Performance analysis of downlink multipath multi-user NOMA-VLC system

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Abstract
In the present paper, we have investigated performance of Non-Orthogonal Multiple Access based downlink multipath multi-user Visible Light Communication System. The Bit Error Rate (BER), sum rate and outage probability have been simulated using Line-Of-Sight (LOS) and LOS plus first reflection (L-R1) signal for two-user and three-user system. The simulation has been carried out for different values of semi-angle \( \frac{\phi}{2} \) of the LED i.e. 30°, 50° and 70°. In the two-user system, the LOS simulation result shows that the error probability is 7.49 × 10⁻³, 4.88 × 10⁻³ and 1.03 × 10⁻¹ when \( \frac{\phi}{2} \) equals to 70°, 50° and 30° respectively for user-1. And for user-2, the BER is found to be 4.89 × 10⁻², 5.84 × 10⁻² and 3.73 × 10⁻¹ using \( \frac{\phi}{2} \) equals to 70°, 50° and 30°. Thus, the optimal semi-angle \( \frac{\phi}{2} \) for user-1 and user-2 using LOS signal is 50°, 70° respectively. However, for the three-user system, the error probability increases when compared to two-user system and the optimal values of semi-angle for user-1 changes to 30° and for user-2 & user-3, it is 70°. Moreover, in two-user system with L-R1 signal, the optimal value is 70° for both user-1 and user-2. The SIC method fails to decode the user’s signal when number of users increases to three in L-R1 signal case. Further, with the far user power allocation coefficient equal to 0.8, the average BER is found to be minimum for two-user system. The sum rate vs. normalized offset has been simulated for different values of semi-angle of the LED. The investigation shows that the maximum sum rate of 278.84 Mbps is achieved at \( \frac{\phi}{2} \) equals to 50° for the two-user system using LOS signal. We have also examined the effect of shadowing (blocked LOS signal) and found that sum rate is almost zero for small values of \( \phi_{1/2} \) i.e. 20° and 30°. Finally, for the semi-angle value of 30° the outage probability (for target rate beyond 3bps/Hz) reaches to 100 percent for both users.

Keywords VLC · NOMA · Semi-angle · BER · Sum rate
1 Introduction

Owing to the increase in demand of data driven-application, Visible light communication (VLC) has emerged as an encouraging supplement to the conventional radio frequency (RF) communication system. The VLC system has dual advantage of illumination as well as communication. It also exhibits numerous advantages when compared to RF system e.g. unregulated license-free spectrum, low cost, less power requirement, long life of light emitting diode (LED) etc. (Chi et al. 2020; Chen et al. 2021, Hong and Li 2021). However, the limited modulation bandwidth of LED reduces the achievable capacity of the VLC system (Matheus et al. 2019). In this context, the conventional multiple access technologies such as frequency division multiple access (FDMA), time division multiple access (TDMA) and code division multiple access (CDMA) have been used to increase the achievable capacity (Liang Yin et al. 2016). To support a more significant number of users and achieve high data transmission rates, Wavelength-Division Multiple-Access (WDMA) has been used in which a distinct wavelength is dedicated for each user (Elsayed et al. 2022a, b). Nevertheless, sufficient resource reuse can’t be achieved using the above-mentioned techniques. The orthogonal frequency division multiple access (OFDMA) facilitates the resources to be reused at the subcarrier level and it has been widely investigated in the VLC system due to its frequency selective channel and the ability to reject intersymbol interference (Wen et al. 2022). Nonetheless, such techniques of orthogonal multiple access degrade the spectral efficiency and bit error rate performance.

Recently, non-orthogonal multiple access (NOMA) has attracted significant attention as a promising multiple access scheme for the 5th generation (5G) wireless network (Marshoud et al. 2016, Dogra and Bharti 2022). NOMA employs superposition coding at the transmit side to aid the simultaneous transmission of signal to several users using a single source. Signals intended for different users are multiplexed by assigning different power levels inversely according to their channel gains. Ding et al. (2014) have shown that the NOMA performs much better in high signal-to-noise ratio (SNR) conditions. Thus, indoor VLC system which offers high SNR due to its short distance between LEDs and photo detector (PD) can utilize the NOMA in the downlink VLC system. Nevertheless, the received signal is composed of superposition of multi-users signal and therefore interference cannot be completely eliminated by SIC techniques which leads to error propagation. To combat such problems, Obeed et al. (2020) have proposed and evaluated a new scheme that combines the advantages of cooperative non-orthogonal multiple-access (Co-NOMA), hybrid VLC/RF, and energy harvesting techniques. Similarly, Alqahtani et al. (2021) have done the performance analysis for a hybrid indoor-outdoor NOMA user, where both users can be served via an outdoor-to-indoor and outdoor-to-outdoor channels. However, the bit error rate (BER) which is metric for evaluating wireless communication system was not investigated in these research articles.

Several pioneer works have been done on the BER performance analysis for indoor VLC system. Dixit and Kumar (2021a, b) have proposed dynamic FOV strategy for two-user 2×2 MIMO-NOMA-VLC system. In the BER analysis they have considered different FOV values i.e. 60°, 40°, 30° and 20° and have found improvement in performance. They have also shown that 2×2 NOMA-MIMO-VLC system outperforms SISO-NOMA-VLC system. Such type of dynamic FOV strategy can be useful in LI-Fi, airports, railway stations etc.

Lin et al. (2017) have proposed single carrier-based NOMA scheme for the VLC system and have found optimum power allocation ratio (PAR) of 0.29 at which best
BER performance is achieved. Chen et al. (2018) have suggested a flexible-rate SIC-free NOMA technique for downlink VLC system. They have revealed that for high power allocation range (PAR), almost same BER performance can be achieved by the near user using proposed constellation portioning coding (CPC) method. Li et al. (2019) have introduced a hierarchical pre-distorted layer asymmetrically clipped optical OFDM (HPD-LACO-OFDM) scheme for NOMA. They have experimentally shown that for the same signal power, the proposed method outperforms dc-biased optical OFDM (DCO-OFDM) and asymmetrically clipped optical OFDM (ACO-OFDM) in the terms of BER performance. Liu et al. (2019) have obtained the closed form expression of BER and found that the difference in BER performance among users decreases with the increase in modulation order at the expense of higher power consumption. Marshoud et al. (2017) have proposed a novel gain ratio power allocation (GPRA) scheme which offers improved BER performance in comparison to the conventional static power allocation method. They have also demonstrated that the tuning of both semi-half power angle of the LED and FOV of the receivers using GPRA method provides more sum rate than that achieved using fixed semi-angle of the LED and fixed FOV of the receiver. Dixit and Kumar (2021a, b) have investigated the BER performance for two-user downlink OOK and L-PPM modulated NOMA-VLC system in the presence of perfect and imperfect CSI. They have simulated BER for different values of power allocation coefficient, FOV, receiver’s position. They have found that the error probability for L-PPM (L > 2) is less than OOK modulation and the BER performance of near and far users improves as FOV reduces. They also found that the channel estimation error has adverse effect on higher order L-PPM modulation in NOMA-VLC system. Similarly, Saxena et al. (2022) have derived mathematical expression of BER & sum rate for two randomly positioned users and have investigated the probability of error with different values of FOV and power allocation coefficient. Nevertheless, in all the above works, the NOMA based BER performance has been investigated using only line-of-sight (LOS) signal.

Hesham et al. (2022) have proposed the hybrid combination of NOMA, asymmetrically-clipped optical (ACO), and filter bank multicarrier (FBMC) technique to minimize the number of unserved (blocked) users. They have shown that to achieve a threshold BER of $10^{-3}$, the power allocation coefficient is 0.2. The authors have also proposed positioning, clustering, and resource allocation algorithm and found that the NOMA-FBMC technique provides 1.8 times more throughput than the NOMA-OFDM scheme. Dixit and Kumar (2020) have examined the BER performance of NOMA-VLC system for different values of FOV, responsitivity of PD, reflection coefficient of wall and receiver’s location using first order reflection signal (blocked LOS). They have found that BER degrades when the reflection coefficient of wall and responsitivity of PD are decreased. Also, the BER improves with the increase in FOV of the receivers. The investigation has been done by considering single-user system with either LOS or first reflection signal but in practical scenario there are multi-users which receive LOS along with reflected signal. There are certain situations in which the BER performance shows different performance with different signal components (Kumar et al. 2018a, b; Kumar and Ghorai 2020a, b). There can be different cases in practical indoor VLC system e.g. LOS blockage, tilted receiver etc. due to which light signal may not be captured through LOS path. Moreover, the LOS component may be comparable or even smaller than non-line-of-sight (NLOS) component in case where horizontal separation between LED and PD is wide enough so that not all incident light rays are received by limited FOV of the receivers. Also, the received power from second reflection is more than that received from first reflection when the LED is located at the center and
PD is at either center or the wall side of the room. Hence, there is a need to investigate the BER performance of multipath multiuser NOMA-VLC system under different scenarios.

In this paper, we have reported BER performance of downlink NOMA-VLC system with the following considerations:

(i) Barry channel models for VLC system.
(ii) Line-of-sight (LOS) and LOS plus first reflection (L-R1) signals for NOMA-VLC system.
(iii) Scenario with blocked LOS.
(iv) Two-user and three-user system.
(v) The semi-angles of the LED are 20°, 30°, 40°, 50°, 60° & 70°.

Based on the above considerations, following are the main contributions of this research paper.

• The BER performance of NOMA-VLC has been investigated with single LED for two-user & three-user system by changing the semi-angle of the LED using LOS and L-R1 signals.
• The sum rate vs. offset has been examined for different number of users using LOS and blocked LOS signal.
• The optimal power allocation factor of far user has been investigated for two-user system.
• Also, the outage probability has been simulated for blocked signal.

The proposed research can be useful in following ways:

• The research work can be useful in enabling technology for massive connectivity and coverage enhancement in 5G.
• Moreover, if LED with proper semi-angle LED is chosen for indoor NOMA-VLC system then users with poor channel conditions can utilize higher transmit power due to severe intercluster interference.
• The investigation on choosing power allocation factor can maximize the sum rate of all the users.
• The NLOS signal based NOMA-VLC system can be useful in situation with blocked path between transmitter and receiver.
• The proposed research work can lead to spatial reuse of frequency resources in better way.

The present research work can be beneficial for use in certain environments such as hospitals, conference rooms, offices, industrial plants, etc.

The remainder of the paper is organized as follows: Sect. 2 presents the indoor multipath NOMA-VLC model and Sect. 3 describes the principal of NOMA-VLC system. Section 4 includes results and discussion while conclusion is provided in Sect. 5.
2 Downlink multipath NOMA-VLC model

In this section, the model of indoor multipath NOMA-VLC system has been described in a room size of 5 m × 5 m × 3 m as shown in Fig. 1a. For simplicity and without loss of generality, single LED located at the center of the ceiling and k number of users have been considered. In the present paper, two-user (k = 2) and three users (k = 3) system have been considered in simulation. The coordinates of LED and user-1, user-2 & user-3 are provided in Table 1. The users are placed at a height of 0.85 m from the floor and so the vertical distance between LED and receiving plane is 2.15 m. The photodetector of each user is facing vertically upward. The light signal from source reaches at receiver through LOS path as well as reflected path. In our case, we have considered first order reflection signal along with LOS path signal. The LOS signals emitted at angle ϕ_o from the LED w.r.t normal axis (unit normal vector \( \hat{n}_s \)) reaches to the PD through the paths \( d_1 \) and \( d_2 \) for the user-1 and user-k respectively. The LOS signal is incident at angle \( \psi_{o,1} \) and \( \psi_{o,k} \) at user-1 and user-k respectively. The NLOS signal radiated by angle \( \varphi_1 \) is incident at \( l^{th} \) grid of wall at angle \( \alpha \) and then it is reflected by angle \( \beta \) w.r.t normal axis of wall (unit normal vector \( \hat{n}_t \)). The reflected light ray is incident at angle \( \psi_{1,1} \) and \( \psi_{1,k} \) on the user-1 and user-k w.r.t to normal axis of receiver (unit normal vector \( \hat{n}_r \)). The LOS along with first reflection (L-R1) signal for user-1 and user-k is shown by the paths \( d_3-d_4 \) and \( d_3-d_5 \) respectively. Since, the LED is assumed at the center of ceiling so maximum coverage radius of the light beam of the LED is \( L = 2.5 \) m.

The LED is assumed to follow Lambertian radiation pattern which is cosine function as given below (Kahn and Barry 1997):

\[
I(\varphi) = \frac{m + 1}{2\pi} \cos^m(\varphi)
\]

(1)

![Fig. 1](image-url) Indoor downlink multipath multi-user NOMA-VLC model
where $\phi$ is the irradiance angle w.r.t normal axis, $m$ is the Lambertian order which is the function of semi-half angle $\phi_{1/2}$ of the LED and is given as $m = -\ln(2)/\ln(\cos\phi_{1/2})$.

The wireless optical channel gain at the receiving side is inversely proportional to the square of the distance between the optical source and the PD and directly proportional to the effective collection area of the PD. At the receiving side, the PD is modelled as an active area $A_r$ collecting the light signal. The LOS and non-line-of-sight (first reflection) channel gains for the $k$th user are denoted by $h_{0,k}$ and $h_{1,k}$ respectively which are expressed as (Kahn and Barry 1997)

$$h_{i,k} = \begin{cases} \frac{1}{d^2} g(\psi_{0,k}) A_r I(\phi_{0,k}) \cos^m(\phi_{0,k}) \cos(\psi_{0,k}) & \text{if } 0 < \psi_{0,k} < \psi_{FOV} \\ 0 & \psi_{L,k} \geq 0 \end{cases}$$

(2)
where $A_r$ is the active area of the PD, $A_l$ is the small reflective area of $l$th grid, $\mu$ is the reflection coefficient of wall, $\alpha$ and $\beta$ are the incidence and reflected angles from the grid of the wall, $\psi_{FOV}$ is the field of view of the concentrator. The light rays which are incident within receiver’s FOV will be captured. The factor $g(\psi)$ is the gain of optical concentrator given by (Kahn and Barry 1997)

$$g(\psi) = \begin{cases} \frac{n^2}{\sin^2(\psi_{FOV})}, & 0 \leq \psi \leq \psi_{FOV} \\ 0, & \psi \geq \psi_{FOV} \end{cases}$$

where $n$ is the refractive index of concentrator. Here $\psi$ can be either $\psi_{o,k}$ or $\psi_{1,k}$.

### 3 Principal of NOMA-VLC system

In NOMA, the bipolar message signal for the different users are superposed in the power domain and a DC bias is added at the LED as given by (L. Yin et al. 2016):

$$x = \sum_{i=1}^{K} \alpha_i \sqrt{P_{elec}S_i} + I_{DC}$$

where $P_{elec}$ is the total electrical power of all the message signals, $I_{DC}$ is the DC bias added to the LED before the signal transmission, $S_i$ and $\alpha_i$ are the modulated message signal and power allocation coefficient for the $i$th user ($i = 1, 2, \ldots, K$). At the $K$th user, the received signal is given by (L. Yin et al. 2016):

$$y_k = \sqrt{P_{elec}h_k} \left( \sum_{j=1}^{k-1} \alpha_j S_j \underbrace{+ \alpha_k S_k}_{\text{signal}} + \sum_{i=k+1}^{K} \alpha_i S_i \underbrace{+ n_k}_{\text{interference}} \right)$$

The first term in above equation is SIC, second term is the signal intended for the $k$th user, third term represents the interference and the fourth term ($n_k$) is the noise. At the $k$th user, SIC is carried out to remove the message signal for the other users with poorer channel conditions i.e. SIC term. The message signal for the users whose channel gains are stronger than the $k$th user is treated as noise i.e. interference term. The noise is having zero mean and variance $\sigma^2_{\text{noise}}$, which comprises shot noise and thermal noise as written below:

$$\sigma^2_{\text{noise}} = \sigma^2_{\text{shot}} + \sigma^2_{\text{thermal}} = (2qI_{bg}I_2B + 2qRP,Bh) + \left( \frac{8\pi KT}{G} \eta A_r I_2 B^2 + \frac{16\pi^2 KTT}{g_m} \eta^2 A_r^2 I_2 B^3 \right)$$

(7)
where \( q \) is electronic charge, \( R \) - responsivity of the receiver, \( B \) - equivalent noise bandwidth which is equal to the modulation bandwidth, \( I_{bg} \) - background noise, \( P_r \) - transmitted optical power, \( h \) - channel gain, \( K \) - the Boltzmann constant, \( T \) - absolute temperature, \( G \) - open loop voltage, \( /u1D702 \) - input capacitance of PD, \( G \) - open loop voltage gain, \( \Gamma \) - FET channel noise factor, \( g_{m} \) - FET transconductance.

After optical to electrical conversion, the achievable data rate per bandwidth for \( k \)th user is given as (L. Yin et al. 2016)

\[
R_k = \begin{cases} 
\frac{1}{2} \log_2 \left( 1 + \frac{(h_k a_k)^2}{\sum_{i=k+1}^{K} (h_i a_i)^2 + 1} \right), & k = 1, \ldots, K - 1 \\
\frac{1}{2} \log_2 \left( 1 + \frac{\rho (h_k a_k)^2}{h_k a_k} \right), & k = K 
\end{cases}
\]

(8)

where \( \rho = \frac{P_{elec}}{N_0} \) represents the transmit SNR and scaling factor of \( \frac{1}{2} \) is due to the Hermitian symmetry.

The schematic block diagram of downlink NOMA-VLC system is represented in Fig. 2a. It has been assumed that user-1,...,user-k,..., user-K are sorted in an ascending order according to their channels, i.e. \( h_1 \leq h_2 \leq \ldots \leq h_K \). Based on NOMA concept, users are served by the transmitter at the same time/code/frequency, but with different power levels \( P_1, \ldots P_k, \ldots, P_K \) [L. Yin et al. (2016)]. The modulated bipolar message signals \( S_1, S_2 \ldots S_k \ldots S_K \) are superposed in power domain based on the channel state information (CSI) so that the message to the user with the weaker channel condition is allocated more transmission power, which ensures that this user can detect its message directly by treating the other user’s information as noise. Then a fixed DC bias is added to obtain unipolar signal for intensity modulation and direct detection (IM/DD) [L. Yin et al. (2016)]. The signal is finally transmitted through the LED and AWGN gets added to it in the indoor multipath channel before it is captured by photodetector. In the receiver side, the received optical signal is converted into electrical signal using photodetector. Finally, after removal of DC term, the SIC is carried out at the \( k \)th user such that user with the stronger channel

\[\text{Fig. 2} \quad \text{Schematic block diagram of downlink k-user NOMA-VLC system}\]
condition needs to first detect the message for its partner, then subtract this message from its observation, and finally decode its own information.

4 Results and discussion

The SIC based decoding order between the multi-users of the LED is decided by the channel gain of each user. On simplification, the channel gain can be stated as (Marshoud et al. 2016)

\[ h \propto \frac{1}{d^{(m+3)} \sin^2(\text{FOV})} \]  

\[ (9) \]

From above Eqn. it can be seen that the channel decoding order depends on the three factors; the Euclidean distance between LED and kth user, the FOV of the receiver and lastly semi-angle of the LED.

All the simulations have been done using MATLAB (2019 version) software. The parameters and their corresponding values used in simulation are provided in the Table 1.

Figure 3 shows the flow chart of BER and sum rate simulation using LOS and first reflection signal.

4.1 BER performance analysis

Practically, the receiver captures not only LOS signal but non-line-of-sight (NLOS) signals are also received by it and hence in this section the BER performance using LOS as well as LOS along with first reflection (L-R1) signal has been analyzed. Figure 4a, b respectively show the BER performance for two-user & three-user system using LOS signal w.r.t transmitted energy against AWGN’s power spectral density. In the BER simulation, three different values 30°, 50°, and 70° of the semi-angle \( \phi_{1/2} \) have been considered. The result of Fig. 4a shows that as angle \( \phi_{1/2} \) decreases, the error probability of user-1 & user-2 increases. For example, at 70 dB SNR, the BER of user-1 is 7.49 \times 10^{-3}, 4.88 \times 10^{-3} and 1.03 \times 10^{-1} for \( \phi_{1/2} = 70^\circ, 50^\circ \) and 30° respectively. Similarly, for user-2, error probability is 4.89 \times 10^{-2}, 5.84 \times 10^{-2} and 3.73 \times 10^{-1} when \( \phi_{1/2} = 70^\circ, 50^\circ \) and 30° respectively. It can be observed that the best BER performance is achieved at \( \phi_{1/2} \) equals to 50° and 70° for user-1 and user-2 respectively. However, the BER curves of Fig. 4b show that the error probability for user-1 at \( \phi_{1/2} \) of 30°, 50° and 70° degrades to 8.31 \times 10^{-3}, 4.46 \times 10^{-2} and 2.67 \times 10^{-1} respectively. Likewise, the error probability for user-2 increases to 4.86 \times 10^{-1}, 3.02 \times 10^{-1} and 2.59 \times 10^{-1} using \( \phi_{1/2} = 30^\circ, 50^\circ \) and 70° respectively. Also, for user-3, the error probability is 4.86 \times 10^{-1}, 3.3 \times 10^{-1} and 2.9 \times 10^{-1} when \( \phi_{1/2} = 30^\circ, 50^\circ \) and 70° respectively. Therefore, the optimal value of \( \phi_{1/2} \) for user-1 is 30° whereas for user-2 & user-3, it is 70°. Thus, it is observed that there is optimal value of semi-angle of LED for a standard room size of 5 m × 5 m × 3 m at which best BER best performance is achieved for multi-user NOMA-VLC system using LOS signal. However, the optimal value of semi-angle of the LED can be different depending on the number of users & therefore proper investigation is to be done before implementing indoor multi-user NOMA-VLC system. The BER curves in Fig. 4b also shows that for all three users, the successive interference cancellation becomes inefficient for large value of semi-angle of the LED (\( \phi_{1/2} \) equals to 70°). The performance of
far user is better than the near user because in the NOMA system the power allocation coefficient for the far user is more. However, the total transmitted power remains constant and hence the power allocation coefficient for each user decreases as the number
of users increases. Further, the increase in semi-angle leads to larger optical attocell which causes an increase in the path loss [L. Yin et al. 2016]. Also, the channel correlation between multi-users (when users have increased from two to three) starts increasing with the increase in the semi-angle of the LED. All these factors lead to poor successive interference cancellation for the users when the semi-angle of the LED increases along with an increase in the number of users. The saturation of BER graphs seems to be occurring all of sudden when the semi-angle of the LED increases from 50° to 70° but this is not true. Figure 4c shows the gradual increase in the probability of error when the semi-angle is increasing from 50° with a small increment of 2° i.e. 50°, 52°, 54°, 56°. It can be observed that for the semi-angle beyond 54° the SIC method fails to decode the signals and there is saturation in the BER curves i.e. BER does not reduce. Since, the channel gain is the order of $10^{-4}$, the electrical path loss at the receiver side is -80 dB and so, there is an offset of 80 dB with respect to received $E_b/N_0$ in Fig. 4.

Figure 5a, b show the BER performance of LOS plus first reflection signal (L-R1) using different values of semi-angle of the LED for two-user and three-user system respectively. The result shows that the bit error rate increases with decrease in semi-angle of the LED (same trend as shown in LOS). However, the error probability using L-R1 signal is more

![Graphs showing BER performance](image-url)
as compared to the previous case i.e. LOS signal. In Fig. 5a, for 80 dB SNR, the error probability for user-1 is $1.66 \times 10^{-2}$, $3.48 \times 10^{-2}$ and $1.42 \times 10^{-1}$ using $\theta_1 = 70^\circ$, $50^\circ$ and $30^\circ$ respectively. Similarly, for user-2, the BER is $4.90 \times 10^{-2}$, $8.62 \times 10^{-2}$ and $5.35 \times 10^{-1}$ using $\theta_1$ of $70^\circ$, $50^\circ$ and $30^\circ$ respectively. Thus, optimal value of $\theta_1$ is $70^\circ$ which gives minimum bit error rate in two-user system. This is because number of reflected light rays increases as $\theta_1$ increases so captured light rays through the receiver’s FOV are also more. Nonetheless, as seen from Fig. 5b, the SIC method fails to decode the user’s intended signal as the number of users increases to three using L-R1 signal. The reason is that channel correlation increases when the number of user increases. Thus, to accommodate more users without performance degradation, we must increase the transmit power.

Moreover, a new problem called SIC error propagation also occurs when the number of users is large. For example, in a three-user system, user-3 must perform SIC for user-1 & user-2’s data. If user-1’s data is decoded in error, then this will lead to a wrong signal being subtracted in the SIC process, which would lead to decoding of user-2’s data erroneously and this error propagates on to the decoding of user-3’s data.

In such scenario the concept of optical attocells can be implemented to make the channel gain uncorrelated as suggested by Haas (2013). Hence, choosing the optimal value of semi-angle of the LED not only depends on the number of users but it also depends on the reflected signals. Therefore, to achieve optimum BER performance, factors such as indoor room scenarios as well as requirements in accordance with the NOMA-VLC system i.e. number of users, position of transmitters & receivers, semi-angle of the LEDs etc. is to be considered.

We have simulated the error probability Vs. power allocation coefficient (of far user) for two-user and three-user system with different values of semi-angle i.e. $70^\circ$, $50^\circ$ & $30^\circ$ using LOS signal as shown below in Figs 6a, b. The result shows that the BER performance for user-1 (far user) improves for higher values of $\alpha$ (greater than 0.5). The reason behind the improved performance of far user is that as $\alpha$ increases the power allocated to far user also increases. For user-2, the BER increases for region $0 < \alpha < 0.2$ then remains constant up to $\alpha = 0.5$ thereafter decreases for $0.5 < \alpha < 0.8$ and then increases for $\alpha > 0.8$. It can be observed that when $\alpha$ is less than 0.2, the BER for user-2 using $\theta_1$ of $30^\circ$ is more than BER achieved using $\theta_1 = 50^\circ$ & $70^\circ$. Also, the BER for $\alpha > 0.5$, the user-2 has less error probability when $\theta_1 = 70^\circ$ than the BER achieved using $\theta_1$ of $30^\circ$ & $50^\circ$. The result displays that the average (of both users) error probability is minimum at $\alpha$ of 0.8.
It means that if we want both users to fairly benefit from NOMA, the optimal power allocation coefficient is 0.8. For three-user system, it is apparent from Fig. 6b that the user-1 exhibits the low bit error rate as compared to user-2 & user-3 using $\phi_{1/2} = 30^\circ, 50^\circ$ and $70^\circ$. Therefore, the result also justifies the outcome of Fig. 4b in context that when number of users increases then SIC method fails to decode the higher order users. This is because as the number of users increases in the network then strongest user will be allocated less and less power. Figure 6c is representing 6a only with minor changes. The plot is shown for varying $\alpha$ (0.4–0.85) at SNR of 123 dB. In this plot, we have done simulation for additional semi-angle e.g. $60^\circ$ to show comparison with previous research work (Dixit and Kumar 2021a, b). From the plot it can be seen that when $\alpha$ is increasing, the BER for user-2 (near user) is increasing and for user-1 (far user), the BER is decreasing. The simulated BER graph for far user and near user using $60^\circ$ semi-angle value matches with the results demonstrated by Dixit and Kumar (2021a, b).

4.2 Sum rate analysis

Figure 7 shows the simulated curves of sum rate vs. normalized offset ($l/L$) for different values of semi-angle of the LED using LOS signal. The normalized offset of user-1 is defined w.r.t user-2 as $l/L$ where L is the maximum coverage range inside the room. The sum rate vs. normalized offset has been simulated for different values of semi-angle of
the LED (20°, 30°, 40°, 50°, 60° & 70°). The result shows that as the position of user-1 is shifted towards the edge of the room, the sum rate decreases. The decrease in sum rate is not clearly evident from Fig. 7 (curves appear straight horizontal line) and so for better clarity it has been shown in the inset diagram with only three curves corresponding
to $50^\circ$, $60^\circ$ and $70^\circ$ of semi-angle. The result displays that with increase in semi-angle, the sum rate increase and reaches to its peak value and thereafter it starts decreasing with further increase in semi-angle. The average value of each curve for different offset values has been calculated and plotted against semi-angles as shown in Fig. 8. It can be observed that the peak average sum rate of 278.84 Mbps is achieved at $\varphi_{1/2}$ of $50^\circ$. Thus $\varphi_{1/2} = 50^\circ$ is the optimal value of semi-angle of the LED for two user system at which maximum sum rate is achieved in the room whose dimension is $5 \times 5 \times 3$ m. The optimal value of $\varphi_{1/2}$ can be different for different number of users (discussed previously). Consequently, it can be noted that the semi-angle of the LED can’t be increased arbitrarily to any value in order to improve BER.

Since, in the previous discussion, reflected signals were considered for BER performance analysis therefore, the sum rate vs. offset has been simulated using first reflection signal. Figure 9 shows the sum rate vs. offset for blocked LOS signal (first order reflection signal). The result shows the opposite trend from that observed in Fig. 7 i.e. the sum rate increases with increase in the offset. This is due to the fact that more optical power is received by user-1 as it is shifted towards the edge of the wall because the wall acts as light source (reflected light) for the user-1. The result also displays that the sum rate keeps on increasing with increase in semi-angle of the LED. It is because greater number of light rays are incident on the walls using higher semi-angle of the LED, and therefore numbers of reflected light rays captured through the FOV of the receiver are also more. Moreover, it is evident from the simulation curves that the sum rate is almost zero for $\varphi_{1/2} = 20^\circ$ and $30^\circ$. It is because the emitted light rays from the LED are confined in very narrow beam and so no light rays are incident on the surface of walls and therefore users are in dark zone. Thus, it can be observed that the multipath reflected signal as well as semi-angle of the LED play a crucial role for the multi-user NOMA-VLC system (Fig. 10).
The Fig. 11 shows the sum rate Vs SNR with different values of $\varphi_{1/2}$ for two-user and three-user system. The result shows that the as semi-angle of LED increases from 30° to 70°, the sum rate of two-user and three-system also increases. By increasing the semi-angle of the LED, sufficient optical power is received by each user’s PD. It is also observed that for three-user system, the achieved sum rate is more than the sum rate achieved using two-user system. The increase in sum rate with increase in number of users is due the reason that NOMA offers better capacity than orthogonal multiple access (OMA). But this works as long as interference levels are manageable and strongest user is given a respectable amount of power (although strongest user is allocated least power). It has been found that the as number of users in NOMA is increased, the sum capacity of network initially increases and then drops and saturates. The drop off point can be regarded as the maximum limit on the number of users which can be supported into the network without any performance degradation. However, if a greater number of users are to be accommodated without performance degradation, then transmitted power also needs to be increased. The sum rate simulation for two-user & three-user system has been shown separately as well as in common figure for better comparison and clarity.

4.3 Outage performance analysis

The essence of shadowing without the discussion of outage probability remains incomplete and so the outage performance analysis has been presented in this section. Figure 12 shows the outage probability for blocked LOS scenario against target rate of far user. It can be observed that the outage probability increases with reduction in semi-angle of the LED when the target rate of far user increases. For the semi-angle values of 30° the outage
probability (for target rate beyond 3bps/Hz) reaches to 100 percent for both users e.g. the coverage area becomes zero percent. This is because reduction of signal due to shadowing is greater than the margin when semi-angle reduces. This result supports the outcomes discussed in previous section for sum rate using $20^\circ$ and $30^\circ$ values of semi-angle. Table 2 shows the comparison of pros & cons, future scope of our proposed work with previously
| References                  | Room size  | No of users       | Modulation technique | LOS/ NLOS | Performance analysis by changing | Limitations/ Future scope                                                                 |
|-----------------------------|------------|------------------|----------------------|-----------|----------------------------------|------------------------------------------------------------------------------------------|
| Marshoud et al. (2017)      | 4 m × 4 m × 3 m | Three-user system | OOK                  | LOS only  | FOV                              | Shown only BER results<br>Not shown the impact of number of users on the performance<br>Not shown the effect of multipath signal |
| Dixit and Kumar (2021a, b) | 5 m × 5 m × 3 m | Two-user system  | OOK                  | LOS only  | FOV                              | Not found optimal $\alpha$ at which lowest average BER is achieved<br>Outage or coverage probability not discussed<br>Not shown the effect of increase in number of users on the performance<br>Not analysed the performance using multipath signal |
| Liu et al. (2019)           | 4 m × 4 m × 3 m | Two-user system  | M-PSK, M-PAM, M-QAM | LOS only  | Different order of modulation    | Not discussed the effect of number of users on user's performance<br>Not shown the effect of offset<br>Not shown the coverage probability<br>Not discussed the impact of multipath signal |
| Proposed work               | 5 m × 5 m × 3 m | Two-user system  | OOK                  | LOS + NLOS| Semi-angle of LED<br>Power allocation coefficient of far user<br>Position of far user w.r.t to near user<br>SNR at receiver<br>Target rate of far user | The work can be extended to MIMO-NOMA-VLC system<br>The impact of higher order i.e. second order reflection signal can be investigated |
published research works. Table 3 presents comparative analysis of our proposed simulated results with different research articles.

### Table 3 Comparative analysis of simulated results with previous research work

| Comparative analysis of BER Vs. SNR for simulated result of Fig. 4a |
|---------------------------------------------------------------|
| Semi-angle of the LED | $\phi_{1/2} = 50^\circ$ | $\phi_{1/2} = 50^\circ$ | $\phi_{1/2} = 60^\circ$ | $\phi_{1/2} = 50^\circ$ |
| Modulation technique | OOK | OOK | OOK | BPSK |
| Number of users | Two | Three | Two | Two |
| BER | Near user | Far user | Near user | Far user | Near user | Far user | Near user | Far user |
| $10^{-1}$ | 60 | 68 | 105 | 97 | 128 | 124 | 105 | 90 |
| $10^{-2}$ | 69 | 75 | 112 | 110 | 131 | 127 | 110 | 95 |
| $10^{-3}$ | 72 | 77 | 117 | 115 | 132 | 129 | 112 | 97 |
| $10^{-4}$ | 74 | 79 | 118 | 117 | 133 | 131 | 115 | 99 |

| Comparative analysis of BER vs. power allocation factor for simulated result of Fig. 6a |
|------------------------------------------------|
| Avg. BER | Power allocation factor for far user in proposed work (Fig. 6a) | Power allocation factor for far user (Marshoud et al. 2017) (Fig. 3c) | Power allocation factor for far user (Dixit and Kumar 2021a, b) | Power allocation factor for far user (Liu et al. 2019) (Fig. 12a) |
|------------------------------------------------|
| $10^{-1}$ | 0.55 | 0.15 | 0.76 | 0.01 |
| $10^{-2}$ | 0.65 | 0.25 | 0.92 | 0.05 |
| $10^{-3}$ | 0.70 | 0.27 | 0.95 | 0.08 |
| $10^{-4}$ | 0.75 | 0.30 | 0.99 | 0.14 |

| Comparative analysis of Sum rate (Mbps) vs. Normalized offset for Fig. 7 |
|------------------------------------------------|
| Normalized offset | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1 |
|------------------------------------------------|
| Proposed work | 274.15 | 273.94 | 274.02 | 274.01 | 272.83 | 271.72 | 271.1 | 269.5 | 267.4 | 265.8 |
| Wang et al. (2020) | 252 | 254 | 253 | 252 | 250 | 245 | 240 | 230 | 220 | 190 |

### 5 Conclusion

In the present paper, BER and sum rate performance of NOMA-VLC using single LED and two-user & three-user system have been investigated for LOS as well as L-R1 signals using different values of semi-angle of the LED. The results show that the BER as well as sum rate of LOS and reflected signals have best performance at optimal semi-angle. However, the optimal value of semi-angle of LED changes with number of users as well as order of reflection of signal. The outage probability for blocked LOS signal display that the for small angle of LED, the outage probability reaches to 100 percent. The overall results show that semi-angle of LED in addition to multipath signal plays a significant role in multi-user NOMA-VLC system. Therefore, proper investigation is to be done before implementing downlink multipath multi-user NOMA-VLC system.
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Declarations

Conflicts of interest The authors declare that they have no conflict of interest.

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