Visible Light Communication System Employing Space Time Coded Relay Nodes and Imaging Receivers

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***Abstract*—In this paper, authors propose a VLC system, whose source of information is assumed to be a power line, and employs a combination of relaying and multiple-input multiple-output (MIMO) techniques. Precisely, the performance of a VLC system, with relay nodes equipped with a MIMO technique called space time block coding (STBC), is investigated. The bit error rate (BER) performance of the Alamouti coding (AC) scheme, which is a type of STBC, is specifically considered. In order to enhance the overall system reliability, we propose to use an imaging receiver (ImR), in conjunction with the relay-MIMO setup. In comparison to when a nonimaging receiver (NImR) is employed, an improved signal-to-noise ratio (SNR) of 7 dB is observed when an ImR with a specific number of pixels, is used, hence, improving the BER. We also investigate and show that the selected number of pixels and receiver location have an effect on the system BER. SNR values of 9 dB, 11 dB and 15 dB were required to maintain a BER of 10^{-4} for imaging receivers with 70, 50 and 20 pixels, respectively.**

***Index Terms*—Alamouti Coding, Imaging receivers, MIMO, Power line communication, Relays, Space time block coding, Visible light communication.**

I. INTRODUCTION

INDOOR broadband users have conventionally been served by systems based on radio frequency (RF) technology, whose spectrum resource is scarce and already congested [1]. Motivated by the limited RF spectrum resource, a hype of research into alternative communication technologies has been demonstrated in the last two decades. Some highly researched alternative communication technologies include, but not limited to visible light communication (VLC) and power line communication (PLC) [2]–[8]. The study of the two communication technologies has focused on a wide range of subjects, including, channel and noise modelling, system optimisation, as well as security enhancement.

VLC is a type of optical wireless communication technology that transmits information signals by visible light electromagnetic waves. Thus, capable of providing illumination and data communication simultaneously. Apart from the much desired wide unlicensed spectrum, in the order of several hundred terahertz (THz), some notable advantages attributed to VLC technology are its non-subjection to electromagnetic sources interference and high level of security as it does not penetrate walls. Some of the potential application areas of VLC are hospitals where wireless fidelity (Wi-Fi) could be undesirable, smart transport systems, smart lighting of smart buildings and underwater communication. VLC transmitters must be availed the information to transmit and therefore, it is required that they be connected to a back-haul network.

Meanwhile, the power line, which is also capable of transmitting information, as demonstrated in [2], [5], [6], naturally provides power to the VLC transmitters. The communication technology that allows information transmission via power lines is referred to as power line communication (PLC). Therefore, taking advantage of the fact that power lines provide power to the lighting infrastructure used for VLC, PLC can be adopted for back-hauling and interconnecting VLC network elements [4], [9]–[11], forming hybrid power line and visible light communication (PLC-VLC) systems. From the initial study in [11], a lot of research addressing the issues of effective integration, coverage optimization, spectrum and power efficiency, to mention but a few, has been conducted [4], [9], [10], [12], [13].

The integration of PLC and VLC presents an opportunity for applying the different communication techniques, that have successfully been developed and implemented for wireless cellular networks. Techniques such as multiple access, modulation, relaying and multiple-input multiple-output (MIMO) can be considered [14]–[16]. In most cases, a combination of schemes and techniques have been explored by researchers. For example, in [17], authors considered a communication system in which, asymmetrically clipped optical orthogonal frequency division multiplexing (ACO-OFDM) and on–off keying (OOK) modulation schemes, were integrated to support the different qualities of service with high spectral efficiency. In [10], multiple access techniques and orthogonal frequency division multiplexing (OFDM), was studied. It was highlighted in [4], that MIMO and relying techniques are possible study

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This work was supported by South Africa's National Research Foundation with Grant No. 112248 & 114626 and was funded, in part, by the framework of the Competitiveness Enhancement Program of the National Research Tomsk Polytechnic University, in part, by the Russian Foundation Basic Research grant No. 19-37-90037 and No. 19-37-90105.

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focus areas for integrated PLC-VLC systems.

In light of the above, we propose a VLC system with a combination of relaying and multiple-input multiple-output (MIMO) techniques. Furthermore, because of the proven integration feasibility of PLC and VLC, the VLC system transmitter in this study, is assumed to be connected to a power line channel and the relays are also assumed to be interconnected via the power line. Precisely, the performance of a system with relay nodes equipped with a MIMO technique called space time block coding (STBC), is investigated. The bit error rate (BER) performance of the Alamouti coding (AC) scheme, which is a type of STBC, is specifically considered. In order to enhance the overall system reliability, we propose to use an imaging receiver (ImR), in conjunction with the relay-MIMO setup.

Apart from the VLC application areas mentioned earlier, the proposed system can also be applied in areas where PLC is traditionally applied, such as, remote meter reading, voice communication and data acquisition required for smart grid applications.

The rest of the paper is organised as follows: Section II briefly outlines the technology and techniques upon which the work in this paper is based. Section III presents the proposed system model and gives a theoretical description of the space time block coding (STBC) technique, precisely, the Alamouti coding technique adopted for the VLC relay nodes. Section IV gives details of the simulation results and discussion of the BER performance of different schemes, scenarios and link alignment. Finally, a conclusion is given in Section V.

II. BACKGROUND

The integration of PLC and VLC requires signal transitions to suit each of the two different channels. The two common methods used to integrate PLC and VLC are amplify-and-forward (AF) and decode-and-forward (DF) [4], [9], [12], [18]. In AF, the received signal, at the integration module, is amplified and then re-transmitted to the destination node. On the other hand, in DF, the received signal is first decoded and re-encoded before re-transmission to the destination node. Additionally, the integrated PLC-VLC channel combines the respective channel characteristics and effects of the PLC and VLC channels. Ideally, the effects of both channels have to be considered in the system performance analysis. However, we would like to categorically clarify at this point that, in this work, the impairments from the PLC channel have not been included in the analysis of this study. We only aim at emphasising the advantage of adopting the power line as an information source and an interconnecting medium for the VLC relays, in the proposed setup. Furthermore, the analysis of the influence of the integration protocols such as the AF and DF, has not been carried out. We, therefore, would like to state the following assumptions made with regards to the presented work:

1) The powerline channel is transparent to the information signals transmitted through it and therefore, its impairments have been neglected.
2) The relay nodes have the perfect information from the source, to be encoded according to the MIMO technique under consideration. As such, the relaying protocol influence on the system performance is equally neglected.

The consideration of the two aspects of the PLC channel impairments and effects of the relaying protocols will be included in the extended work, in future.

In VLC systems, the commonly used source of light are light emitting diodes (LEDs), whose propagation model is considered to be Lambertian. The propagation of the the VLC signals is normally characterised by both line-of-sight (LOS) and non-line-of-sight (NLOS) components. The NLOS component is largely due to reflections from the indoor surfaces. A generalised VLC channel frequency response (CFR) function is given by [19] as:

$$H_{vlc}(f) = \sum_{i=1}^{N} h_{los,i}\, e^{-j2\pi f \tau_{los}} + \frac{h_{ref}}{1 + jf/f_0} e^{-j2\pi f \tau_{ref}}, \quad (1)$$

where N is the number of LED chips and h_{los} and h_{ref} denote the channel gain for the LOS and NLOS signal, respectively. f_0 is the cut-off (3-dB) frequency of the purely diffuse channel, while τ_{los} and τ_{ref} denote the signal delays over the LOS and NLOS links. When the Lambertian propagation model is considered, the channel gain of the LOS component for a receiver located at a distance of d and angle of irradiance, θ, with respect to the transmitter, can be approximated as [20],

$$h_{los} = \begin{cases} \frac{A_r(m+1)}{2\pi d^2} cos^m(\theta) cos(\psi), & 0 \leq \psi \leq \Psi_c, \\ 0, & \text{elsewhere}, \end{cases} \quad (2)$$

where A_r is the effective collection area of the detector, ψ is the angle of incidence with respect to the receiver axis and m is the Lambertian emission order given by $m = \frac{\text{-ln2}}{\text{ln}cos(\Phi_{1/2})}$, $\Phi_{1/2}$ is the transmitter semi-angle at half power. For an $N_r \times N_t$ system, where N_r denotes the number of photo-detectors at the receiver and N_t denotes the number of transmitters, the channel gain matrix is represented by real valued elements as

$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} & \dots & h_{1N_t} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_t1} & h_{N_t2} & \dots & h_{N_rN_t} \end{bmatrix}. \quad (3)$$

When the indoor reflections are considered, the resulting channel gain between the relays and the receiver is defined by the distance d_1 between the relay and the reflection point, and the distance between the reflection point and the receiver, d_2. As shown in Fig.1, respective angles of iradiance and incidence, θ, α, β and ψ also have an influence on the resulting channel gain values. The channel gain due to first order reflections is given by

$$h_{ref1} = \frac{A_r(m+1)}{2(\pi d_1 d_2)^2} cos^m(\theta) cos(\alpha) cos(\beta) cos(\psi) d_{A1} \rho_1, \quad (4)$$

where d_{A1} and ρ_1 denote the area of the reflection element and the reflection coefficient of the reflector, respectively.

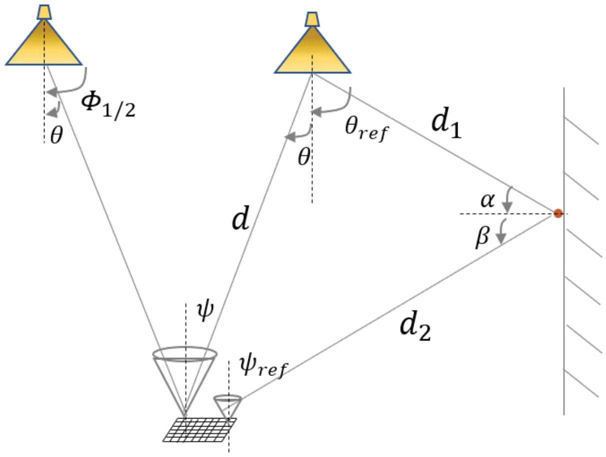

Fig. 1. VLC propagation model for LOS and reflections (NLOS)

Similarly, for the second order reflections, the resulting channel gain is given by

$$h_{ref2} = \frac{A_r(m+1)}{2(\pi d_1 d_2 d_3)^2} cos^m(\theta)cos(\alpha)cos(\beta)cos(\gamma) \\ cos(\delta)cos(\psi)d_{A1}\rho_1 d_{A2}\rho_2. \tag{5}$$

γ and δ denote the angles of irradiance and incidence with respect to the normal of the first reflection element and normal to the second reflection element, respectively. d_{A2} and ρ_2 denote the area of the reflection element and the reflection coefficient of the second reflector. VLC systems often operate in the presence of ambient background lights, which add a shot noise component in the receiver. This noise is normally modelled as white, Gaussian and independent of the transmitted optical power [20], [21]. Furthermore, when little or no ambient light is present, the thermal noise which is due to the receiver electronics, is always present and is also signal-independent and Gaussian. When both are present, a summation of both noise components is considered and generally modelled as AWGN.

Multiple-input multiple-output (MIMO) techniques have been widely studied and practically implemented for radio frequency (RF) technology, offering reliable communication by diversity and high data rate since the system spectral efficiency is increased. Motivated by the successful implementation of RF MIMO, various research works aimed at achieving high capacity with increased spectral efficiencies, have been undertaken [21], [22]. In MIMO systems, it is desirable to have spatially uncorrelated channels in order to avoid inter-channel interference. However, optical MIMO (O-MIMO) systems, especially those employed for indoor applications, are highly correlated, thus enabling only minor diversity gains [21]. Several MIMO techniques have been studied and proposed to reduce the correlation effect of O-MIMO systems. Some of these techniques include power imbalance between transmitters [23] as well as link blockage between some transmitter-receiver pairs [21]. Others are Repetition Coding (RC) to mitigate the correlation nature of indoor O-MIMO by increasing the transmit diversity gains where all transmitters emit the same signal simultaneously, spatial modulation (SM) [21], [22], which was shown to be robust to high channel correlation since it completely avoids inter-channel interference (ICI) by activating only one transmitter at any transmit interval and the spatial multiplexing technique demonstrated to achieve higher data rates. Another MIMO technique of interest is STBC where multiple copies of the message symbols are transmitted across a number of antennas to exploit the various received versions of the transmitted message and consequently improve the reliability of the communication system. Particularly, Alamouti coding (AC) is a type of STBC that we will consider in the analysis of this work. However, because AC was originally proposed for RF systems [24], it requires the use of complex signals and therefore, cannot be directly applied without modification to optical systems that deal with real and non-negative signals. Consequently, the authors in [25], describe a brilliant way of combining AC with OOK and adopted it for free-space optical (FSO) communication with direct detection (DD). They describe the modification of the Alamouti code and the associated decision metric such as to maintain all of the desirable properties of the original Alamouti scheme. Based on the modification of AC by [25] and the general STBC techniques, some studies on the performance analysis of AC for optical wireless systems have been conducted with system performance improvements demonstrated [26]–[28]. These studies show that STBC is attractive for indoor visible light communication.

A relay-assisted diversity scheme is another technique that has been widely used and implemented to address the issue of signal fading due to multi-path propagation and strong shadowing [29]–[32]. A relay-assisted communication system simply has one or an array of intermediate nodes that convey a message from transmitting node/s to receiving node/s. In summary, an investigation on the performance of an Alamouti based relay-assisted VLC system, assumed to be connected to a PLC channel, is conducted. The use of an imaging receiver, where the receiver is segmented into multiple receiving pixels was proposed for use in indoor environments with good system performance enhancement [33], [34]. Thus, the proposed Alamouti based relay-assisted VLC system in this study, employs an imaging receiver. The principal advantage of an imaging receivers (ImR) is that all pixels use the same imaging concentrator, therefore, the cost and size are reduced, increasing its potential for use in hand-held devices.

The system setup considered in our study is based on the idea of [33], where an office space of specific dimensions has an array of relays installed in the ceiling, while the transmitter and receiver are stationary and located at a specific height above the floor, see Fig.2. However, the work in [33], did not consider a MIMO configuration for the relays. Furthermore, the relays in [33] were assumed to be connected via fiber optic cables, while we propose relay interconnection by power line, leveraging on existing infrastructure for cost benefits. To the best of our knowledge, none of the mentioned works in literature have considered the analysis of optical AC with ImRs. In this work, the use of a MIMO technique that enhances spectral efficiency and reliability via link diversity, is employed. The MIMO relay nodes are each connected to a common controller via a power line channel, an option that

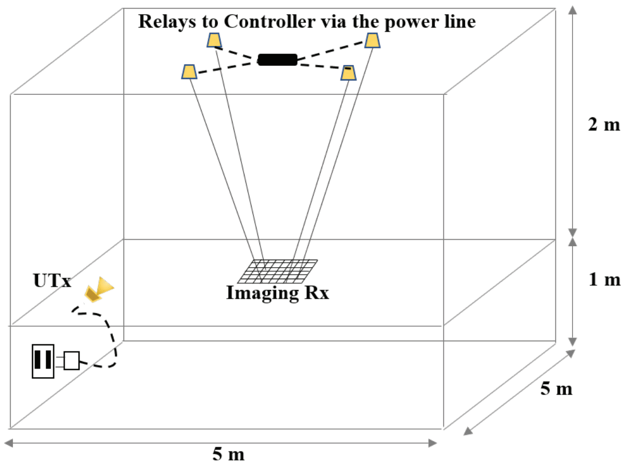

Fig. 2. VLC system room setup: upright transmitter, relays and imaging receiver

would be easily implemented and cost effective. The controller coordinates the relay operations, including ensuring synchronisation of the relays. A STBC technique is adopted in order to maintain a non-correlation scenario of the MIMO channels. Additionally, the use of an ImR is expected to further enhance the system performance as it helps decorrelate MIMO channel matrix coefficients [35]. Moreover, the effect of the physical arrangement of the relays and the receiver, is investigated with a practical consideration of signal reflections that would impact the overall system. In this work, the reflections are considered as NLOS links.

III. SYSTEM MODEL

In this study, we consider a room scenario of dimensions 5 m x 5 m x 3 m (width x length x height) and focus on three main communication elements, i.e. the upright transmitter (UTx), the relay nodes and imaging receiver (ImR). Both the transmitter and imaging receiver are located at a particular height above the floor, while the relay nodes are installed in the ceiling of the room. The information source of the UTx is the power line connected via a power plug, in the considered room. The UTx transmits the information to the ImR only via the relay nodes and it is assumed that there is no direct communication between the UTx and the ImR. We further assume an interference free scenario between the lights of the transmitter and that of the relay nodes. The two primary roles of the relays installed in the ceiling are illumination and information transfer between the UTx the ImR.

The information flow of the system is presented by a block diagram of Fig.3. The UTx, receives the information to be sent, from the power line. We adopted a PLC-VLC conversion structure proposed by [18], where the modulation schemes and carrier spectrum of PLC and VLC are the same.

The UTx, then sends an amplified version of the received signal to the relay nodes via a VLC channel. The relays are interconnected and controlled via a common controller that equally ensures synchronisation of the relays. The controller also coordinates all the relay operation to ensure the STBC configuration is achieved.

The Alamouti encoded data are transmitted to the destination, the ImR, via the VLC channel. At the receiver, the photocurrents received in each pixel of the ImR are amplified and decoded separately using the maximum likelihood decision metric. After individual pixel decoding and estimation, the reconstruction processes of the message is done based on a majority voting decision technique using the estimated messages by individual pixels. Although the aspect of the control feedback from the ImR to the relay unit has not been discussed in this study, we suggest the use of a low data rate infrared (IR) link to achieve this.

A. Two-hop transmission process

As represented in Fig.2, the VLC information source, the UTx, located on the communication plane, transmits the information to all the relays which are interconnected and cooperate in operation. The transmitter-relay scenario is a single-input multiple-output (SIMO). The received signals at the relay nodes are processed by maximum ratio combining (MRC) at the controller, after which they are re-encoded for re-transmission to the destination.

As already mentioned, we consider relay nodes operated in an AC scheme. According to the conventional AC scheme of [24], that considers two transmitters and one receiver, the symbols to be transmitted, x_1 and x_2, coded in space and time are represented as

$$\mathbf{x} = \begin{bmatrix} x_1 & -x_2^* \\ x_2 & x_1^* \end{bmatrix}, \tag{6}$$

where x_1^* and x_2^* are complex conjugate components. If the channel parameters between transmit antennas 1 and 2 and the receiver, are denoted by h_1 and h_2, then the received signals r_1 and r_2, at the two time intervals can be written as

$$\begin{Bmatrix} r_1 = h_1 x_1 + h_2 x_2 + n_1 \\ r_2 = -h_1 x_2^* + h_2 x_1^* + n_2 \end{Bmatrix}, \tag{7}$$

where n_1 and n_2, are complex random variables representing receiver noise.

In VLC, however, there exists a signal constraint, that requires the transmitted signals to be real and positive, since light signals are neither imaginary nor negative. Therefore, we adopt the modified Alamouti coding scheme in [25], which considers this constraint. According to [25], the coded symbols to be transmitted at the first and second time intervals are represented as

$$\mathbf{x} = \begin{bmatrix} x_1 & \bar{x}_2 \\ x_2 & x_1 \end{bmatrix}, \tag{8}$$

where, a complement symbol $\bar{x}_i$ can be represented as $\bar{x}_i = -x_i + A$ and A is a positive constant related to the intensity of the light source. The Alamouti coded symbols are then transmitted over an optical wireless channel with channel gains between any transmitter-receiver pair denoted as h_{ij}, i and j denote the receiver and transmit indices. Accordingly, adopting the mathematical model of [25], the received electrical signals for each transmit interval are denoted as y_1 and y_2 and given as

$$\begin{Bmatrix} y_1 = h_{11} x_1 + h_{12} x_2 + n_1 \\ y_2 = h_{11} \bar{x}_2 + h_{12} x_1 + n_2 \end{Bmatrix}, \tag{9}$$

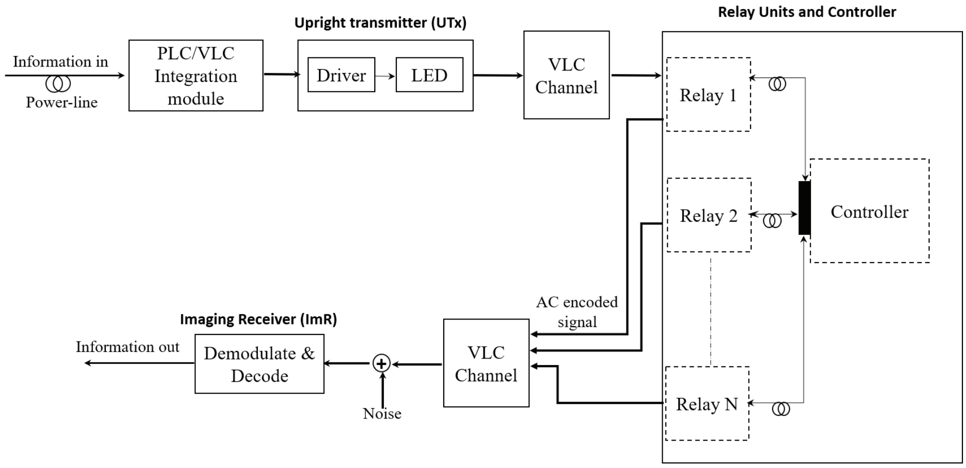

Fig. 3. System block diagram of an upright VLC transmitter connected to a PLC channel with Alamouti coded relay nodes and imaging receiver

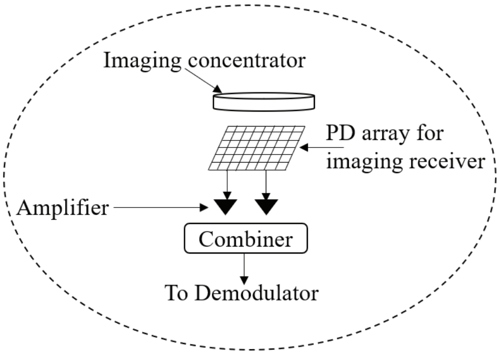

Fig. 4. Imaging receiver structure [33]

where n_1 and n_2 are noise components modeled as independent zero-mean Gaussian real random variables with variance σ^2. With the assumption that the receiver has perfect knowledge of the channel, the receiver can use y_1 and y_2 of (10) to statistically construct the symbols transmitted at each interval [25] as:

$$\begin{Bmatrix} \tilde{x}_1 = h_{11}y_1 + h_{12}y_2 - h_{11}h_{12} \\ \tilde{x}_2 = h_{12}y_1 + h_{11}y_2 - h_{11}^2 \end{Bmatrix}. \tag{10}$$

From the derivation of [25] and considering that the transmitted information symbols, x_1 and x_2, are independently chosen from the input symbol stream, a maximum likelihood decision is made separately on each of them by using,

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

and finally a decision rule is made that $x_i = \hat{x}_i$, if

$$\begin{aligned} (\tilde{x}_i, \hat{x}_i)^2 + (h_{11}^2 + h_{12}^2 - 1)\ \hat{x}_i^2 \leq (\tilde{x}_i, x_i)^2 \\ +(h_{11}^2 + h_{12}^2 - 1)x_i^2, \text{ for } x_i \neq \hat{x}_i. \end{aligned} \tag{12}$$

This is the decision metric that we will use in our simulation to demonstrate the enhanced performance of the system under consideration.

B. Imaging receiver

In [33], two main receiver types for VLC systems were investigated, i.e. non-imaging angle diversity receivers (ADRs) and imaging receivers (ImR). In their investigation and analysis, they demonstrated that the ImR outperforms the ADR systems in terms good robustness against shadowing and the ability to maintain LOS even in the harsh environment of shadowing. Therefore, in this paper, we propose to use an ImR in order to use its merit that enhances the intersymbol interference (ISI) avoidance. The avoidance of ISI is achieved by the fact that the ImR consists and uses a number of pixels that only detects a limited number of signals that could reach the receiver at different times due to different path lengths. Having a combination of Alamouti coded relays with the ImR, combines the advantages that the individual elements/technique possess. Thus, the proposed system is robust against shadowing and allows mobility due to a number of installed relays. The adopted structure of the ImR is shown in Fig.4. When the transmitted signal is received at each pixel, the metric specified in (11) is individually applied at each pixel and then a majority voting techniques is applied to finally construct the received message.

IV. SIMULATION RESULTS AND DISCUSSION

In this section, we evaluate and discuss the performance of an optical wireless MIMO system based on the Alamouti technique, in terms of the BER. Firstly, the performance comparison of a nonimaging receiver and ImR, considering both the LOS and NLOS, are presented. Further, we considered imaging receivers with different number of pixels and varied the receiver location in the room to investigate the impact on system performance. Referring to Fig.2 for the room setup and using the simulation parameters in Table I, the obtained results are presented in subsequent subsections.

It should be noted that due to the symmetry of the room under consideration, when relay position combinations, A and B or C and D are assumed, the results of each relay pair are equal. A, B, C and D are ceiling positions with the following respective x and y coordinates: A(x = 1.25 m, y = 1.25 m),

TABLE I
SIMULATION PARAMETERS USED

Room Parameters	
Parameter	***value***
Room size (W × L × H)	5 m × 5 m × 3 m
Wall reflectivity (ρ)	0.8
Area of reflection elements, d_A	5 m × 5 m
Number of reflection elements	2500
Transmitter and Relay Parameters	
Parameter	***Value***
Number of Transmitters (UTx)	1
UTx height from floor	1 m
Locations (x,y,z)	(1,1,1)
Number of Relays	4 (2 for each AC configuration)
Relay Locations (x,y,z)	(1.25,1.25,3), (1.25,3.75,3) (3.75,1.25,3), (3.75,3.75,3)
Transmitted Optical Power	2 W
Receiver Parameters	
Parameter	***Value***
Receiver plane height from floor	1 m
Number of Receiver Pixels	20, 50, 70
Receiver locations (x,y,z)	(1.25,1.5,1), (2.5,1.5,1) (1.25,4.5,1), (2.5,4.5,1)
Single detector FOV	70

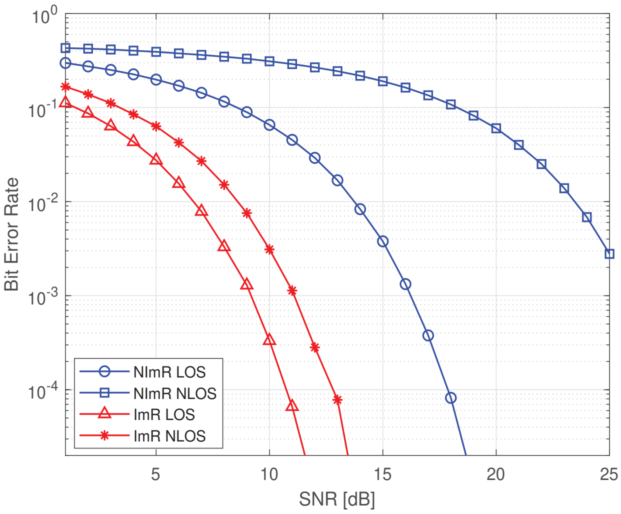

Fig. 5. Performance comparison for non-imaging and imaging receivers

B(x = 3.75 m, y = 1.25 m), C(x = 1.25 m, y = 3.75 m) and D(x = 3.75 m, y = 3.75 m). Thus, we only considered one relay pair for our analysis.

A. BER performance comparison for nonimaging and imaging receivers

The BER performance comparison was carried out for nonimaging and imaging receivers with relay nodes positioned at, x = 1.25 m, y = 1.25 m and x = 3.75 m, y = 1.25 m, while the receiver location was x = 1.25 m, y = 1.5 m. We specifically considered two scenarios; firstly, for the LOS propagation and secondly, NLOS up to the second order reflections. Fig.5 shows that the Alamouti system using an ImR outperforms the Alamouti system using a NImR, by about 7 dB, when LOS is considered. This is due to the fact that the array of the receiver pixels is seen as multiple receivers, hence, the benefit of high receive diversity. Additionally, the majority voting technique for imaging receivers increases decoding accuracy. When compared to the performance of the NImR, the logarithmic decrease of the BER for the ImR at lower SNR, is very clear from Fig.5. This demonstrates the combinational benefit of the AC MIMO technique with the ImR, in that both techniques have a capability of decorrelating the inherent highly correlated indoor O-MIMO links. Thus, this demonstrates the potential of the proposed scheme in achieving high link reliability. Furthermore, the combination of relays and ImR, enhances the robustness against shadowing as evidenced by the performance of the NLOS links in comparison to both LOS and NLOS links, when the NImR scheme is used. We observe an enhanced performance of over 5 dB and 10 dB respectively, at a BER of 10^{-3} .

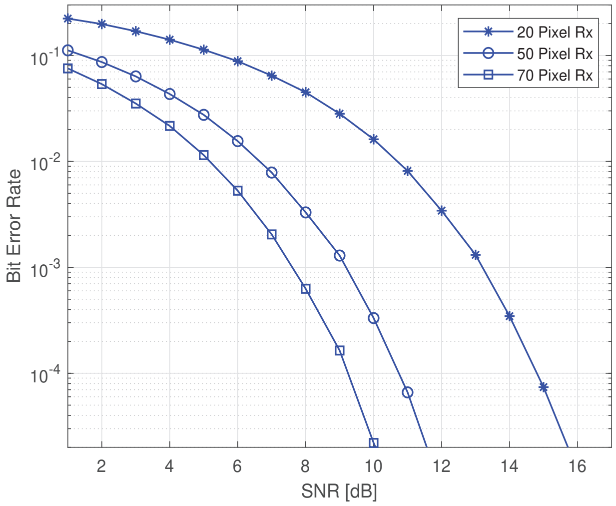

Fig. 6. Performance comparison: Imaging receivers with different number of pixels

B. Performance evaluation for different number of receiver pixels

In Fig.6 we observe that the system BER performance is proportional to the number of pixels used for a particular receiver. When the number of pixels is reduced from 50 to 20, it is observed that an additional 4 dB SNR is required to achieve a BER of 10^{-4}, while an increment to 70 pixels improves the system SNR by approximately 2 dB. This enhancement is attributed to individual pixel decoding metric and the high probability accurate decoding by majority voting when a large sample size is considered. With increased number of pixels, one of the advantages of MIMO, which is, enhanced link diversity, resulting in system performance improvement, is evident. Thus, imaging receivers with hundreds of pixels would definitely enhance system performance. However, a very high number of pixels would require more processing resources. Therefore, a trade off between the system performance and the processing speed, needs to be well analysed.

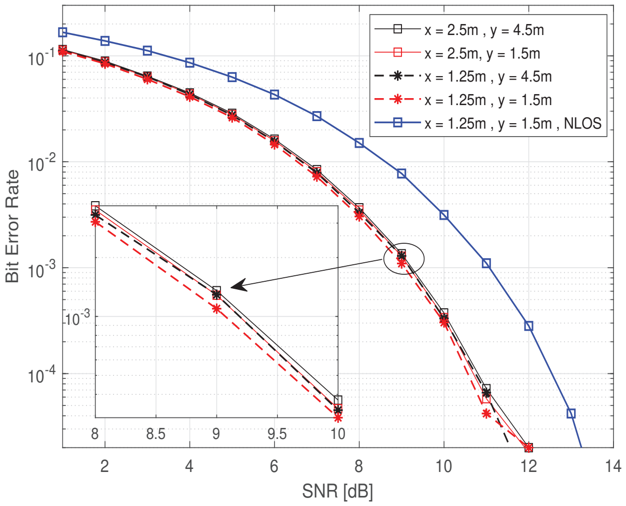

Fig. 7. Performance variation due to receiver location

C. Performance impact due to receiver location

Two x-coordinates, x = 1.25 m and x = 2.5 m, with varying y-coordinates were used to investigate the receiver location impact on system performance. From Fig.7, though the performance difference is not huge, it was observed that when the ImR was place along x = 1.25 m, the BER performance was better than when it was placed along x = 2.5 m. The difference in performance at different receiver locations, with better performance being at (x,y) = (1.25 m, 1.5 m), is due to the expected difference in channel gains, where, higher gains are expected at locations closer to the relays. On the other hand, the minimal performance differences along the y-axis is a demonstration of the robustness of the combination of the AC relays and the ImR, where MIMO links are well decorrelated by the AC scheme and LOS establishment due to multiple relays and multiple pixels. Further, when the LOS links were blocked and only NLOS propagation was available, the performance degradation in terms of BER of was evident, proving the high dependence of LOS propagation in VLC links.

V. CONCLUSION

In this paper, we have proposed and investigated a combination operation of relays, applying the Alamouti MIMO coding technique and imaging receivers, of a VLC system. The system performance enhancement in terms of BER was demonstrated by comparing the results of our proposed scheme to that of an Alamouti system using non-imaging receivers. The improved performance is attributed to the robustness of the relay and ImRs against shadowing, as well as the ability of the AC to decorrelate MIMO links. Further, the impact of the number of pixels on the imaging receiver was investigated and it is shown that the BER performance is proportional to the number of receiver pixels. This is attributed the probabilistic decision based on the majority voting technique that was applied in the scheme using an ImR. It has also been shown that the distance and orientation of the source-destination link has a great influence on link performance. The farther and out of the transmitters view the receiver is, the more the performance of the system degrades. Since the proposed VLC system was assumed to be integrated with PLC, it would be necessary to also investigate the effects of the PLC channel, on the proposed system. Further, signal transition by AF or DF, at the relay units, where the PLC-VLC integration exists, needs to be analysed. Therefore, part of the future work, that will build on the work presented in this paper, must be the investigation and analysis of the effect of the hybrid noise model and the integration techniques, on the system's performance.

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