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Performance Analysis of MIMO Techniques for a Pyramid Receiver in an Indoor MIMO-VLC System

Aamir Ullah KHAN*[1], Sultan ALDIRMAZ ÇOLAK[1], Yasin ÇELİK[2]

Abstract

In an indoor multiple-input multiple-output (MIMO) visible light communication (VLC) system, line of sight (LoS) channel links are present between a light-emitting diode (LED) based transmitter and a photodetector (PD) based receiver. The PDs in the receiver are closely packed resulting in a high channel correlation. To overcome channel correlation and improve the performance of the MIMO-VLC system, angle diversity receivers (ADRs) are commonly employed. The channel matrix entries depend on the normal vectors of the PDs, which in turn depend on the elevation angle (EA) of the PDs. Thus, by having normal vectors pointing in different directions, the channel correlation can be considerably reduced. This paper considers a special type of ADR called pyramid receiver (PR) and employs a 4x4 MIMO-VLC system. In this paper, different MIMO algorithms such as repetition coding (RC) and spatial multiplexing (SMP) are considered to exhibit and compare the bit-error-rate (BER) performance of the fixed and variable EA MIMO-VLC systems. The results show that an SMP-employed MIMO-VLC system outperforms the RC-employed MIMO-VLC system. SMP results in an spatial multiplexing gain that varies linearly with the number of LEDs whereas RC does not yield any spatial multiplexing gain. To attain the same spectral efficiency i.e. 4 bit/s/Hz, a larger signal constellation size is required for RC employed MIMO-VLC system to achieve the same BER as of an SMP employed MIMO-VLC system. Similarly, the BER performance of variable EA MIMO-VLC systems is better as compared to fixed EA MIMO-VLC systems.

Keywords: Angle diversity receivers, optical wireless communications, pyramid receiver, visible light communication

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1. INTRODUCTION

Wireless connectivity has become an absolute necessity nowadays. It is no more regarded as a luxury but as an utter need of time. Due to technical developments, the cost of handheld devices has become relatively lower over recent years, due to which their availability is no more an issue. According to the wireless world research forum, 7 billion people will be served by 7 trillion devices by the end of the year 2020. Similarly, it is also expected that the number of wirelessly connected devices will reach 1000 times the human population [1]. Similarly, a recent study [2] has anticipated that mobile networks will become the major source of data and around 77 exabytes of data traffic will be transmitted by mobile networks every month.

The number of digital users has been growing over recent years and there has been a rapid increase in the demand for wireless data communication. With the saturation of the radio frequency (RF) spectrum, it is very difficult to meet the growing demand for high-speed connectivity. In order to alleviate the looming spectrum crisis, scientists have started to look for new means to accommodate the new users. In recent years, optical wireless communications (OWC) specifically visible light communication (VLC) has become a prevalent wireless communication technique among researchers to complement traditional RF communications, especially for indoor environment-based communications. VLC is viewed as a very promising complementary technology to traditional RF-based indoor technologies, due to the inherent advantages of low-cost front-ends, unregulated spectrum, high data rates, and simultaneous illumination and data transmission.

In VLC, the visible part of the spectrum in 390nm-750nm is exploited for communication. In a VLC system, light-emitting diodes (LEDs) are used as transmitters, and photodetectors (PDs) are used as receivers. Air acts as a medium between source and destination. With the advancements in solid-state lighting technology over the years, it is now possible to modulate light at such high frequencies that human eyes cannot detect. Solid-state sources e.g. LEDs will substitute traditional illumination sources as they offer a greater lifetime, lower cost, and lower energy consumption. These properties, along with many others, make VLC an ideal, economic, and suitable choice for communication [3]. Employing white light LEDs as transmitters, VLC has been a rapidly-growing OWC technology and gained much consideration in recent years. In most cases, communication is a secondary function shadowed by illumination. This is what makes VLC different from other wireless communication standards having only the sole purpose of communication.

The modulation capability of commercially available LEDs is very limited. As a result of this limitation, the transmission bandwidth of the VLC systems is restricted to several MHz as compared to the available optical bandwidth of 400THz. As high data rates are required for high-speed communication, this restraint in bandwidth presents a challenge for researchers to design an effective VLC system [4].

Different approaches have been adopted by researchers to overcome the bandwidth limitations of VLC systems and design high-speed VLC systems. The performance of the VLC systems can be improved by employing high-order constellations orthogonal frequency division multiplexing (OFDM) [5]. In [6], OFDM has been shown as a suitable scheme for VLC for achieving high data rates because of combating inter-symbol interference and utilizing the spectrum more efficiently. Due to the physical nature of LEDs and PDs, intensity modulation direct detection (IM/DD) must be used in VLC systems [7]. The traditional OFDM results in polar signals. As IM/DD is employed in a VLC system, therefore, the transmitted signal must be real and positive all the time as negative signals cannot be modulated. Due to this limitation, in [8], different OFDM techniques are specifically designed for IM/DD based VLC systems are compared and analyzed.

With the use of multiple parallel LEDs for illumination and communication in an indoor environment, spectral efficiency can be improved by employing multiple-input multiple-output

(MIMO) techniques. MIMO can enhance the data rate without any additional bandwidth expansion. It was shown that optical MIMO has great potential in improving spectral efficiency for short-range high-speed data transmission [9]. A link adaptation method for the OFDM-based MIMO-VLC system is investigated in [10]. The proposed method supports repetition coding (RC) and spatial multiplexing (SMP) as MIMO modes. The switching of the spatial mode depends on the channel conditions. The proposed MIMO mode selection along with the bit loading scheme results in a more spectral efficient (SE) system while satisfying the target bit-error rate (BER).

In a line-of-sight (LoS) based indoor MIMO-VLC system, the entries of the channel matrix can be highly correlated. This correlation of channel matrix entries can yield a rank deficient channel matrix resulting in poor performance [11]. It is, therefore, important to have an uncorrelated channel matrix. The rank of the indoor MIMO-VLC system highly depends on the geometries of LEDs and PDs. In [12], authors have explored the impact of PDs placement on the performance of the MIMO-VLC system. It is shown that certain PD alignments result in a rank-deficient channel matrix. An irregular PD configuration has been proposed to overcome the issue of the rank deficient channel matrix.

Different methods have been adopted by the researchers to overcome the challenge of channel correlation in an indoor MIMO-VLC system. An aperture-based angular diversity receiver for the MIMO-VLC system is investigated in [13]. It is shown that a well-designed receiver can receive signals from different directions with low multi-stream interference. This results in a well-conditioned channel matrix. In order to obtain uncorrelated channels, an angle diversity receiver (ADR) has been proposed in [14]. A highly uncorrelated channel matrix is obtained by placing PDs on ADR in such a way that normal vectors of PDs point in different directions from one another. The performance of an ADR-based indoor MIMO-VLC can be reduced greatly as a result of inter-cell interference (ICI). In [5], a new angle diversity multi-element receiver is proposed. It is shown that this type of receiver cannot only overcome ICI but also results in robustness against the receiver's random rotations. Similarly, an interference management scheme to overcome the co-channel interference has been proposed in [15]. The authors have employed a constrained field-of-view (FOV) ADR along with least square channel estimation with maximum-likelihood (ML) detector. It is shown that the proposed system in [15] results in superior BER performance. Moreover, the proposed system outperforms the time division multiple access (TDMA) techniques at all positions and orientations of ADR. In [16], a comprehensive lighting configuration for an efficient VLC is presented. An efficient VLC system with mobility and link switching is considered along with illumination, signal-to-noise ratio (SNR), and received power constraints.

The use of pre-equalization methods to increase the bandwidth of white LEDs for VLC systems is discussed in [17]. The impact of different factors e.g., LED's array, FOV angle of the receiver, and the LED's transmission angle, influencing the performance of the MIMO-VLC systems are also elaborated and analyzed in [17]. Different diversity techniques such as select best combining, equal gain combining, and maximum ratio combining for LoS links are analyzed and compared in [7]. The performance of the ADR receiver is also compared with the traditional single PD receiver in terms of signal to interference plus noise ratio (SINR) and area spectral efficiency. It is shown that the ADR performs better as compared to the traditional receiver. Moreover, the SINR suffers from great fluctuations due to ICI in a multi-cell indoor MIMO-VLC system. To improve the performance of such a MIMO-VLC system, a generalized ADR is adopted by researchers in [18].

In [19], the authors have investigated the impact of MIMO modulation schemes on the performance of the indoor MIMO-VLC system. The authors have considered generalized spatial modulation (GSM) and SMP for the LOS and diffused channel links for vertical and angular detectors. It is shown that angular detectors result in a better BER performance compared to vertical detectors. Moreover, GSM outperforms SMP in terms of BER performance. Similarly, different transmission mechanisms such as spatial modulation (SC), RC, and SMP are compared and analyzed in [9]. The overall spectral efficiency is improved by the application of adaptive modulation and per antenna rate coding. Similarly, in [20], a pyramid receiver (PR) based on the principle of ADR is proposed in which the elevation angle (EA) of PDs was varied to generate uncorrelated channel matrix entries. The EA was kept constant for all the PDs for a constant receiver's position. A similar approach was implemented in [21] in which EAs of PDs were varied independently of one another resulting in optimum variable EAs for PDs. As a result of variable EAs, the throughput of the MIMO-VLC improves as compared to the fixed EA MIMO-VLC system.

In this paper, we compare the BER performance of a PR-based fixed and variable EA MIMO-VLC system. The authors in [21] have only addressed the channel throughput and provided a comparison in terms of throughput between fixed and variable EA MIMO-VLC systems. To the best of our knowledge, it is the first time where the BER performance of variable EA MIMO-VLC system for RC and SMP schemes is provided. Moreover, the comparison between fixed and variable EA MIMO-VLC systems has also been done for the first time. For both the fixed and variable EA MIMO-VLC systems, the optimum EA values given in [20, 21] are considered.

The rest of the paper is organized as follows. Section 2 presents the system model for both fixed and variable EA MIMO-VLC systems. Section 3 presents the simulation parameters and simulation results of BER for fixed and variable EA MIMO VLC systems. The paper is concluded and summarized in Section 4.

Throughout the introduction, we have used several abbreviations. To summarize, we have listed them in Table 1.

2. SYSTEM MODEL

In this paper, we have considered an M x N indoor MIMO-VLC system where M indicates the number of LEDs and N is the number of PDs. For optical modulation and demodulation, we have employed IM/DD schemes, respectively. We have only considered shot and thermal noises and they are modeled as additive white gaussian noise (AWGN) and added in the electrical domain at the receiver. We have assumed only LoS components in our scenario. The different stages of a VLC system are shown in Figure 1.

At first, the signal to transmit is modulated using unipolar K-PAM for its output being real and positive. The q_{th} modulated signal is represented as $\mathbf{s_q}$ ε $[0, \ldots., (K-1)]$ where K is the modulation size of the constellation alphabet. This modulated signal is grouped into a vector of length M which is denoted by $\mathbf{s}$ $=[s_0, s_1, s_2, \ldots \ldots, s_{M-1}]^T$. The $\mathbf{s_q}$ signal is sent to

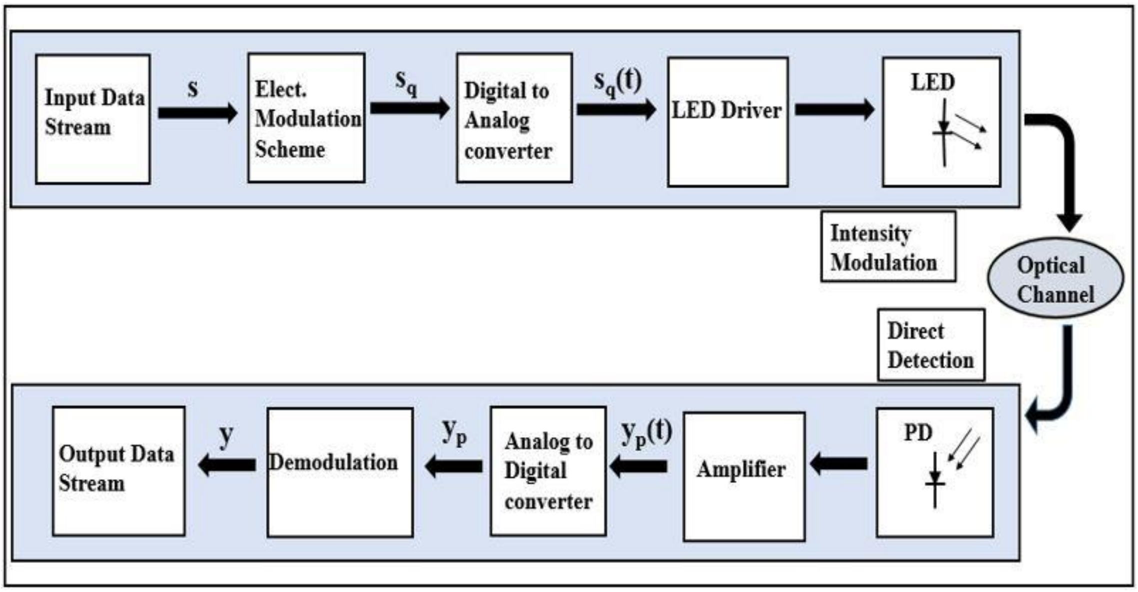

Figure 1 Block diagram of the VLC system adopted from [22]

Table 1 Abbreviations of systems under consideration

Abbr.	
ADR	Angle diversity receiver
EA	Elevation angle
FOV	Field-of-view
GSM	Generalized spatial modulation
IM/DD	Intensity modulation direct detection
LED	Light-emitting diode
ML	Maximum likelihood
PAM	Pulse amplitude modulation
PDs	Photodetectors
PR	Pyramid receiver
RC	Repetition coding
SC	Spatial modulation
SMP	Spatial multiplexing

the digital-to-analog converter (DAC) to form $\mathbf{s_q}$ **(t)** and is sent to the optical transmitter. In the optical transmitter, optical modulation i.e., IM is performed and data is sent to the optical receiver via the optical channel. The current generated at PD as a result of incident photons is sent to an amplifier. The amplified signal is sent to the analog-to-digital converter (ADC) to generate $\mathbf{y_p}$ to form a receive vector of length N as $\mathbf{y_p}$ = $[y_0, y_1, y_2, \dots \dots, y_{N-1}]^T$. The transmitted data is recovered by performing electrical demodulation on the received digital signal **y**. The description of the overall system is given in Equation 1:

$$\mathbf{Y = HS+W}, \tag{1}$$

where **S** is the (Mx1) transmitted signal vector, **Y** is the (Nx1) received signal vector whereas **W** is the (Nx1) noise signal vector. In Equation 1, **H** is the (NxM) channel matrix which can be represented as:

$$\mathrm{H} = \begin{bmatrix} \boldsymbol{h_{11}} & \dots & \boldsymbol{h_{1M}} \\ . & \vdots & . \\ . & \vdots & . \\ \boldsymbol{h_{N1}} & \dots & \boldsymbol{h_{NM}} \end{bmatrix} \tag{2}$$

In Equation 2, h_{mn} represents the channel between the n[th] LED and m[th] PD. It can be mathematically expressed as [14]:

$$h_{mn} = \frac{(\boldsymbol{p}+\mathbf{1})\, \boldsymbol{A_{PD}} \cos^{\boldsymbol{p}}(\boldsymbol{\alpha_{mn}}) \cos^{\mathrm{k}}(\boldsymbol{\beta_{mn}})}{\mathbf{2}\boldsymbol{\pi d_{mn}^2}}, \tag{3}$$

where α_{mn} and β_{mn} should be in the range $\left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$. The value of h_{mn} is considered to be 0 if it is outside the given range of α_{mn} and β_{mn}. In Equation 3, A_{PD} represents the PD's active area, d_{mn} is the distance between LED n and PD m, k is the FOV coefficient, α_{mn} represents the irradiance angle at LED n with respect to PD m, and β_{mn} is the angle of incidence at PD m with respect to LED n. The Lambertian emission order is represented by p in Equation 3 and can be mathematically given as [14]:

$$p = \frac{\ln 2}{\ln(\cos \emptyset_{1/2})}, \quad (4)$$

where $\emptyset_{1/2}$ is the LED's semi-angle that is calculated at half-power [11].

For a particular link between LED *n* and PD *m*, we have three vectors of interest. These vectors determine the values of α_{mn} and β_{mn}, which in turn determine the values of channel matrix entries as given in Equations 4 and 5 of [20]. As shown in Figure 2, these vectors include:

1. $\overrightarrow{A_n}$ is the normal vector in the direction irradiance from LED n,
2. $\overrightarrow{B_m}$ is the vector in the direction incidence from PD m,
3. $\overrightarrow{O_{mn}}$ is the vector from LED n to PD m.

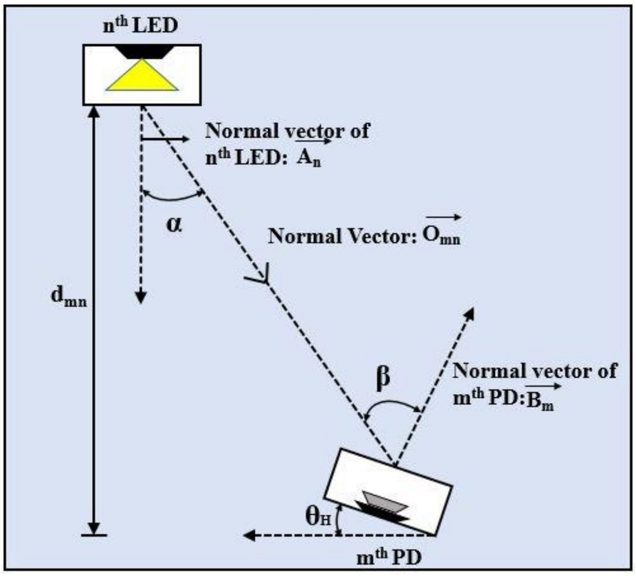

Figure 2 The geometry of LED-PD pair

In our system model, we have assumed channel state information is readily available at the receiver. Similarly, we have assumed that power is allocated uniformly among the M number of LEDs. In our system model, we have assumed different transmission techniques such as RC and SMP. All the considered MIMO-VLC systems employ an ML detector for the detection of the estimated received signal $\hat{s}$ at the receiver. The process of ML detection process can be mathematically expressed as [23]:

$$\hat{s} = arg \max_{S} \rho_y (\boldsymbol{y}|\mathbf{s}, \mathbf{H}) = arg \min_{S} \|\boldsymbol{y} - \mathbf{Hs}\|_F^2, (5)$$

where $\rho_y(\boldsymbol{y}|\mathbf{s}, \mathbf{H})$ represents the conditional probability density function whereas $\|.\|_F$ is the Frobenius norm.

2.1. Transmission Schemes

In our paper, we have employed RC and SMP schemes for the transmission of information from source to destination. RC is the simpler of the two. In RC, the same information is transmitted from all the transmitters such that $s_1 = s_2 = \cdots = s_{M-1} = s_M$. The intensities from different LEDs add up constructively at the receiver enhancing the received optical power. As a result, RC achieves a good performance in free space OWCs. In this paper, a unipolar K-PAM together with RC is considered which results in spectral efficiency of $\log_2 K$ bit/s/Hz. The upper bound BER expression along with BER expression for RC employed MIMO-VLC system is given in Equations 7 and 8 of [23].

Another important transmission mechanism that is commonly adopted for the MIMO-VLC system is SMP. RC results in an increase in reliability. However, that comes at a cost of spectral efficiency as the same information is sent from all the transmitters. SMP results in a more spectral efficient system as independent data streams can be used from all the transmitters simultaneously for the transference of information. SMP employed MIMO-VLC system results in spectral efficiency of $M \log_2 K$ bit/s/Hz where M is the number of transmitters i.e., LEDs. The BER expression for an SMP-employed MIMO-VLC system is given in Equation 10 of [23].

In both the transmission mechanisms, the available optical power is divided equally among all the LEDs. Similarly, the mean transmission power and modulation scheme are also considered the same for both RC and SMP. The intensity levels for K-PAM is given as [23]:

$$I_i^{K-PAM} = \frac{2I}{K-1} i \text{ where } i = 0, 1, \ldots, K-1, \quad (6)$$

where I indicate the mean optical power emitted.

2.2. Coordinate System

In our system model, the respective positions of LEDs and PDs are displayed with the help of normal vectors in the $[x, y, z, \theta, \phi]$ format. The (x, y, z) represents the originating position of the respective normal vector. θ represents the EA from the positive z-axis whereas ϕ represents the azimuth angle from the positive x-axis. The range of θ and ϕ should be $[0, 180^0)$ and $[0, 360^0)$, respectively.

The normal vector $\overrightarrow{B_m}$ of the m^{th} PD located at $(x_{PD}^m, y_{PD}^m, z_{PD}^m)$ can be represented as $[x_{PD}^m, y_{PD}^m, z_{PD}^m, \theta_{PD}^m, \phi_{PD}^m]$ for $1 \le m \le N$ as shown in Figure 3. In a similar fashion, the n^{th} LED's normal vector $\overrightarrow{A_n}$ located at $(x_{LED}^n, y_{LED}^n, z_{LED}^n)$ can be represented as $[x_{LED}^n, y_{LED}^n, z_{LED}^n, \theta_{LED}^n, \phi_{LED}^n]$ for $1 \le n \le M$.

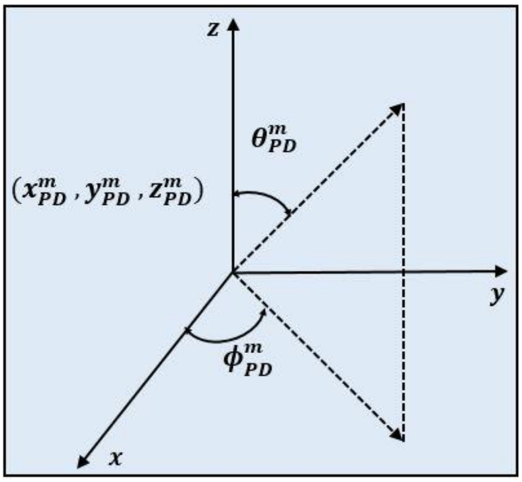

Figure 3 The coordinate system representation

2.3. Placement of PDs in PR

In our system model, we have assumed a circular arrangement of PDs in a circle of radius (r) for $1 \le m \le N$. The respective coordinates of PDs can be represented as [20]:

$$(x_{PD}^m, y_{PD}^m, z_{PD}^m) = \left(x_{PD} + \frac{r\cos 2(m-1)\pi}{N}, y_{PD} + \frac{r\cos 2(m-1)\pi}{N}, h_{PD}\right) \quad (7)$$

In Equation 7, (x_{PD}, y_{PD}) represents the (x, y) coordinates of the m^{th} PD whereas h_{PD} is the height of the receiver from the surface of the ground. As EAs of the PD m can be the same or different from one another depending upon the fixed and variable EA MIMO-VLC systems, the orientation can be defined as:

1. The EA can be different or the same for all the PDs,
2. The azimuth angle should be arranged as: $\phi_{PD} = \frac{2(m-1)\pi}{N}$ such that all the angles are symmetrically aligned.

The PR's horizontal orientation can be varied by ϕ_H resulting in a total azimuth angle of $\phi_{PD}+\phi_H$. The horizontal rotation can be introduced to improve the performance of the MIMO-VLC system as shown in Figure 4.

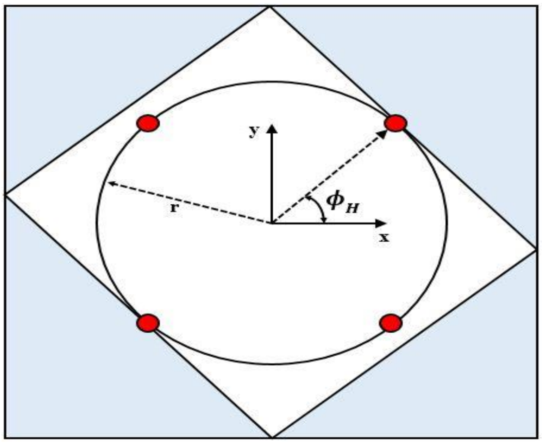

Figure 4 PD placement in PR

Similarly, the variation in the horizontal position of PR may also arise from the random orientation of the PR. Although the PDs are placed very close to one another in a PR, the orientation of PDs can be very different from one another as shown in Figure 5. Finally, the overall indoor setup is shown in Figure 6.

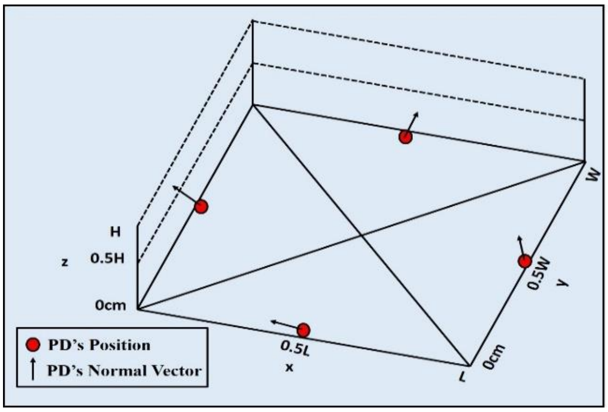

Figure 5 Normal vectors orientation in PR

3. SIMULATION PARAMETERS AND RESULTS DISCUSSION

In order to compare the BER performance of the 4x4 MIMO-VLC system, we have considered similar parameters as given in [20, 21]. A 4mx4mx2.7m dimension room is considered. The LEDs are placed in the ceiling at a height of 2.7m and are arranged in a square manner such that the center of the room and the center of the square coincide with one another. For all the LEDs, a similar normal downward angle is considered e.g. θ_{LED} = [0, 180^0]. The separation distance between LEDs i.e.,d_{tx} is considered the same for all LED separations.

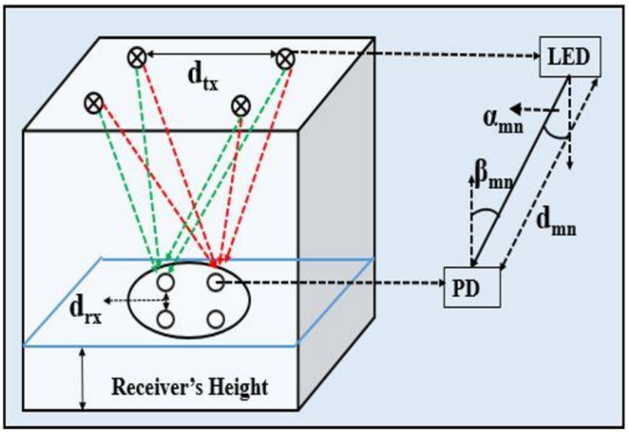

Figure 6 Indoor MIMO-VLC system

Similarly, we have also considered 7 receiver positions as given in Figure 7 according to [20].

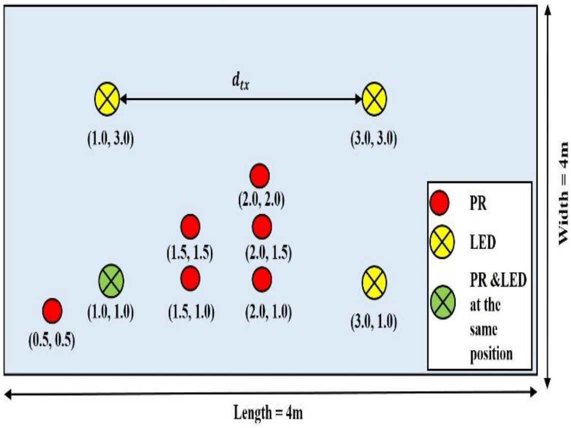

Figure 7 LEDs' placement and considered receiver positions adopted from [22]

The PDs are arranged in a circular manner according to Equation 7 with an r value of 0.5cm. The rest of the simulation parameters are given in Table 2.

Table 2 Parameters for MIMO-VLC system

Parameter	Value
Dimension of room	4m x 4m x 2.7m
Radius for PD placement	0.5cm
Separation between LEDs (d_{tx})	2m
Number of LEDs (M)	4
Number of PDs (N)	4
Active area of PD (A_{PD})	1.5mm^2
FOV coefficient (k)	1.4738
Semi-angle at half power($\emptyset_{1/2}$)	60^0
Height of LEDs (h_{LED})	2.7m
Height of PDs (h_{PD})	0.8m

As our goal is to compare the BER performance of RC and SMP employed MIMO-VLC systems, we evaluated the BER performance at all the considered receiver positions. The BER performance for fixed and variable EA MIMO-VLC systems is evaluated and compared with respect to optimum EA for both systems.

In Figure 8, we have considered the same optimum fixed EA values for respective receiver positions as given in [20]. It has been observed that position 1 performs the best, whereas, position 6 results in the worst performance. The performance gap between different receiver positions is very small i.e., a performance gap of around 2dB is observed for position 1 and position 6 for RC employed fixed EA MIMO-VLC system. Similarly, the BER performance of RC employed variable EA MIMO-VLC system is given in Figure 9. The variable EA values for considered receiver positions are adopted from [21]. For the variable EA MIMO-VLC system, every PD has its own independent EA angle. As can be seen from Figure 9, position 2 and 3 performs the best whereas position 0 results in the worst performance.

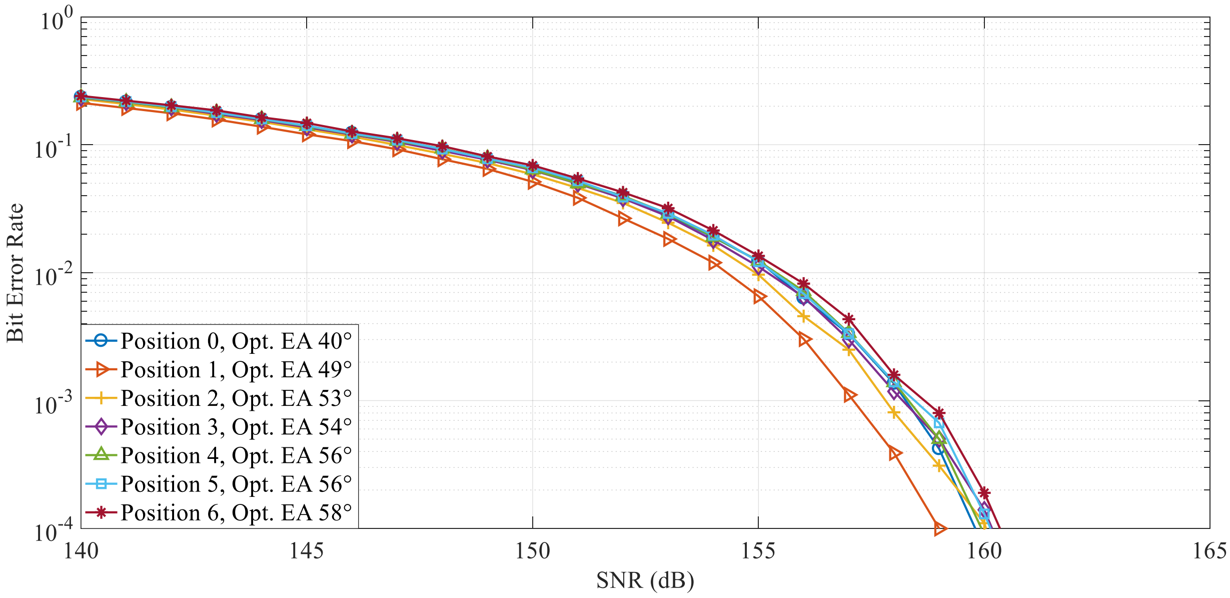

Figure 8 BER performance of RC employed fixed EA MIMO-VLC system

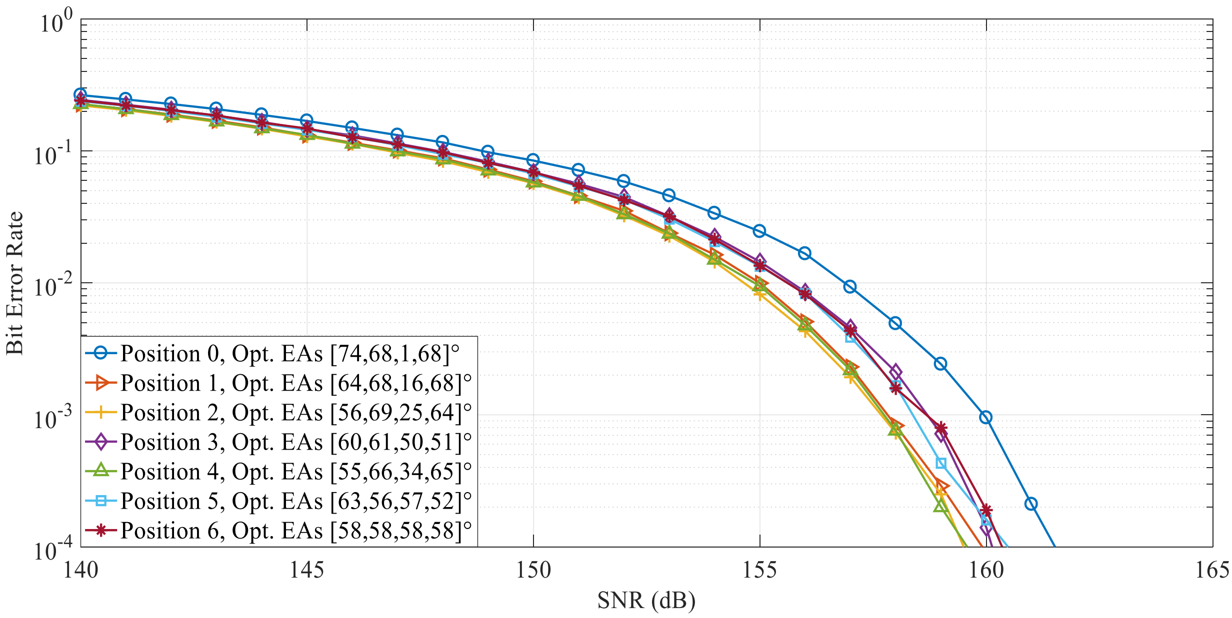

Figure 9 BER performance of RC employed variable EA MIMO-VLC system

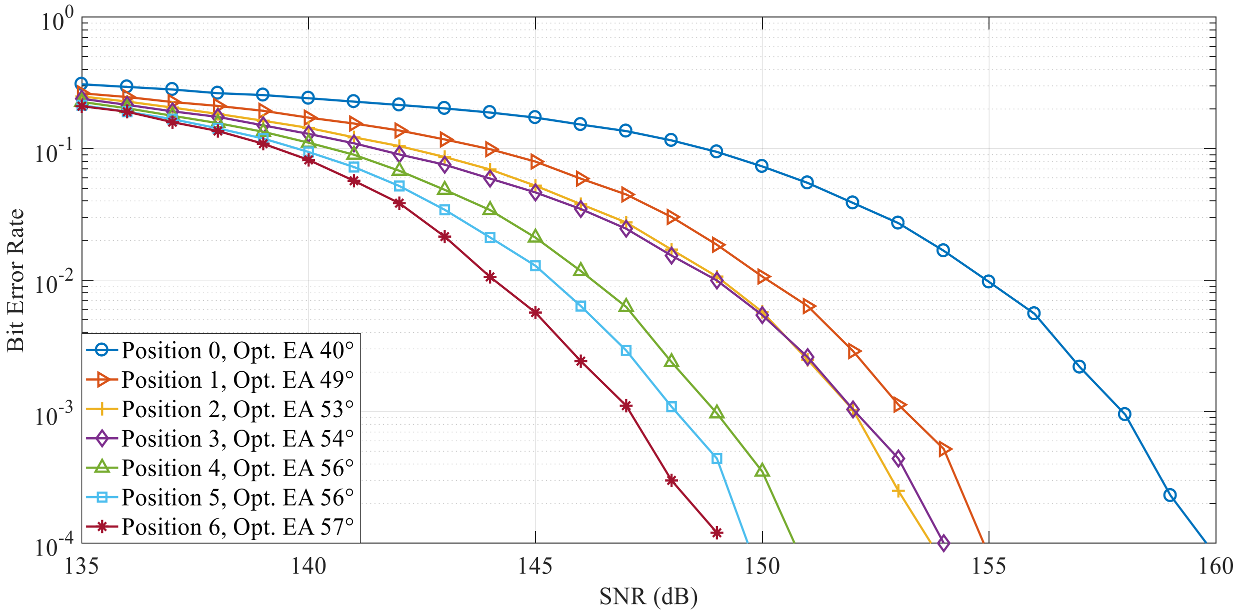

Figure 10 BER performance of SMP employed fixed EA MIMO-VLC system

Similarly, the BER performance of SMP employed fixed EA MIMO-VLC system is given in Figure 10. Position 6 performs the best as it is located at the center of the room. Position 0, which is located at the corner of the room, performs the worst. An SNR gap of 11dB is observed between positions 6 and 0. A similar trend is observed for the SMP employed variable EA MIMO-VLC system as given in Figure 11. As can be seen in Figure 11, an SNR gap of 11dB is observed between positions 6 and 0, where position 6 results in the best performance whereas position 0 results in the worst BER performance.

We have considered three positions i.e., position 1 (1.0, 1.0, 2.7), position 4 (1.5, 1.5, 2.7), and position 6 (2.0, 2.0, 2.7) for the BER performance comparison of RC and SMP employed MIMO-VLC systems. These positions are considered such that a fair comparison can be established between the RC and SMP employed MIMO-VLC systems. As it can be seen from Figure 12, the SMP employed MIMO-VLC system outperforms

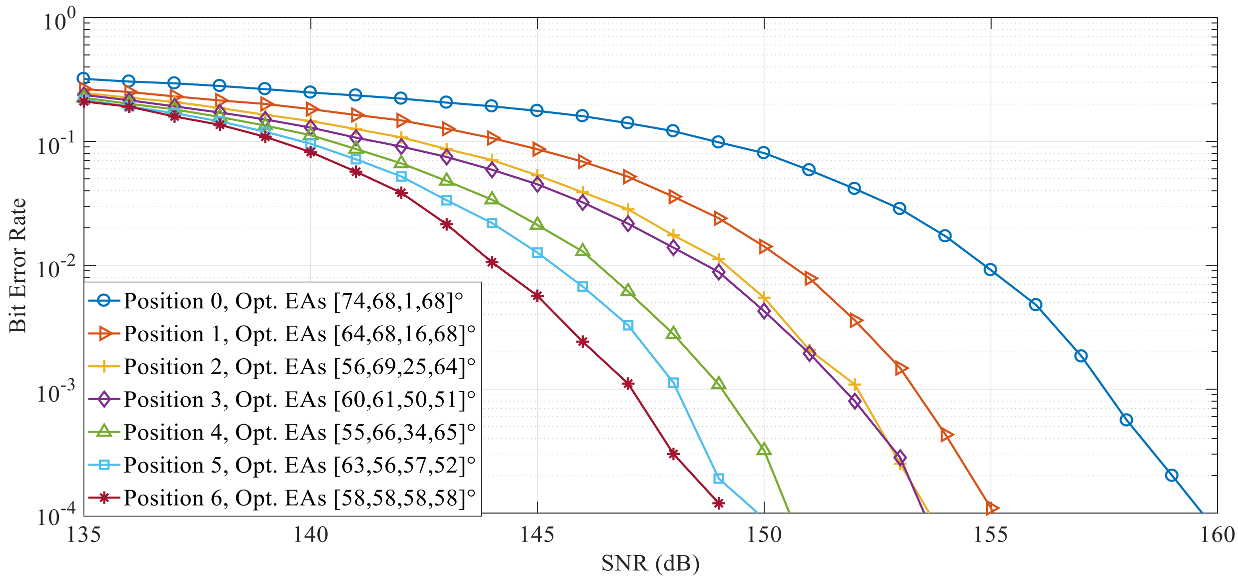

Figure 11 BER performance of SMP employed variable EA MIMO-VLC system

the RC employed the MIMO-VLC system. The performance of both systems depends on the difference between the channel factors. Depending upon the respective position of the receiver and the corresponding channel matrix entries, the performance of RC and SMP employed MIMO-VLC systems varies. The spatial multiplexing gain in an SMP-employed MIMO-VLC system increases linearly with the number of involved transmitters. However, there is no spatial multiplexing gain associated with an RC-employed MIMO-VLC system.

Similarly, to have the same spectral efficiency, we require a larger constellation size for RC as compared to SMP. That's why we have used 16-PAM for RC employed MIMO-VLC system whereas 2-PAM is used for SMP employed MIMO-VLC system. The RC-employed MIMO-VLC system requires an additional SNR of 12.5dB to attain the same performance as SMP employed MIMO-VLC system. For all the considered receiver positions, the performance of the SMP employed MIMO-VLC system is better as compared to the RC employed MIMO-VLC system. A similar trend is observed for RC and SMP employed variable EA MIMO-VLC systems.

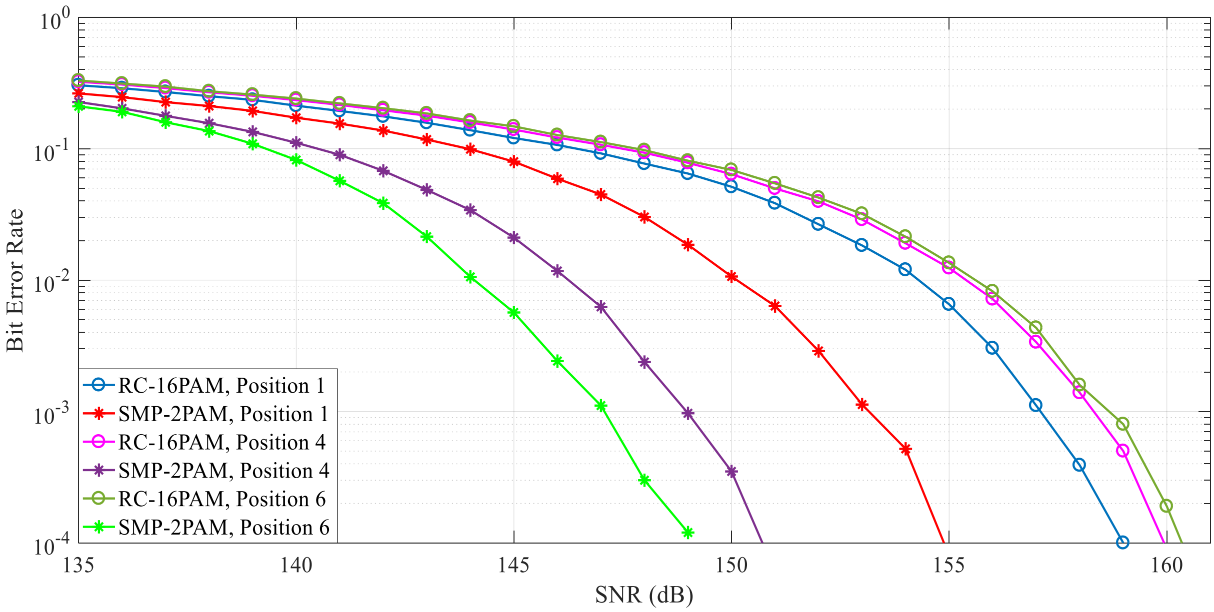

Figure 12 BER performance comparison of RC and SMP

4. CONCLUSION AND SUMMARY

In this paper, we have studied the BER performance of fixed and variable EA MIMO-VLC systems when different transmission schemes are employed for PR in an indoor environment. A 4x4 MIMO-VLC system with a static transmitter array is considered. Several receiver positions are considered across the room to evaluate the BER performance of the RC and SMP employed MIMO-VLC systems. We have shown that for a PR, the channel matrix entries depend on the EA of the PDs. The channel matrix correlation can be reduced by adopting a variable EA MIMO-VLC system. It has been exhibited that SMP results in an increase in the spectral efficiency of an IM/DD-employed MIMO-VLC system. However, a sufficiently low channel correlation is required to take full advantage of the spectrum efficiency presented by SMP. A PR-based MIMO-VLC system results in the low channel correlation required by an indoor SMP employed MIMO-VLC system. It has also been shown that the reliability of the MIMO-VLC system can be increased by adopting RC. The variable EA MIMO-VLC system results in better throughput as compared to the fixed EA MIMO-VLC system. However, the BER performance of fixed and variable EA MIMO-VLC systems is almost identical. It has been shown that SMP employed MIMO-VLC system outperforms RC employed MIMO-VLC systems for both fixed and variable EA employed systems. RC requires a larger signal constellation size to achieve the same spectral efficiency as SMP, which results in degrading the performance of an RC-employed MIMO-VLC system. An additional SNR of 12.5dB is required for an RC employed MIMO-VLC system as compared to SMP employed MIMO-VLC system to achieve a similar BER of 10^{-4} for position 6 of the receiver.

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No conflict of interest or common interest has been declared by the authors

Authors' Contribution
The first author contributed 50%, the second and third authors contributed 25% each.

The Declaration of Ethics Committee Approval
This study does not require ethics committee permission or any special permission.

The Declaration of Research and Publication Ethics
The authors of the paper declare that they comply with the scientific, ethical, and quotation rules of SAUJS in all processes of the paper and that they do not make any falsification on the data collected. In addition, they declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

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