Performance Evaluation of Space Time Coding Techniques for Indoor Visible Light Communication Systems

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***Abstract*—In this paper, the performance of visible light communication (VLC) systems, employing Space Time Block Coding (STBC) and Repetition Coding (RC) techniques for an indoor environment is investigated and analyzed. The indoor channel impulse response is taken into account assuming line-of-sight (LOS) and Non-LOS (NLOS) scenarios. The proposed systems employ multiple transmit light emitting diodes (LEDs) with one and two photodetectors (PDs). Various physical arrangements and placements of the LEDs and PD within the indoor scenario are considered. Simulation results show that, for a specific LEDs and PDs arrangement, RC techniques outperform the respective STBC techniques. Furthermore, a 2x2 multiple-input multiple-output (MIMO) VLC system implementing Alamouti STBC is investigated and compared with the RC scheme using a single receiver. It is shown that adding another PD can achieve a signal-to-noise ratio (SNR) improvement of about 5 dB and 2 dB over the Alamouti and RC schemes with a single PD, respectively.**

***Index Terms*—Visible Light Communications, Alamouti Space Time Block Coding, Repetition Coding, Performance Evaluation.**

I. Introduction

Visible light communication (VLC) systems provide means of delivering both high data rate and illumination services over indoor or short-distances outdoor environments, as shown in Fig. 1. The high data rates are supported due to the higher spectral efficiency since VLC systems have a vast amount of unregulated bandwidth and a limited coverage that enables extensive frequency re-use. Additionally, the short carrier wavelength and large square-law photodetector (PD) used in VLC systems enable a spatial diversity that reveals immunity against multipath fading [1]. The maximum transmitted power in VLC systems is governed by safety considerations, and the noise arising from conventional fluorescent lamps and sunlight will limit the maximum achievable optical signal-to-noise ratio (SNR) [1], [2].

Indoor VLC systems are characterized by smaller distances and they are free from atmospheric degradations; however, VLC links suffer from interference induced by multipath propagation. Hence, the performance of VLC systems can be significantly enhanced by utilizing multiple transmit light emitting diodes (LEDs) and receive PDs at either/both ends of VLC terminals. It is more convenient, however, to add these LED elements at the transmitter side to provide both data communication and the necessary illumination. Hence, multiple-transmit LEDs VLC systems are becoming more

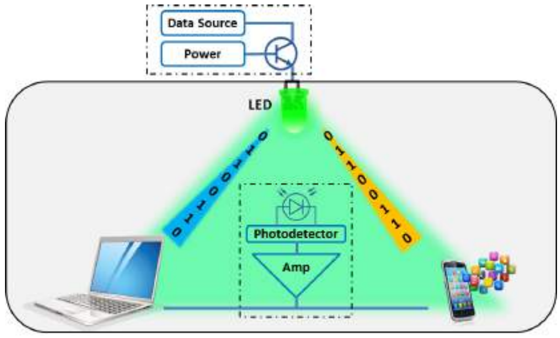

Figure 1: The concept of VLC system.

attractive and this has led researchers to explore the Multiple-Input Multiple-Output (MIMO) techniques for VLC systems with or without Space Time Block Coding (STBC) [2]–[9] as well as the Repetition Coding (RC) techniques [4], [5], [10]. STBC and RC techniques have proven to be promising for the VLC systems [1], since they can increase capacity and improve the performance without any increase in transmitting optical power, and with only a simple linear processing at the receiving end [3], [11].

Previous researches in the literature have considered the infrared (IR) optical wireless communication (OWC) systems, in which the works have studied the STBC [1], [12], the RC [12], [13], and the MIMO [1], [13] systems. Moreover, there have been a limited and specific number of studies of the potential of using STBC and RC for VLC systems. The work in [5] demonstrated the feasibility of binary system employing only Alamouti STBC with one camera receiver in an outdoor image-sensor-based VLC system. The authors in [10] considered a Multiple-Input Single-Output (MISO) VLC system utilizing only RC scheme in which they added a pilot bit to ensure a reliable blind estimation of channel coefficients. The work in [4] proposed a 2×2 MIMO system with only Alamouti STBC in a VLC system using image sensor-based direct detection (DD) with a high-speed camera. The authors in [2] introduced spatial modulation (SM) into layered STC that is used in image sensor-based VLC systems. The work in [6] proposed a design of linear space codes for an indoor MIMO VLC with two transmitters and multiple receivers. The authors in [7] considered RC and SM coding schemes, and they tried to optimize the placement and power of the LEDs in a 4×4 MIMO configuration to obtain a uniform SNR for the desired BER and data rate. However, these works that are

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related to the STBC VLC are limited to the Alamouti STBC and they do not consider higher order coding schemes such as the 4×4 STBC. Furthermore, the works that are related to the RC do not provide any comparison with the STBC scheme to describe or emphasize which one of these two coding techniques is the best to be used with the VLC systems. Additionally, none of these works has devoted to the impact of the line-of-sight (LOS)/Non-LOS (NLOS) scenarios or the LED/PD arrangements on the VLC system performance.

In this paper, a comprehensive numerical performance analysis is conducted for both the STBC and RC, in order to investigate which one of these coding techniques is the best to be used with VLC systems. The performances of these two coding schemes are quantitatively and qualitatively compared considering LOS and NLOS scenarios with various LEDs/PD arrangements. We first consider the Alamouti STBC, 4×4 STBC, and RC with one PD for the LOS and NLOS scenarios. Then, the performance of the Alamouti STBC is studied for the 2×2 MIMO VLC system in a LOS scenario. Each of these proposed systems is analyzed by obtaining the simulation results in terms of SNR vs bit error rate (BER).

The rest of this paper is organized as follows. Section II provides the proposed system model of the VLC system under the STBC and RC techniques with a special focusing on the Alamouti STBC. Section III gives a comprehensive description of the simulation procedure for the LOS and NLOS scenarios that are considered in this paper, along with the performance analysis and discussion of the results obtained. Finally, section IV summarizes the paper.

II. STBC AND RC VLC SYSTEM MODEL

In this work, we consider VLC systems using intensity modulation and direct detection (IM/DD) equipped with N_T transmit LEDs per array and one or two PDs per receive array. Fig. 2 shows the block diagram of the VLC system considered in this paper. The proposed system is studied using STBC (either Alamouti or 4×4 STBC) and RC schemes. It should be noted that most of the analysis considers the Alamouti scheme; however, the 4×4 STBC follows the same concept. In IM/DD VLC scheme, the LEDs require positive and real modulated symbols since the LED cannot differentiate the phase of the input signals [1], [3], [4], [12], [14]. Therefore, the binary phase shift keying (BPSK) to on-off keying (OOK) Mapper block is used to generate the OOK sequences x_1 and x_2 from the BPSK sequences s_1 and s_2, respectively, as shown in Fig. 2. These OOK sequences are then applied to either the STBC encoder (Alamouti or 4×4) or the repetition encoder. The transmitted OOK symbols at two consecutive symbol periods 1 and 2 from each element of the two-LED array in the Alamouti STBC (or at the four consecutive symbol periods 1, 2, 3, and 4 from each element of the four-LED array for the 4×4 STBC) are shown at the top right corner of Fig. 2. This Alamouti scheme is called the modified orthogonal Alamouti STBC [4], [12], [14]. The received signals from PD1 and PD2 at the first symbol period after DD are denoted by r_1 and r_2, respectively, and the respective signals at the second symbol period are denoted by r_3 and r_4 as shown in the bottom right corner of Fig. 2. For the RC, on the other hand, the same OOK symbol is transmitted from all the available LEDs at a particular symbol period [12], [13] as shown in the top right corner of Fig. 2 for the $N_T = 2$ RC case. Note that the same logic is applied for $N_T > 2$. In STBC or RC techniques, there is no additional optical power needed, since the power will be equally divided between all the N_T LEDs [1]. The OOK encoded optical signals will then propagate through the diffused VLC optical channel.

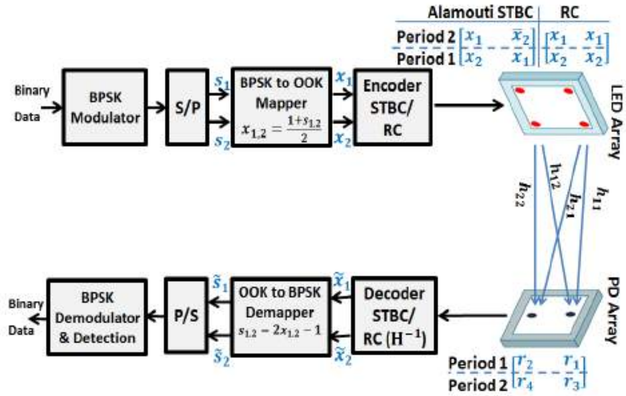


Figure 2: The block diagram of the proposed VLC system that employs STBC and RC techniques.

A. Alamouti STBC System Model

Although we analyze the performance of both 4×4 and Alamouti STBC, we focus on the Alamouti orthogonal STBC with either one or two PDs, as shown in Fig. 2. We assume background noise limited optical receivers in which the shot noise caused by background radiation is dominant relative to the thermal noise [1], [3], [12]. Since the optical channel does not introduce any nonlinearity [3], the overall noise components are modeled as an additive white Gaussian noise (AWGN) [3], [12]. Based on these assumptions, the received electrical signals after DD from the two PDs at the two symbol times, are given by [12], [14]:

$$\begin{aligned}
r_1 &= \frac{R}{N_T}\Big(h_{11}x_1 + h_{12}x_2\Big) + n_1, \\
r_2 &= \frac{R}{N_T}\Big(h_{21}x_1 + h_{22}x_2\Big) + n_2, \\
r_3 &= \frac{R}{N_T}\Big(h_{11}\overline{x}_2 + h_{12}x_1\Big) + n_3, \\
r_4 &= \frac{R}{N_T}\Big(h_{21}\overline{x}_2 + h_{22}x_1\Big) + n_4.
\end{aligned} \tag{1}$$

where R is the PD responsivity. If only one PD is used, we have only r_1 and r_3 in Eq. (1). To obtain the LOS indoor optical wireless channel DC gains h_{ij} for a single LED, the modified Monte Carlo method is used with the arrangement shown in Fig. 3(a), so we have [1], [3], [7], [13]:

$$h_{LOS} = \begin{cases} P_{TX}\frac{(m+1)A_{PD}}{2\pi D^2}cos(\phi)cos^m(\theta) & 0 \leq \phi \leq \Psi_{\frac{1}{2}} \\ 0 & \phi > \Psi_{\frac{1}{2}} \end{cases} \tag{2}$$

where P_{TX} is the transmit optical power, m is the mode number of the Lambertian source, which is related to the half power semi angle ($\Phi_{\frac{1}{2}}$) of the LED by $m = -ln2/cos(\Phi_{\frac{1}{2}})$, $\Psi_{\frac{1}{2}}$ is the field-of-view (FOV) semiangle of the PD, D is the distance between the LED and the PD, A_{PD} is the effective area of the PD, and θ and ϕ are the irradiance and incident angles, respectively as depicted in Fig. 3(a).

At the decision logic of the Alamouti ST decoding, it is assumed that the receiver has a perfect knowledge of the VLC optical channel DC gains [3], [4], [12], [14]. Therefore, the decision statistics formed from the PDs at the two symbol periods are given by [14]:

$$\begin{aligned} \widetilde{x}_1 &= \sum_{i=1}^{N_T} h_{i1} r_i + \sum_{i=1}^{N_T} h_{i2} r_{i+2} - \sum_{i=1}^{N_T} h_{i1} h_{i2}, \\ \widetilde{x}_2 &= \sum_{i=1}^{N_T} h_{i2} r_i + \sum_{i=1}^{N_T} h_{i1} r_{i+2} + \sum_{i=1}^{N_T} h_{i1}^2, \end{aligned} \quad (3)$$

Finally, the maximum likelihood (ML) decision is made separately on each of the transmitted information signals x_1 and x_2 using the metric [4], [14]:

$$m(\tilde{x}_i, x_i) = (\tilde{x}_i - x_i)^2 + (h_{11}^2 + h_{12}^2 - 1)x_i^2, \quad i = 1, 2 \quad (4)$$

and the respective decision rule is to choose $x_i = \hat{x}_i$ if:

$$\begin{aligned} (\tilde{x}_i - \hat{x}_i)^2 + (h_{11}^2 + h_{12}^2 - 1)\hat{x}_i^2 &\leq (\tilde{x}_i - x_i)^2 \\ +(h_{11}^2 + h_{12}^2 - 1)x_i^2. &\quad x_i \neq \hat{x}_i \end{aligned} \quad (5)$$

B. RC System Model

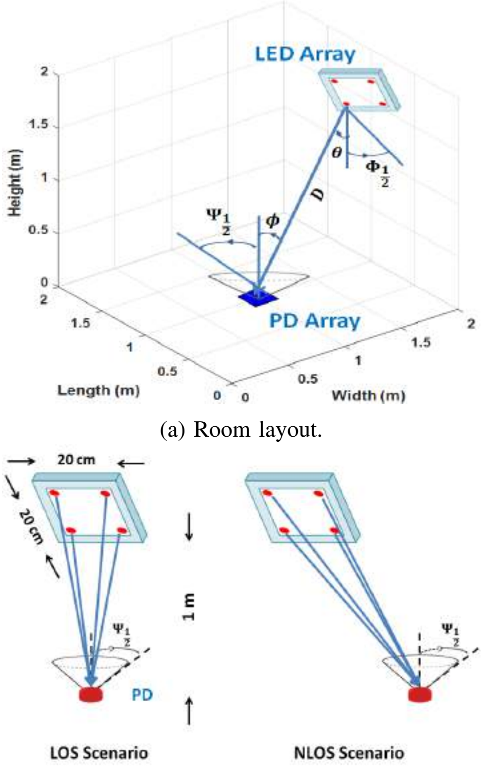
One advantage of using IM in the VLC systems is that transmit diversity can be realized through RC [12], [13], [15]–[17]. In RC, the same OOK signal is simultaneously transmitted from all the available N_T LEDs as shown in the top right corner of Fig. 2 for the $N_T = 2$ RC case. Since the optical channel DC gains h_{ij}'s are real and positive, the intensities coming from the several independent transmit LEDs in RC will add up at the PD side [12], [13]. In RC, the received signal over a single symbol period is given by [12]:

$$r = \frac{R}{N_T} \sum_{i=1}^{N_T} h_i x + n, \quad (6)$$

The major advantage of RC scheme is that it combines the faded signals before noise accumulation, unlike the SIMO scheme which combines the noisy faded signals. Therefore, the performance of RC is better than SIMO scheme [12], [17].

III. Results and Analysis

In this section, the performance of the two coding techniques discussed above will be investigated and analyzed considering various LOS and NLOS scenarios with different LEDs/PD configurations. For the STBC, the modified Alamouti and 4×4 STBC will be considered with one PD at the receiver side. Whereas, the RC is considered with $N_T = 2, 3,$ and 4 LEDs per array and one PD. The BER vs SNR performance results of all these coding schemes are then qualitatively and quantitatively compared. Finally, the impact of using the 2×2 MIMO with Alamouti STBC on system performance will be demonstrated in LOS scenarios.



(a) Room layout.

(b) LOS and NLOS scenarios.

Figure 3: Simulation setup: (a) room configuration (b) LOS and NLOS scenarios.

A. Simulation Setup

Fig. 3(a) shows the communication setup of the VLC system that is considered in the simulation, which is equipped with LED and PD arrays. The room has dimensions of 4 m × 4 m × 3 m. The LED array has a first order Lambertian pattern and is oriented vertically towards the floor. The rest of the simulation parameters are shown in Table I.

B. Performance Evaluation of the LOS Scenarios

In the LOS case, we further consider three scenarios and investigate their impacts on the VLC system performance. These scenarios are: the effects of changing the LEDs spacing within the array, the effects of the separation distance between the LED array and the PD, and the effects of the implementation of 2×2 MIMO Alamouti STBC scheme.

1) Effects of LEDs Spacing Within the Array:

The spacing between LED elements within transmit array

Table I: SIMULATION PARAMETERS

Parameter	Value
Room dimensions	(4, 4, 3) m
P_{TX}	30 dBm
Responsitivity	1
$\Phi_{\frac{1}{2}}$	70°
PD area	1 cm^2
$\Psi_{\frac{1}{2}}$	90°
Electrical baseband modulation	BPSK

must be deliberately adjusted in such a way, small spacing is required so that the LEDs can be integrated in the same end-device, whereas, large spacing is required to exploit the spatial diversity. To carry out this study, we consider the LOS scenario shown in Fig. 3 (b), in which the single PD is placed at the midpoint of the LOS view of the LED array with a 1 m LED-PD separation distance, while the LED spacing is varied from 20 cm to span the whole area of the room's roof.

Fig. 4 shows the performance of all the coding schemes for the case when the LED spacing is 20 cm. At a fixed BER, the RC with $N_T = 2$ outperforms the modified Alamouti STBC. For example, at BER= 10^{-3}, the SNR for RC is around 18 dB compared to around 22 dB for the Alamouti STBC, which means that the RC requires less SNR of around 4 dB, hence it is more power efficient. The performance of the 4×4 STBC is identical to the $N_T = 2$ RC, and worse than the $N_T = 4$ RC. Furthermore, the performance of RC rapidly increases as the number of transmitting LEDs increases. These results clearly conclude that RC is performing better than the STBC when considering the same N_T; therefore, they are the best to be used with VLC systems. Similar conclusions have been reported in [1], [12], [13] for the infrared OWC. It is worthy to mention that these trends are applicable for all the case studies considered in this paper. The major difference is how much reduction/enhancement in SNR achieved in each case study. The performance results of the LOS scenario shown in Fig. 4 are considered as the reference for the quantitative analysis with other scenarios. To examine the impact of increasing the LEDs spacing on the systems performances, Fig. 5 shows the simulation results when the spacing increases to 1 m, for the same PD position (i.e. in the midpoint of the LEDs LOS view) and the same LED-PD separation distance (i.e. 1 m). Increasing the LEDs spacing will deteriorate the performance for all the coding schemes, since we require additional SNR (or power) to achieve a fixed BER. The reason is that the contribution of the LOS component intensity decreases as the LED elements go away from the PD. For example, compared with the reference scenario in Fig. 4, to maintain the same BER of 10^{-3}, an increase in the SNR of about $18 - 13 = 5$ dB is required for $N_T = 4$ RC and around $28-22 = 6$ dB for the modified Alamouti STBC. To capture the general trends of SNR as a function of the LEDs spacing, the position of the PD was fixed to be at the midpoint of the LEDs' LOS view with a LED-PD height of 1 m, while allowing the LEDs' spacing to span over the whole area of the roof (for the 4 LEDs elements or the whole length of the roof for the 2 LED elements). It was shown that the SNR that is required to maintain a particular BER increases approximately linearly as a function of the LEDs spacing for all the coding schemes.

2) Effects of Separation Distance Between LED Array and PD:
In this section, the impact of changing the separation distance between the LED array and PD, on the VLC system performance is investigated. The simulation scenario for this case is similar to the LOS scenario shown in Fig. 3(b) (i.e. the LED spacing is 20 cm and the PD is placed at the midpoint of the LED array LOS view). The only difference is that

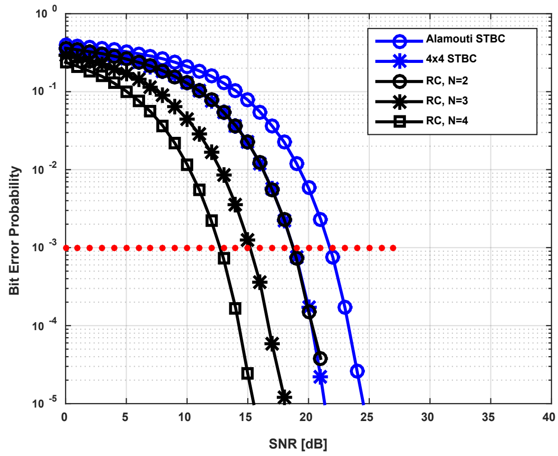


Figure 4: BER vs SNR performance for the LOS scenario shown in Fig. 3(b), with LED spacing of 20 cm, LED array-PD separation of 1 m. This case is considered as the reference for the quantitative analysis.

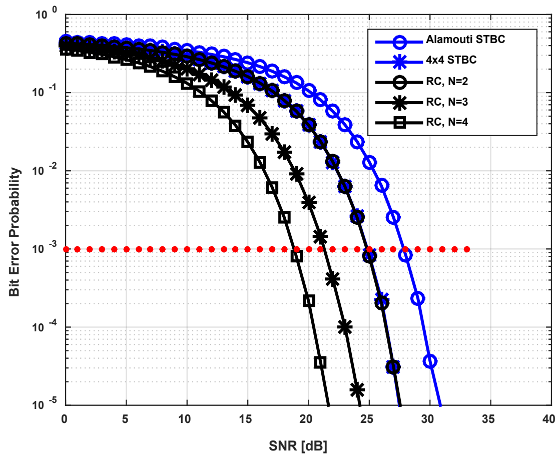


Figure 5: BER vs SNR performance for the LOS scenario shown in Fig. 3(b), with LED spacing of 1 m, LED array-PD separation of 1 m.

the separation distance between the LED array and the PD will now be changed. Fig. 6 shows the performances of all the coding schemes when the separation distance is 3 m. Compared with the reference scenario that is shown in Fig. 4, as the separation increases, the SNR that is required to achieve a particular BER increases. For example, compared with Fig. 4, to achieve a BER of 10^{-3}, we need an extra SNR (or power) of around $32 - 13 = 19$ dB for $N_T = 4$ RC and around $41 - 22 = 19$ dB for Alamouti STBC. If, however, the separation distance is decreased to 50 cm, the results shown in Fig. 7 are obtained. A huge enhancement is now achieved in the SNR performance. For instance, a SNR reduction of around $13-3 = 10$ dB for $N_T = 4$ RC and around $22-13 = 9$ dB for Alamouti STBC is obtained when comparing Fig. 4 with Fig. 7. Therefore, simulation results show that the separation distance between the LED array and PD play a crucial role in the VLC systems. To study the general trends of SNR as a function of the LED-PD separation distance, the

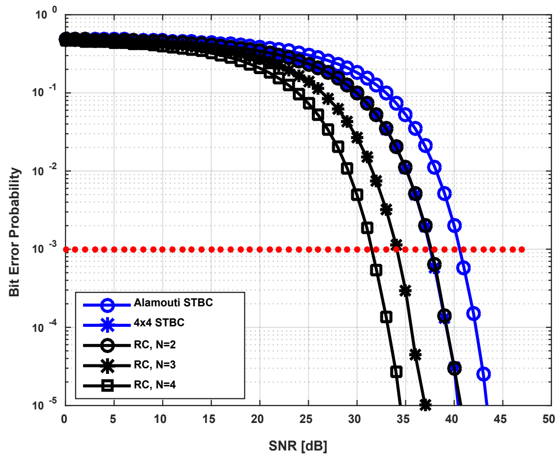


Figure 6: BER vs SNR performance for the LOS scenario shown in Fig. 3(b), with LED spacing of 20 cm, LED array-PD separation of 3 m.

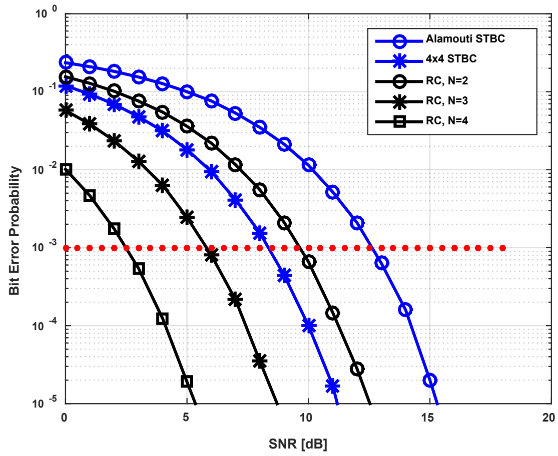


Figure 7: BER vs SNR performance for the LOS scenario shown in Fig. 3(b), with LED spacing of 20 cm, LED array-PD separation of 50 cm.

spacing between the LEDs within array were fixed to 20 cm and the PD was positioned at the midpoint of the LED array LOS view, while allowing the LED array to go apart from the PD to reach the room's roof. It was shown that the SNR that is required to maintain a specific BER increases logarithmically as a function of the LED-PD separation distance. It was also shown that the RC with $N_T = 4$ requires the least amount of additional SNR at any specific separation distance, whereas Alamouti STBC requires the highest additional SNR.

3) 2x2 MIMO Alamouti STBC for VLC:
This section investigates the performance of VLC systems when implementing 2×2 MIMO (i.e. two LEDs per transmit array and two PDs per receive array) with Alamouti STBC. The simulation layout of this case is similar to the LOS scenario shown in Fig. 3(b), except another PD was added and placed 10 cm away from the previous one. Fig. 8 shows the simulation results of three systems: 2×1 Alamouti, 2×2 MIMO Alamouti, and 2×1 RC. The 2×2 MIMO Alamouti

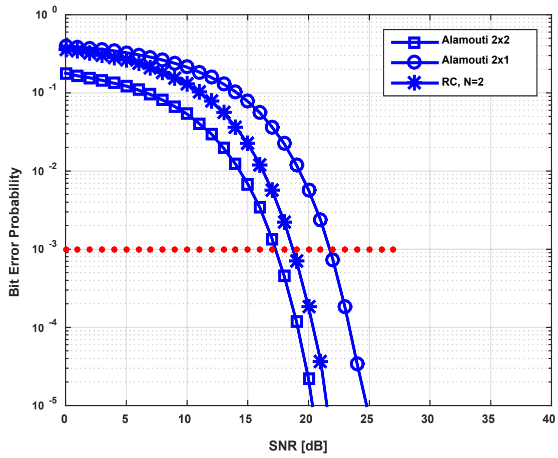


Figure 8: 2×2 MIMO Alamouti STBC BER vs SNR performance for the LOS scenario shown in Fig. 3(b).

STBC has the best performance for any fixed level of BER, followed by the RC then by the 2×1 Alamouti. For example, at a BER of 10^{-3}, the 2×2 MIMO system requires around $22 - 17 = 5$ dB and around $19 - 17 = 2$ dB SNR less than the 2×1 Alamouti and the 2×1 RC, respectively. This enhancement, however, comes with an additional complexity at the receiver side.

C. Performance Evaluation of the NLOS Scenarios

This section investigates the partial NLOS scenario in which only the first reflected paths are considered at the PD. We analyze the effects of the position of the PD with respect to the LOS view of the LED array. Fig. 3(b) shows the scenario in which the single PD is positioned "or misaligned" 90 cm outside the LOS view of the LED array, and Fig. 9 shows the simulation results obtained for all the considered coding schemes. The performance drastically deteriorates due to the decrease in the received optical intensities as the PD is not within the LOS view of the LED array. Comparing these results with the LOS results shown in Fig. 4, to achieve a fixed BER of 10^{-3}, an extra SNR of around $23 - 13 = 10$ dB for $N_T = 4$ RC and around $32 - 22 = 10$ dB for Alamouti STBC are required. The results show that even if the PD is slightly placed in a NLOS communication links with respect to the LED array, the VLC system encounters severe reduction in the performance. In general, it was observed that the SNR that is required to achieve a fixed BER, increases linearly as a function of the PD distance from the edge of the LED array for all the considered coding schemes.

IV. Conclusion

This paper presents performance analysis of the STBC and RC techniques for VLC systems. It is shown that the performance of RC is better than the STBC in a single PD reception case; however, if MIMO VLC implemented, STBC outperforms the RC at an expense of additional complexity at the receiver side. The effects of LOS and NLOS scenarios as

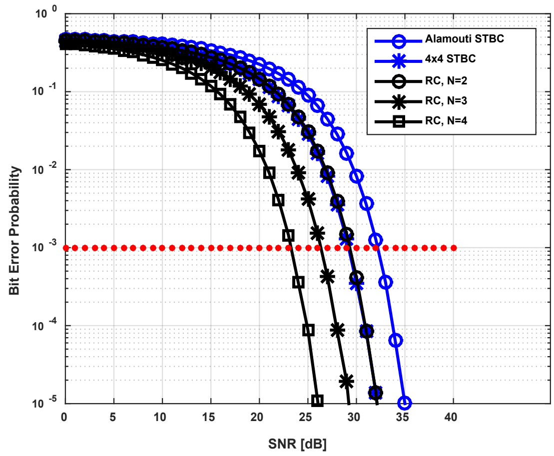


Figure 9: BER vs SNR performance for the NLOS scenario shown in Fig. 3(b), with LED spacing of 20 cm, LED array-PD separation of 1 m and the PD is placed 90 cm apart from the LED array edge.

well as the LEDs/PD physical arrangements on VLC system performance was also investigated. Three parameters were investigated which heavily contribute to the VLC performance which are: the spacing of LEDs within the array, the position of the PD with respect to the LOS view of the LED array, and the LED-PD separation distance. Simulation results show that even if the PD is slightly placed in NLOS communication links with respect to the LED array, the performance of VLC system encounters severe deterioration. Furthermore, proper placement of the PD could enhance the SNR up to 19 dB in LOS scenarios. Our future work is to investigate and analyze the performance of imaging angle diversity for MIMO VLC systems.

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