODUCTION

The development of advanced smart technologies and the need for intelligent homes and workplaces have led to the demand for internet services, mobile network devices, and higher data rates, resulting in the saturation of radio frequency (RF) bands. Optical wireless communication provides high data transfer rates and makes efficient use of the visible light spectrum for communication [1]. VLC technique is one of the approaches proposed recently for wireless communication. The electromagnetic spectrum's 380 nm–780 nm wavelengths range contains the light signals that are visible to the human eye.

Light emitting diodes (LEDs), increasingly prevalent in lighting applications, enable simultaneous data transfer with the illumination. In this manner, we can accomplish the data transfer and interior lighting of a space without requiring an additional connection infrastructure. This technique is known as VLC [2, 3]. LEDs are the best choice for VLC systems because of their superior illuminating capabilities [4]. The use of LEDs as transmitters and photodetector-assisted receivers, which are cost-effective and extremely energy-efficient in a VLC, has many advantages for both illumination and wireless communication. LED lighting systems are simple to install and safe for people to see. LEDs are available in different configurations to enhance specialized lighting and communication features, including superior modulation efficacy, extended lifespan, and exceptional brightness. Furthermore, the minimal energy consumption and rapid data transmission provided by LEDs, along with the utilization of the extensive bandwidth accessible in the unlicensed spectrum, create an innovative model for data communication. Additionally, we can achieve energy-efficient lighting and illumination capabilities [5].

Still, achieving high data rates in indoor VLC systems remains difficult due to multiple issues, including path loss, delay spread, multipath propagation, and crosstalk, which can have significant impact on data rates [6, 7]. WDM technology can be utilized in VLC systems with RGB-LEDs (Red, Green, Blue-LEDs) type, allowing the simultaneous multiplexing of multiple optical signals at different wavelengths and the transmission of multiple data streams through an optical wireless channel, thus enhancing overall data throughput [8]. VLC systems can enhance transmission rates and efficiency through the successful implementation of WDM. In WDM, different colored LED sources are used to deliver each data stream at different wavelengths. The transmitter can then combine the output from colored sources, using an optical lens as a mixer to generate white light. We employ wavelength-specific filters to de-multiplex the incoming data streams at the receiver [3, 7].

In this research, WDM is used to enhance the user's data transmission rate. We employ a simulated indoor environment to simulate an indoor channel of the VLC system, taking into account the impact of crosstalk. In addition, the present research shows an enhanced WDM-VLC system through the selection of different lenses with defined FOV to reduce crosstalk. This research distinctly defines the FOV and discusses its optimization process prior to presenting the results. The optical receiver's FOV indicates the angular range within which it can detect incoming light signals. A wide field of view enhances the likelihood of capturing signals from different sources, resulting in increased interference and crosstalk. Reducing the FOV filters out unwanted signals, hence enhancing the SINR. To improve the FOV for this study, the receiver's angular ac-

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ceptance has to be changed to reduce crosstalk while keeping enough received power. This study's optimization of FOV involves choosing multiple lenses, with each possessing a distinct FOV, and determining the ideal values within this range of values. Any more reduction past the ideal point would lead to the loss of the line-of-sight (LOS) signal. A comparison study is performed to highlight the advantages of the proposed strategy relative to present techniques. Previous studies have investigated several significant works about the implementation of WDM techniques in VLC systems. In [9], the maximum channel bandwidth and maximum data transmission rate in a WDM-VLC system using LEDs are investigated for channel crosstalk by constructing models of LED spectrum, and the crosstalk formula was constructed from the VLC link, which incorporates the transmittance of the optical filter and the spectral response of the detector. An experimental configuration with various wavelengths of LEDs is employed to validate the crosstalk analysis. The SNR, which encompasses signal power, channel crosstalk, and detector noise, determines both the number of channels and data transmission rate. The work in [10] focused on the complete modeling of WDM in combination with orthogonal frequency division multiplexing (OFDM) in VLC systems to evaluate and mitigate spectral crosstalk (SC). The spectral overlap-induced SC can reduce the efficiency of the WDM-VLC system, as adjacent WDM channels might generate considerable interference in the desired channel. The system is completely designed with dual optical diversity (DOD), utilizing RGB commercial LEDs. The models considered the non-ideal characteristics of different components, including the response curve of the photodiodes. They proposed a more precise model for the transmittance of optical filters. The proposed SC mitigation technique evaluated the characteristics of WDM channels, allowing the decrease of a significant amount of SC at the receiver by eliminating interfering signals through zero-forcing (ZF) and minimal mean-squared error (MMSE) equalizers. The results of the simulated system demonstrate its efficacy by measuring the bit error rate (BER). In [11], the authors explored how different color combinations affect WDM-based VLC, defined a trichromatic technique, and examined how color combinations affect the achievable data transmission rates. Also, the paper showcases LED-based communications that achieve a data transmission rate exceeding 10 GB/s using a rate-adaptive OFDM method. Ref. [12] developed a hybrid OFDM and WDM VLC. Direct detection was utilized instead of intricate digital signal processing techniques, such as channel estimation, channel equalization, and forward error corrections. Standard RGB-LEDs were employed for rapid-speed WDM in three-channel VLC, whereas white LEDs were utilized for indoor lighting. The authors employed direct current optical OFDM in each channel to enhance the effectiveness of frequency utilization. They presented an experimental data rate of 288 Mb/s over a transmission distance of 1 meter for indoor applications. Ref. [13] presented the results of experimentation of a VLC system achieving a data transmission rate of 15.73 GB/s after the implementation of forward error correction (FEC) coding across a 1.6 m link. It employed WDM to effectively modulate four wavelengths within the visible light spectrum. They selected four monochromatic, low-cost, commercially accessible LEDs as light sources. This demonstrates the practicality and capability of VLC for high data transmission rate communication. They utilized OFDM with adaptive bit allocation. In addition, the work described the system's accessible parts and found the best settings for its variables, such as LED driving points and OFDM signal's peak-to-peak scaling factor. Angle imaging diversity receiver was proposed with WDM to obtain a high data rates of 10 GB/s for indoor VLC system [14].

This work aims to reduce the effect of the crosstalk in indoor WDM-VLC system, which enhances the data rate and improves the performance of the communication link. WDM is used to improve the data rate for a single user. The field of view (FOV) of the optical receiver is optimized to reduce the crosstalk between different channels which leads to improving the connection link's performance. This paper is organized as follows. Section 2 gives the construction of the room environment that is used and the configuration of the transmitter and receiver. Section 3 presents the results and discussion, while Section 4 summarizes the conclusions.

2. VLC SYSTEM MODEL

As any wireless communication system, VLC system has three components: a transmitter, a receiver, and a visible light channel. Currently, the most common transmitters and receivers are LEDs and photodiodes (PDs). Considering the visible light channel, the illustrated actual room shown in Fig. 1 is used to evaluate the efficiency of the system that we propose. It is an empty room with no windows or doors used as the transmission medium's model for the optical signal, and this presumption was made in order to consider the impact of crosstalk inside the system. As in the empty room, we guarantee that all reflected signals from all colors will reach the PD. This represents the worst-case scenario in the indoor VLC systems. However, for a realistic room, some reflected rays may not reach the PD due to the obstacles, which decreases the crosstalk. Thus, using an empty room leads to evaluating the performance of the system in its worst case. This room has dimensions of $6 \times 6 \times 3$ meters in length, width, and height, respectively. It has four light sources installed on its ceiling in a regular pattern, where each lamp is made up of 32 LED chips, serving as a transmitting device for the optical signal that carries the data to be sent, and its light emission adds to the total power received. This work considered first-order reflections because second- and higher-order reflections slightly affect the received optical power [15]. We assume that the room's reflective surfaces (the walls, ceiling, and floor) behave as Lambertian reflectors, exhibiting reflection coefficients of 0.8 for the walls and ceiling and 0.3 for the floor [16, 17]. The receiver is located at one meter above the floor. To simulate reflections off the walls, we divided the space's surfaces into small, equal-area, each with an area of (dA). Each wall section works as an additional light source. Figure 1 represents the structure of the proposed indoor environment, where α is the angle of irradiance with respect to the axis normal to the transmitter surface; Ψ is the angle of incidence with respect to the axis normal to the receiver surface; d denotes the distance between the LED and receiver plane; θ_{ir}

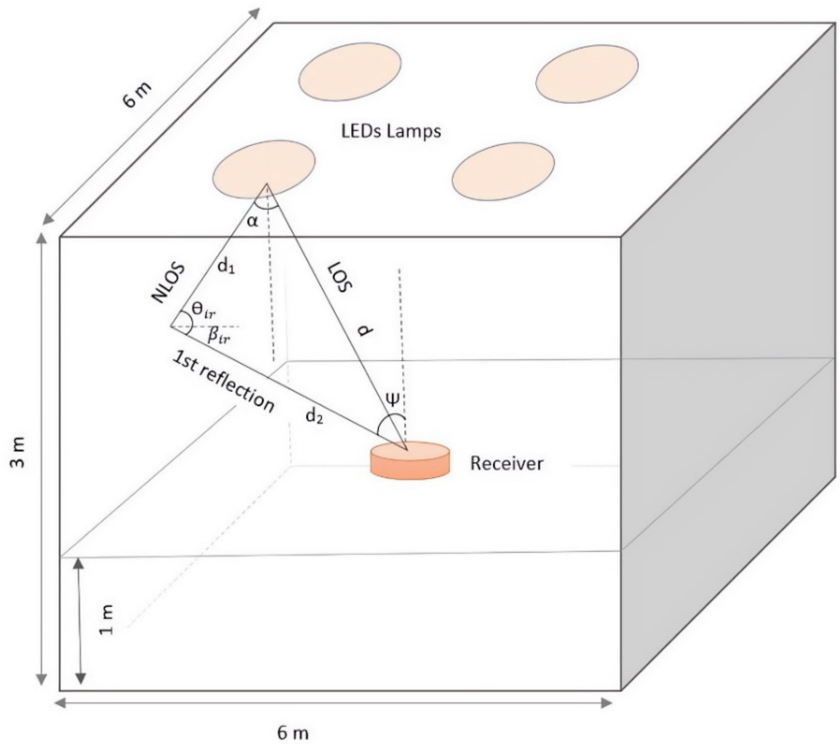

FIGURE 1. Structure of the indoor VLC environment.

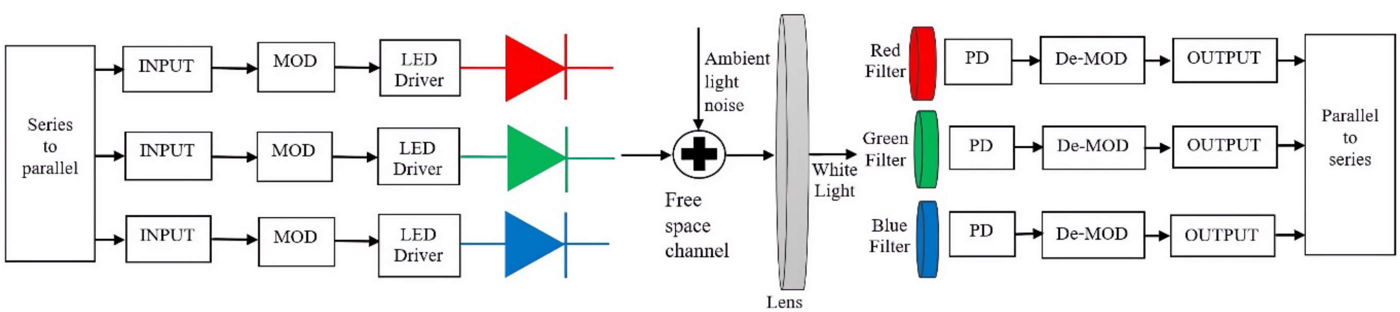

FIGURE 2. The block diagram of the WDM-VLC system.

and β_{ir} represent the angle of irradiance to a reflective point and the angle of incidence from the reflective surface to a receiver, respectively, while distances d_1 and d_2 are respectively those between the LED and reflecting point and between the reflecting point and PD [18].

In this work, we used RGB-LEDs as transmitters (see Fig. 2) and the same configuration of the RGB-LED used in [1]. The light units, composed of multiple RGB-LED chips, are situated within the room's perimeter, with their coordinates being (1.5, 1.5, 3), (1.5, 3.5, 3), (3.5, 1.5, 3), (3.5, 3.5, 3). Because plaster makes up the walls, each color of the RGB-LED has a unique reflection coefficient, which is 0.86 for the red, 0.72 for the green, and 0.67 for the blue [19]. The utilization of RGB-LEDs for illumination and data transmission requires three individual photodetectors, with each containing an optical filter (red, green, and blue) as illustrated in Fig. 2. Each PD has an area equal to 1 cm^2.

In this work, we used WDM to enhance the data transmission rate for a single user. Thus, we used series-to-parallel components at the transmitter and parallel-to-series components at the receiver as shown in Fig. 2.

Modeling the channel is necessary for comprehending the performance of the VLC indoor system. In this work, we considered line of sight (LOS) and NLOS components to assess the efficiency of our proposed system. Calculations of receiving optical power and illumination due to LOS and NLOS can be found in [15] and [18]. Calculating the received optical power enables us to find many crucial parameters that influence the system performance in indoor VLC channel modeling. These parameters are delay spread, channel bandwidth, signal-to-noise ratio (SNR), and signal-to-interference plus noise ratio (SINR).

2.1. Delay Spread (DS)

Root mean square (RMS) delay spread represents the distribution of signal arrival times in optical wireless communication channels and estimates the dispersion of signal arrival times as a result of many signal paths arriving at the receiver having different delays due to multipath propagation. An accurate assessment of the channel's susceptibility to inter-symbol interference (ISI) can be obtained by computing the RMS delay spread (DS_{RMS}), which is defined as [15]:

$$DS_{RMS} = \sqrt{\frac{\int_{-\infty}^{\infty} (t - \tau_o)\, p^2(t)\, dt}{\int_{-\infty}^{\infty} p^2(t)\, dt}} \quad (1)$$

here p is the received optical power of each ray, t the time delay of each ray, and τ_o the mean delay which given as [15]:

$$\tau_o = \frac{\int_{-\infty}^{\infty} t h^2(t)\, dt}{\int_{-\infty}^{\infty} h^2(t)\, dt} \quad (2)$$

The channel impulse response is defined as $h(t)$, which characterizes the behavior of a communication channel, detailing the reception of an impulse signal sent across the channel over time [20]. Calculating the delay spread leads us to obtain the channel bandwidth (BW_{-ch}) of our proposed system. The maximum BW_{-ch} can be given as [15]:

$$BW_{-ch} = \frac{1}{10 DS_{RMS}} \quad (3)$$

2.2. SINR

The most important parameter is SNR, which represents the relationship between the received signal's power and noise's power. Since a higher SNR indicates that the signal is stronger than the noise and causes less transmission errors, it typically indicates better system performance. It should be noted that in this work, we consider the effect of crosstalk, which is represented as interference. Thus, we obtained the SINR instead of SNR. In this paper, we consider the crosstalk between WDM channels. This crosstalk was modelled as interference. Thus, we obtained SINR instead of SNR. The SINR can be given as [3, 6]:

$$SINR = \frac{(RP_{re})^2}{\sigma^2_{Total} + \sigma^2_{Shot-cross}} \quad (4)$$

here P_{re} denotes the total received power; R is the PD's responsivity; σ_{Total} is the standard deviation of the thermal noise (σ_{ther}) and shot noise (σ_{shot}), given as $\sigma_{Total} = \sqrt{\sigma^2_{ther} + \sigma^2_{shot}}$; and $\sigma_{Shot\text{-}intr}$ is the same as $\sigma_{Shot\text{-}cross}$ which represents the shot noise caused by crosstalk interference between different colors of the RGB-LEDs. Both show how the undesirable signal from one color channel interferes with others in the WDM system, leading to increased noise and affecting the system's SINR. Interference due to the crosstalk can be given as:

$$\sigma_{Shot-intr} = \sigma_{Shot\text{-}cross} = 2qRP_{re\text{-}cross}B \quad (5)$$

where q is the electron charge, $P_{re-cross}$ the received crosstalk power due to the crosstalk between different transmitted colors, and $B(HZ)$ the bandwidth of the electrical filter of the receiver. Calculations of σ_{Total} can be found in [15] and [21].

Due to using three channels to transmit the data, the SINR of each channel must be obtained to determine the impact of crosstalk on system efficacy. The electrical $SINR$ can be calculated for each received color from the RGB LEDs as:

$$SINR_{red} = \frac{(R_{red}P_{re\text{-}red})^2}{\sigma^2_{Total-red} + \sigma^2_{Shot\text{-}cross\text{-}red}} \quad (6)$$

$$SINR_{green} = \frac{(R_{green}P_{re\text{-}green})^2}{\sigma^2_{Total\_green} + \sigma^2_{Shot-cross-green}} \quad (7)$$

$$SINR_{blue} = \frac{(R_{blue}P_{re-blue})^2}{\sigma^2_{Total\text{-}blue} + \sigma^2_{Shot\text{-}cross\text{-}blue}} \quad (8)$$

It is worth knowing that the interference between each pair of transmitted colors defined as the amount of the total received power by each PD apart of its desired color. For example, to calculate the interference received by the blue PD, we calculated the amount of power of the green color that interferes with the blue PD as shown in Fig. 3. Fig. 3 depicts the intensity of each transmitted color with its wavelength to generate the white color. As can be seen, there is an interference between the blue and green colors; however, the red color has no crosstalk. These wavelengths are used in this work to generate the white color. Hence, the $\sigma_{Shot\text{-}intr}$ due to each color can be given as:

$$\sigma_{Shot\text{-}cross\text{-}red} = 2qR_{red}P_{re\text{-}red\text{-}cross}B \quad (9)$$

$$\sigma_{Shot\text{-}cross\text{-}green} = 2qR_{green}P_{re\text{-}blue\text{-}cross}B \quad (10)$$

$$\sigma_{Shot\text{-}cross\text{-}blue} = 2qR_{blue}P_{re\text{-}green\text{-}cross}B \quad (11)$$

It should be noted that the red channel has the minimum interference as shown in Fig. 3, which means the red channel offered best performance as will be shown later.

3. RESULTS AND DISCUSSION

In our simulation, we compute the total received power for each color of RGB LEDs that are illustrated as optical sources by summing the power received from both LOS and NLOS paths inside the room. The light signal reflects from the room's wall at different locations for the receiver, which is one meter above the ground. The parameters used in our system are shown in Table 1.

In order to make sure that the lighting level meets the acceptable standards for our proposed environment, we obtained the illumination of the white color on the floor of the room as shown in Fig. 4. As can be seen from Fig. 4, the minimum lighting level was not less than 400 lux while the maximum was not more than 1500 lux. These values agree with the standard of illumination in indoor environments [18].

Figure 5 shows the optical received power of each color. We obtained the received power to find the other parameters that affect the system performance. Fig. 5 was obtained when the FOV of the optical receiver was 90°. As can be seen, the blue

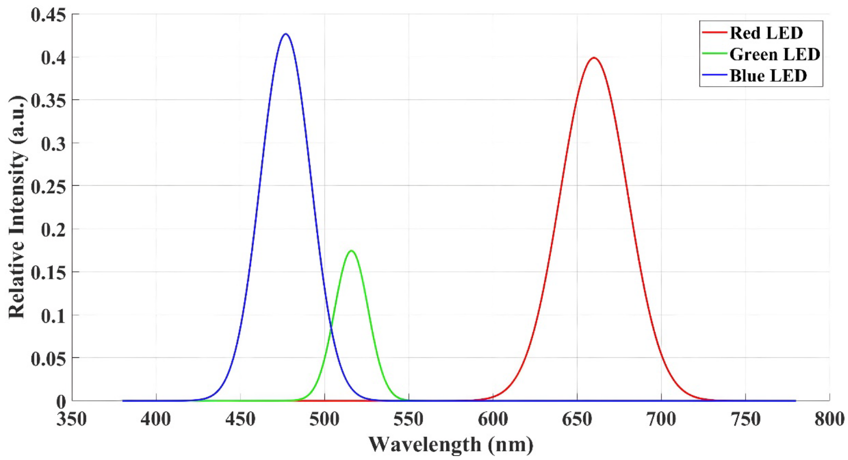

FIGURE 3. Relative intensity of the RGB LEDs.

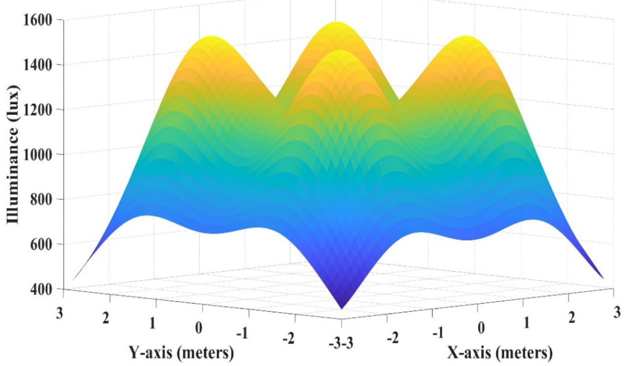

FIGURE 4. Total illumination from the LOS and NLOS paths in the room.

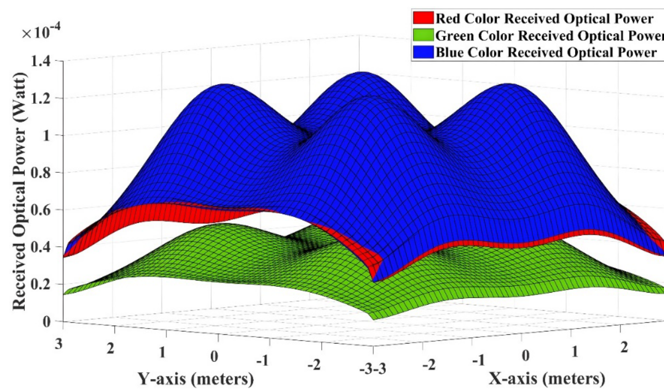

FIGURE 5. Total received power distributions from LOS and NLOS of each color in the room. The maximum power for the red is 0.12165 mW, for the green is 0.052455 mW, and for the blue is 0.12752 mW.

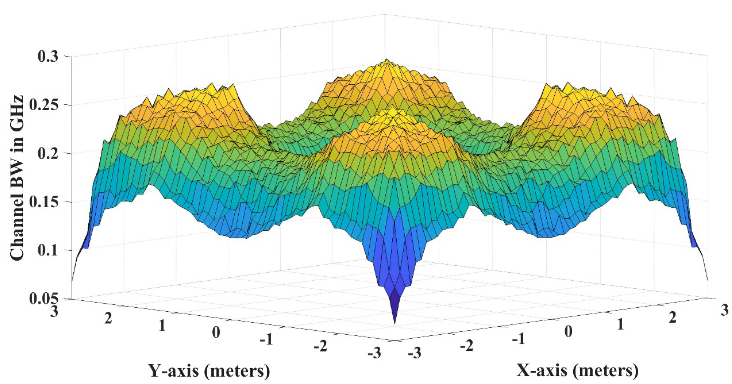

FIGURE 6. Channel bandwidth distribution.

color has maximum received power due to many reasons, including the transmitted power and the responsivity of PD.

A crucial component of channel modeling is the computation of channel bandwidth (BW). Fig. 6 illustrates the result of our channel bandwidth computation. The channel bandwidth's lowest value is observable when the receiver was located at the corner of the room. This is related to the fact that at these locations the received optical signal suffers from several multi-path components. However, the maximum channel BW was 273 MHz, while the minimum was equal to 67 MHz, which facilitates the operation of our systems at a data transmission rate of (100 b/s). It is worth knowing that the channel BWs of the three colors are similar, as the channel BW depends on the environment of the room.

Figure 7 shows the SINR of our proposed system with different data rates (50 Mb/s, 100 Mb/s, 150 Mb/s, and 200 Mb/s) of

TABLE 1. Parameters for simulation.

	Paramete	Configurations
Room	Size (length × width × height)	$(6 \times 6 \times 3)\,\mathrm{m}^3$
	Reflection Coefficient of Red color [19]	0.86
	Reflection Coefficient of Green color [19]	0.72
	Reflection Coefficient of Blue color [19]	0.67
Source Transmitters (RGB LEDs	Four Transmitters/light unit at coordinates (x, y, z) m	(1.5,1.5,3), (1.5,3.5,3) (3.5,1.5,3), (3.5,3.5,3)
	Semi-Angle at Half power	60°
	Number of RGB LEDs per unit	32 × 32 (1024)
	Center Luminous Intensity [18]	300-910 lx
	Optical power of Red LED [1]	4.89 mW
	Optical power of Green LED [1]	2.14 mW
	Optical power of Blue LED [1]	5.23 mW
	Total luminous Intensity [1]	4.7 cd
	Lambertian emission order (m)	1
Receiver	Receive plane above the floor	1 m
	Number of PD	3
	Active Area ($A_{detector}$)	$1\,\mathrm{cm}^2$
	PD's responsivity (red) [1]	0.45 A/W
	PD's responsivity (green) [1]	0.28 A/W
	PD's responsivity (blue) [1]	0.24 A/W
	Receiver bandwidth	308 MHz
Optical Filter	Gain [18]	1.0
A Lens at the PD	Refractive Index [18]	1.5

each color. The results were acquired when the optical receiver was moved along the x-axis with step of 1 m when $y = 1$ m. In order to mitigate the effect of the crosstalk, the FOV of the optical receiver was reduced from 90° to 50°. As can be seen, reducing the FOV of the optical leads to enhancing the SINR. This is because the crosstalk represents the amount of received power by the optical receiver from other interfering colors (see Fig. 3). Additionally, enhancing the data transmission rate for each color leads to reducing the SINR, and this is because of the impact of the co-channel interference. As can be seen from Fig. 7, the red channel has the best SINR, and this is because red color has the longest wavelength and suffers from the lowest crosstalk. It should be noted that the FOV was varied between 90° and 50° to ensure that the optical receiver sees at least one light unit at any location in the room's floor. This means that reducing the FOV less than 50° leads to making the receiver receive power from NLOS components only. It should be noted that for our system parameters, using an FOV less than 50 degrees leads to the PD not seeing any light unit on the ceiling. This means that at some locations on the floor of the room, the PD will not receive an LOS signal, which degrades the system's performance.

It can be seen that our suggested system can achieve an overall data rate of 750 Mb/s with SINR not less than 7 dB for the three colors. This gives a good channel connection between the transmitter and receiver.

The comparison as shown in Table 2 illustrates how our methodology enhances current techniques by maintaining lower complexity and cost while ensuring high scalability, making it a practical choice for real-world implementation.

The proposed technique for reducing the FOV illustrates important efficiency advantages; however, its practical implementation faces challenges, such as the lens selection process that identifies commercially available lenses with accurate field of view specifications suitable for visible light communication applications, while also considering alignment sensitivity, where even a slight misalignment of the receiver can lead to a decline in signal quality and performance that fluctuates with the receiver's movement. Individuals navigating an interior environment might face varying performance and hardware limitations. Current photodetector technology may necessitate additional optical components to enhance the field of view selection.

It should be noted that this paper emphasizes optimizing the receiver's field of view (FOV) to reduce crosstalk during the process of detection, rather than mainly depending on optical filters. This reduces interference in a more flexible and practical method without adding significant hardware complexity. In addition, our work mitigates the requirement for increased digital signal processing (DSP) complexity by employing simple changes to the optical receiver. Effectively narrowing the field of view cuts out unnecessary light components, hence reducing crosstalk with little system change. Moreover, our method-

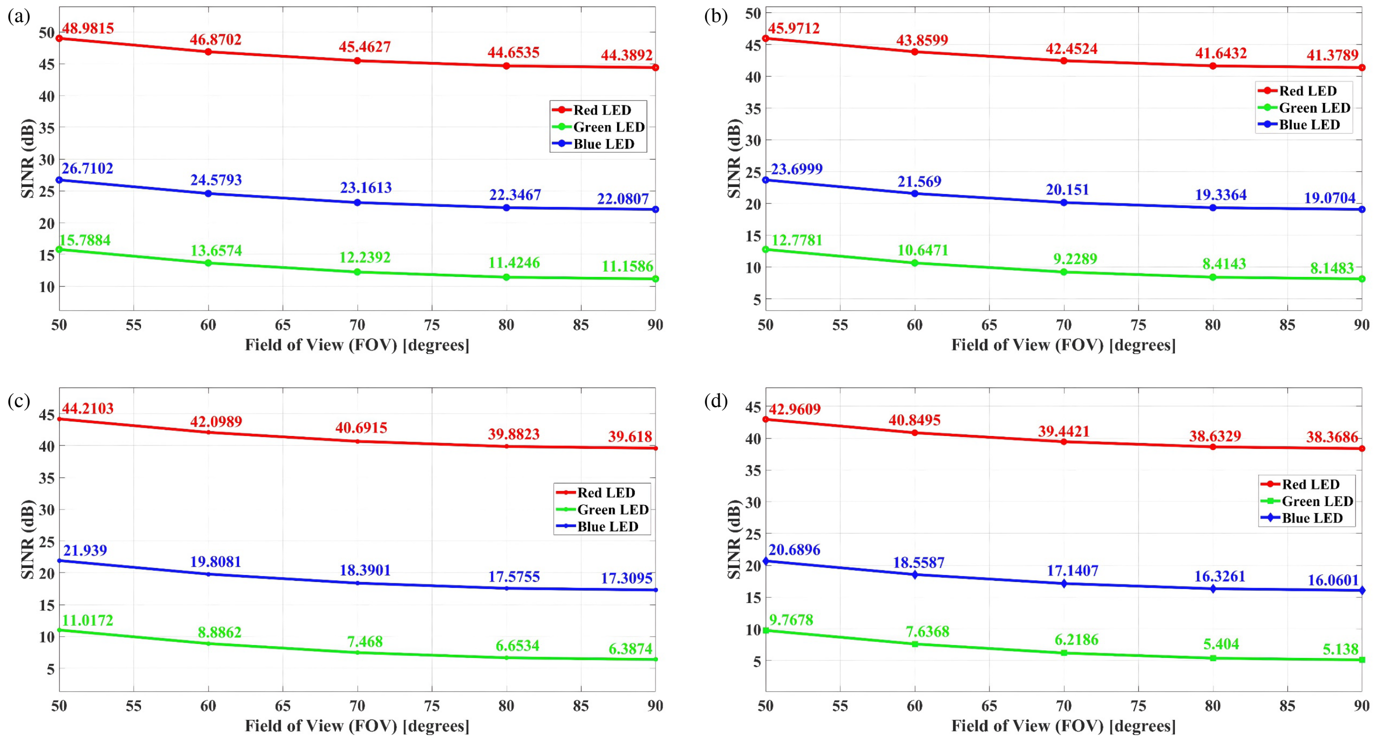

FIGURE 7. (a): SINR vs. FOV at 50 Mb/s. (b): SINR vs. FOV at 100 Mb/s. (c): SINR vs. FOV at 150 Mb/s. (d): SINR vs. FOV at 200 Mb/s.

TABLE 2

Parameters	Proposed system	Prior work [9]	Prior work [10]	Prior work [11]
Complexity	Medium	High	High	Medium
Scalability	High	Medium	Low	High
Cost	Low	High	Medium	Medium

ology combines economic RGB LEDs with enhanced receiver specifications, guaranteeing a balance between efficiency and practicality. This important development enables our technology to attain transmission rates that provide enhanced flexibility for practical indoor VLC applications.

4. CONCLUSIONS

This research optimized the FOV of optical receivers to provide an effective method of minimizing crosstalk in WDM based VLC systems. Simulations showed that reducing the FOV significantly decreased the crosstalk and enabled data rates up to 750 Mb/s with good communication link while using simple RGB LEDs. The red channel has the highest SINR, indicating that it is the most reliable channel for data transmission because of its longer wavelength and lower crosstalk. By reducing the FOV of the PD, the SINR was improved by 7 dB. In the future, this model could be extended to more complex multi-user scenarios and adaptive FOV. The proposed technique shows that VLC is an achievable alternative to the present and future data rate demands in indoor wireless communication.

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