# Optimal Precoder for MIMO Schemes in Indoor Wireless VLC Systems

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***Abstract*—In multiple-input multiple-output (MIMO) indoor visible light communication (VLC) systems, channel gains are highly correlated. As a result, the bit error rate (BER) of the system is degraded. To improve the BER performance of the system, we propose two precoders, namely, an optimal precoder and a diagonal precoder for MIMO schemes in VLC systems with $N_t$ light emitting diodes (LED) and $N_r$ photo detectors (PD). The optimal precoder maximizes the minimum euclidean distance of the received signal set under non-negativity and maximum power constraints. The diagonal precoder, on the other hand, induces transmit power imbalance to alleviate the degradation due to channel correlation. We compare the performance of spatial multiplexing (SMP), generalized spatial modulation (GSM), and spatial modulation (SM) MIMO schemes with and without precoding. Our simulation results show that MIMO schemes with the proposed precoders outperform the MIMO schemes without precoder by up to 49 dB at $10^{-4}$ BER, and that in the presence of precoding, SMP can outperform GSM and SM.**

***Keywords*** – *Visible light communication, precoding, spatial multiplexing, generalized spatial modulation, spatial modulation.*

## I. INTRODUCTION

Radio frequency (RF) spectrum gets increasingly crowded due to various wireless communication systems being installed in industrial, scientific and medical (ISM) bands and telecommunication bands, thereby leading to shortage of available bandwidth. Optical wireless communication (OWC) is emerging as a complementary technology to RF, where the information is conveyed by modulating the intensity of optical signals. In recent times, there has been significant advancements in solid state lighting technology due to which inexpensive high-luminance light emitting diodes (LED) can be used to provide both energy-efficient lighting as well as high-speed short range communication. Multiple-input multiple-output (MIMO) techniques, which are well established and popular in RF communication [1],[2], can be implemented in VLC to achieve high data rates. Modulation schemes and precoder designs used in radio frequency (RF) cannot be directly adopted in VLC systems because of the non-negativity condition for the input signal of intensity modulation (IM) and direct detection (DD) channel. In the context of VLC systems, MIMO techniques including spatial multiplexing (SMP), generalized spatial modulation (GSM), spatial modulation (SM), generalized space shift keying (GSSK), and space shift keying (SSK) have been investigated in the literature [3],[4]. In [4], it has been shown that transmit power imbalance reduces channel correlation, thereby making the channel gains more distinguishable at the receiver side. A precoder that minimizes the mean square error was proposed in [5]. In [6], a throughput maximizing precoder was proposed. The precoder designs in [5] and [6] use DC bias to ensure non-negativity for the input signal. A precoder that maximizes the minimum euclidean distance at the receiver for improving the BER performance of a VLC system with 2 LEDs was proposed in [7]. In this paper, we propose two MIMO VLC precoding schemes, namely, $i)$ an optimal precoder and $ii)$ a diagonal precoder. The idea in the proposed optimal precoder design is to maximize the minimum euclidean distance of the received signal set under non-negativity and maximum power constraints. The idea in the diagonal precoder is to alleviate the performance degradation due to channel correlation by inducing transmit power imbalance. We study the performance of SMP, GSM, and SM MIMO schemes in an indoor VLC setting. Our numerical results show that the MIMO schemes with precoding can achieve performance gains up to 49 dB at a BER of $10^{-4}$ compared to these schemes without precoding. Also, it is observed that, in the presence of precoding, SMP can outperform GSM and SM.

The rest of this paper is organized as follows. In Section II, we present the considered indoor MIMO VLC system model. Section III presents the proposed precoding schemes. Simulation results and discussions are presented in Section IV. Conclusions are presented in Section V.

## II. VLC SYSTEM MODEL

Consider an indoor MIMO VLC system inside a room of dimension 5m×5m×3.5m, where a transmitter with $N_t$ LEDs is placed 0.5 meters below the ceiling and a receiver with $N_r$ photo detectors is placed on a table located at 0.8 meters above the ground. At the transmitter side, LEDs convert the incoming electrical signals to optical signals and at the receiver side, the incident optical signals are converted back to electrical signals. We assume the Lambertian radiation pattern [8],[9] for the LEDs. Let $h_{ij}$ denote the channel gain between $j$th LED and $i$th photo detector, $j = 1, 2, \cdots, N_t$ and $i = 1, 2, \cdots, N_r$. As in [4], we consider only the line-of-sight (LOS) paths between the LEDs and the photo detectors. The LOS channel gain $h_{ij}$ is given by [8]

$$h_{ij} = \frac{q+1}{2\pi} \cos^q \phi_{ij} \, \cos\theta_{ij} \frac{A}{R_{ij}^2} \text{rect}\Big(\frac{\theta_{ij}}{FOV}\Big), \qquad (1)$$

where $\phi_{ij}$ is the angle of emergence with respect to the $j$th source (LED) and the normal at the source, $q$ is the mode number of the radiating lobe given by $q = \frac{-\ln(2)}{\ln\cos\Phi_{\frac{1}{2}}}$, $\Phi_{\frac{1}{2}}$ is

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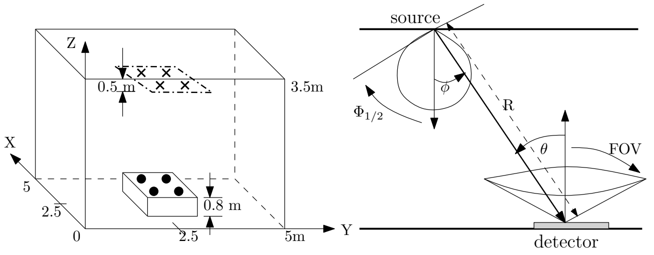


Fig. 1. Geometric set-up of the considered indoor VLC system. A dot represents a photo detector and a cross represents an LED.

the half-power semiangle of the LED [9], $\theta_{ij}$ is the angle of incidence at the $i$th photo detector, $A$ is the area of the detector, $R_{ij}$ is the distance between the $j$th source and the $i$th detector, FOV is the field of view of the detector, and $\text{rect}(z)$ is a rectangular function that takes value 1 when $|z| \leq 1$. The geometric set-up of the considered indoor VLC system is shown in Fig. 1. The LEDs are apart by a distance $d_{tx}$ and the photo detectors are apart by a distance $d_{rx}$ as shown in Fig. 2(a) and Fig. 2(b), respectively. Let $x_i$ denote the light intensity emitted by the $i$th LED. Then, the $N_r \times 1$ received signal vector at the receiver is given by

$$\mathbf{y} = r\mathbf{H}\mathbf{x} + \mathbf{n}, \tag{2}$$

where $r$ denotes the responsivity of the detector, $\mathbf{H}$ denotes the $N_r \times N_t$ channel matrix with $h_{ij}$ as $(i,j)$th entry, $\mathbf{x} = [x_1\ x_2\ \cdots x_{N_t}]^T$ denotes the $N_t \times 1$ non-negative transmit signal vector, and $\mathbf{n}$ is the noise vector whose entries are modeled as independent and identically distributed (i.i.d.) Gaussian random variables with zero mean and variance $\sigma^2$. The average received signal-to-noise ratio (SNR) is given by $\overline{\gamma} = \frac{r^2 P_r}{\sigma^2}$, where $P_r = \frac{1}{N_r}\mathbb{E}[||\mathbf{H}\mathbf{x}||^2]$.

## III. PRECODING IN VLC SYSTEMS

In this section, we propose two precoders, namely, an optimal precoder and a diagonal precoder for MIMO VLC systems.

### *A. Transmitter*

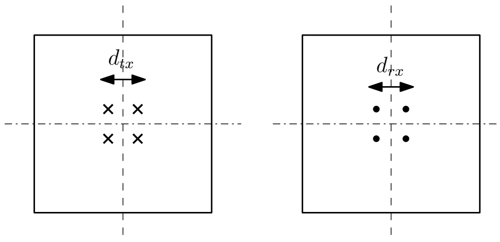
The VLC system with precoding is shown in Fig. 3. In each channel use, the transmitter takes information bits and encodes (maps) them to a $N_t \times 1$ modulation symbol vector $\mathbf{s} \in \mathbb{S}^{N_a}_{N_t,M}$, where $\mathbb{S}^{N_a}_{N_t,M}$ denotes the signal set of the modulation scheme, $N_a$ and $M$ are the parameters that depends on the modulation scheme. In this work, we consider SMP, GSM, and SM schemes. The achievable rates and signal sets for these MIMO modulation schemes are given below.

*1) SMP:* The achievable rate $\eta_{\text{smp}}$ in bits per channel use (bpcu) and signal set $\mathbb{S}^{N_t}_{N_t,M}$ of the SMP scheme are given by

$$\eta_{\text{smp}} = N_t \lfloor \log_2 M \rfloor \text{ bpcu} \tag{3}$$

$$\mathbb{S}^{N_t}_{N_t,M} = \{\mathbf{s} : s_i \in \mathbb{M}_{s,M}\}, \tag{4}$$

where $s_i$ denotes the $i$th entry of $\mathbf{s}$ and $\mathbb{M}_{s,M}$ denotes the set of intensity levels given by $\mathbb{M}_{s,M} = \{\frac{2m}{M} : m = 0, \cdots, M-1\}$.



(a) Transmitter, $N_t = 4$ (b) Receiver, $N_r = 4$

Fig. 2. Placement of LEDs and photo detectors.

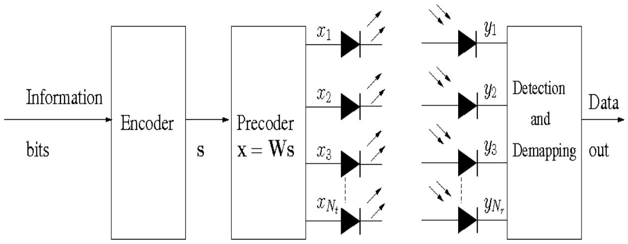


Fig. 3. Transmitter and receiver for indoor VLC system with precoding.

*2) GSM:* The achievable rate $\eta_{\text{gsm}}$ and signal set $\mathbb{S}^{N_a}_{N_t,M}$ of the GSM scheme are given by

$$\eta_{\text{gsm}} = \lfloor \log_2 \tbinom{N_t}{N_a} \rfloor + N_a \lfloor \log_2 M \rfloor \text{ bpcu} \tag{5}$$

$$\mathbb{S}^{N_a}_{N_t,M} = \{\mathbf{s} : s_i \in \mathbb{M}_{g,M} \cup 0, \|s\|_0 = N_a, \mathcal{I}(\mathbf{s}) \in \mathbb{S}^{N_t,N_a}_{g}\}, \tag{6}$$

where $1 \leq N_a < N_t$, $\mathbb{M}_{g,M}$ denotes the set of intensity levels given by $\mathbb{M}_{g,M} = \{\frac{2m}{M+1} : m = 1, \cdots, M\}$, $\mathcal{I}(\mathbf{s})$ is a function that gives the non-zero location vector (gives $N_t \times 1$ vector that has entry 1 in $i$th coordinate when $s_i \neq 0$ and zero when $s_i = 0$), and $\mathbb{S}^{N_t,N_a}_{g}$ is a collection of $2^{\lfloor \log_2 \binom{N_t}{N_a} \rfloor}$ such non-zero location vectors chosen from the set of $\binom{N_t}{N_a}$ possible vectors.

*3) SM:* The achievable rate $\eta_{\text{sm}}$ and signal set $\mathbb{S}^{1}_{N_t,M}$ of the SM scheme can be obtained by setting $N_a = 1$ in (5) and (6).

The modulation symbol vector $\mathbf{s}$ is pre-multiplied by a precoder matrix $\mathbf{W}$ to get the transmit vector $\mathbf{x} = \mathbf{W}\mathbf{s}$ that drives the LEDs, i.e., $i$th LED emits the light intensity $x_i$.

### *B. Precoder design*

Using union bound, the BER can be upper bounded as

$$P_b \leq \frac{1}{\mathcal{A}\eta} \sum_{i=1}^{\mathcal{A}} \sum_{j=1, i\neq j}^{\mathcal{A}} \delta(\mathbf{x}_i, \mathbf{x}_j) Q\left(\frac{r}{2\sigma}\|\mathbf{H}(\mathbf{x}_i - \mathbf{x}_j)\|\right), \tag{7}$$

where $\mathcal{A}$ is the size of the signal set $\mathbb{S}^{N_a}_{N_t,M}$, $\eta$ is the achieved rate of the system, $\delta(\mathbf{x}_i, \mathbf{x}_j)$ is the Hamming distance between the bit mappings corresponding to the signal vectors $\mathbf{x}_i$ and $\mathbf{x}_j$. At high SNRs, the BER is dominated by the minimum euclidean distance in the received signal set (i.e., $\{\mathbf{H}\mathbf{W}\mathbf{s}_i\}_{i=1}^{\mathcal{A}}$), which is given by

$$d^{\mathbf{W}}_{min,\mathbf{H}} \triangleq \min_{\forall\ i\neq j} \|\mathbf{H}\mathbf{W}(\mathbf{s}_i - \mathbf{s}_j)\|. \tag{8}$$

Using (8), the BER in (7) can be further upper bounded as

$$P_b \leq \frac{1}{\mathcal{A}\eta} \sum_{i=1}^{\mathcal{A}} \sum_{j=1, i \neq j}^{\mathcal{A}} \delta(\mathbf{x}_i, \mathbf{x}_j) Q\left(\frac{r}{2\sigma} d^{\mathbf{w}}_{min,\mathbf{H}}\right). \quad (9)$$

*1) Optimal precoder:* Let $\mathbf{W}_{opt}$ be the optimal precoder matrix which maximizes the minimum euclidean distance at the receiver. The optimal precoder matrix $\mathbf{W}_{opt}$ can be obtained by solving the following optimization problem :

$$\begin{aligned} \max_{\mathbf{W}} \quad & \min_{\forall\, i \neq j} \|\mathbf{HW}(\mathbf{s}_i - \mathbf{s}_j)\|^2 \\ \text{s.t} \quad & \mathbf{0}_{N_t \times 1} \leq \mathbf{W}\mathbf{s}_i \leq p_{max} \mathbf{1}_{N_t \times 1} \quad \forall\, i\ , \\ & w_{kl} \geq 0, \end{aligned} \quad (10)$$

where $p_{max}$ is the maximum output power below which the LED operates in the linear region, $\mathbf{0}_{N_t \times 1}$ denotes the $N_t \times 1$ all zero vector, $\mathbf{1}_{N_t \times 1}$ denotes the $N_t \times 1$ all one vector, and $w_{kl}$ is the $(k,l)$th element of $\mathbf{W}$. The first constraint in (10) is to make sure that the LEDs operate in the linear region and the second constraint is because of non-negativity condition for the IM and DD channel. The optimization problem (10) can be written as [10]:

$$\begin{aligned} \max_{\mathbf{W}, t} \quad & t \\ \text{s.t} \quad & t \leq \|\mathbf{HW}(\mathbf{s}_i - \mathbf{s}_j)\|^2 \quad \forall\, i \neq j, \\ & \mathbf{0}_{N_t \times 1} \leq \mathbf{W}\mathbf{s}_i \leq p_{max}\ \mathbf{1}_{N_t \times 1} \quad \forall\, i, \\ & w_{kl} \geq 0 \quad \forall\, k, l. \end{aligned} \quad (11)$$

By vectorizing the first constraint in (11), we get

$$\begin{aligned} \max_{\mathbf{W}, t} \quad & t \\ \text{s.t} \quad & t \leq vec(\mathbf{W}^T)^T\ \mathbf{K}\ vec(\mathbf{W}^T) \quad \forall\, i \neq j, \\ & \mathbf{0}_{N_t \times 1} \leq \mathbf{W}\mathbf{s}_i \leq p_{max} \mathbf{1}_{N_t \times 1} \quad \forall\, i, \\ & w_{kl} \geq 0 \quad \forall\, k, l, \end{aligned} \quad (12)$$

where $\mathbf{K} = (\mathbf{H} \otimes (\mathbf{s}_i - \mathbf{s}_j)^T)^T (\mathbf{H} \otimes (\mathbf{s}_i - \mathbf{s}_j)^T)$, $(.)^T$ denotes the transpose operation, and $\otimes$ represents the kronecker product. The above optimization problem is a quadratic optimization problem with quadratic constraints which is solvable using CVX toolbox [11].

*2) Diagonal Precoder:* In [4], it has been shown that creating transmit power imbalance, which is equivalent to multiplying the signal vector by a diagonal matrix, can improve the BER performance. Also, in [7], it is shown that the optimal precoder turns out to be diagonal for certain LED and PD geometries. Motivated by the above two observations, we propose a diagonal precoder. Let $\mathbf{W}_D$ be the diagonal precoder (i.e., precoder with zeros as off-diagonal entries) which maximizes the minimum euclidean distance between the received points. Diagonal precoder can also be considered as a linear transformation that induces power imbalance at the transmitter. The diagonal precoder can be obtained by solving the optimization problem in (12) with an additional constraint $w_{kl} = 0$ when $k \neq l$.

| | | |
|---|---|---|
| Room | Length ($X$) | 5m |
| | Width ($Y$) | 5m |
| | Height ($Z$) | 3.5m |
| Transmitter | No. of LEDs ($N_t$) | 4 |
| | Height from the floor | 3m |
| | $\Phi_{1/2}$ | 60° |
| | Mode number, $q$ | 1 |
| | $d_{tx}$ | 0.2 to 5m |
| | $p_{max}$ | 5 W |
| Receiver | No. of PDs ($N_r$) | 4 |
| | Height from the floor | 0.8m |
| | Elevation | 90° |
| | Azimuth | 0° |
| | Responsivity, $r$ | 0.4 Ampere/Watt |
| | FOV | 85° |
| | $d_{rx}$ | 0.1m |

TABLE I
SYSTEM PARAMETERS IN THE CONSIDERED INDOOR VLC SYSTEM.

### *C. Demodulation*

The maximum likelihood (ML) estimate of the transmit vector $\mathbf{s}$ is given by

$$\hat{\mathbf{s}} = \underset{\mathbf{s} \in \mathbb{S}^{N_a}_{N_t,\mathbb{M}}}{\text{argmin}} \|\mathbf{y} - r\mathbf{H}\tilde{\mathbf{W}}\mathbf{s}\|^2, \quad (13)$$

where $\tilde{\mathbf{W}}$ denotes the optimal/diagonal precoder matrix. The detected vector $\hat{\mathbf{s}}$ is demapped to get the corresponding information bits. Equation (13) can be viewed as a decision rule for the equivalent system, where the channel matrix is $\mathbf{H}\tilde{\mathbf{W}}$ and the LEDs transmit the vector $\mathbf{s}$.

## IV. RESULTS AND DISCUSSIONS

In this section, we present the BER performance of SMP, GSM, and SM schemes with precoding. The VLC system parameters considered in the simulations are listed in Table I.

In Fig. 4, we present the BER performance of SMP with precoding. The considered system parameters are $N_a = 4$, $M = 2$, $d_{tx} = 0.6$m, and 4 bpcu. The channel matrix $\mathbf{H}$ for $d_{tx} = 0.6$m is given by

$$\mathbf{H} = 10^{-5} \begin{bmatrix} 0.6250 & 0.6101 & 0.5958 & 0.6101 \\ 0.6101 & 0.6250 & 0.6101 & 0.5958 \\ 0.5958 & 0.6101 & 0.6250 & 0.6101 \\ 0.6101 & 0.5958 & 0.6101 & 0.6250 \end{bmatrix}. \quad (14)$$

From Fig. 4, it can be seen that BER performance of SMP without precoder is quite poor. This is because of the lower $d_{min,\mathbf{H}}$ value that results from the high correlation between the channel gains in $\mathbf{H}$. It is also seen that the precoding improves the performance. For example, to achieve $10^{-5}$ BER, SMP with diagonal precoder requires about 47 dB less SNR compared to SMP without precoder. The reason for this can be explained as follows. The diagonal precoder $\mathbf{W}_D$ obtained by solving (12) for SMP scheme is given by $\mathbf{W}_D = \text{diag}\{0.2154, 0.4290, 0.3568, 0.5\}$ and the resultant channel matrix $\mathbf{HW}_D$ is given by

$$\mathbf{HW}_D = 10^{-5} \begin{bmatrix} 0.1346 & 0.2617 & 0.2126 & 0.3051 \\ 0.1314 & 0.2681 & 0.2177 & 0.2979 \\ 0.1283 & 0.2617 & 0.2230 & 0.3051 \\ 0.1314 & 0.2556 & 0.2177 & 0.3125 \end{bmatrix}. \quad (15)$$

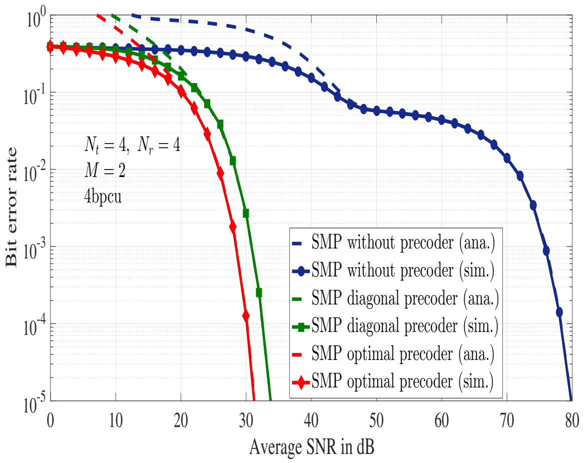


Fig. 4. BER performance of diagonal and optimal precoders in VLC system using SMP with $N_a = 4$, $M = 2$, $d_{tx} = 0.6$m, and 4 bpcu.

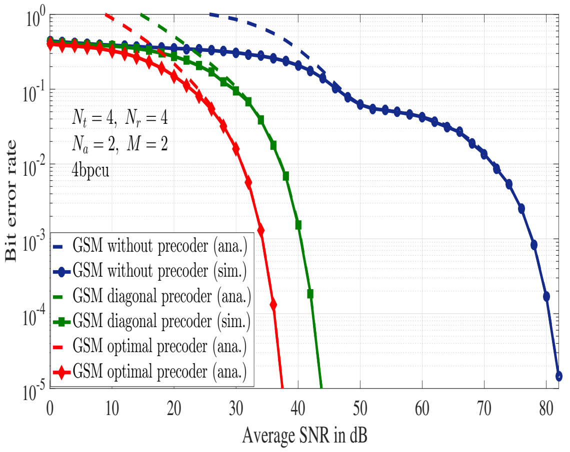


Fig. 5. BER performance of diagonal and optimal precoders in VLC system using GSM with $N_a = 2$, $M = 2$, $d_{tx} = 0.6$m, and 4 bpcu.

It can be seen that with the diagonal precoder, the channel gains are more distinguishable at the receiver. The SMP with diagonal precoder has larger $d_{min,\mathbf{H}}$ compared to that of SMP without precoder. This also illustrates the BER performance advantage possible with systems that employ transmit power imbalance when the channel is highly correlated. Further, it is seen that the SMP with optimal precoder achieves better BER performance compared to SMP with diagonal precoder. For example, to achieve $10^{-5}$ BER, SMP with optimal precoder requires about 2.4 dB less SNR compared to SMP with diagonal precoder. It is also seen that the upper bound is tight for moderate to high SNRs. Similarly, in Figs. 5 and 6, we present the BER performance of precoding in GSM and SM, respectively. The system parameters considered are as follows. GSM: $N_a = 2$, $M = 2$, $d_{tx} = 0.6$m, and 4 bpcu. SM: $M = 4$, $d_{tx} = 0.6$m, and 4 bpcu. Similar observations as in Fig. 4 can be made in Figs. 5 and 6.

We now examine the SNR gains analytically as follows. Let SNR$_{opt}$ and SNR$_D$ denote the SNRs required by the optimal and diagonal precoders, respectively, to achieve the same BER.

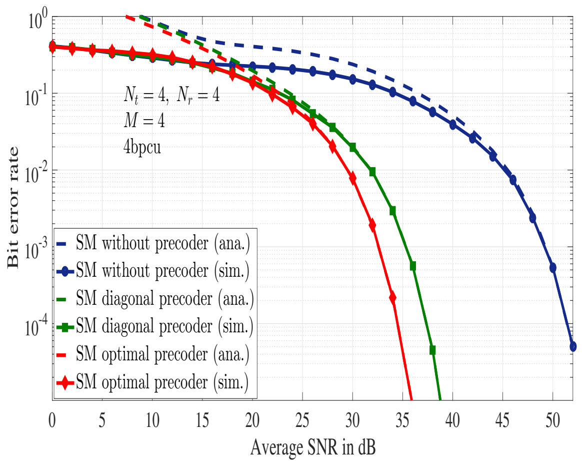


Fig. 6. BER performance of diagonal and optimal precoders in VLC system using SM with $N_a = 1$, $M = 2$, $d_{tx} = 0.6$m, and 4 bpcu.

| Modulation Scheme | SNR gain with diagonal precoder | SNR gain with optimal precoder |
|---|---|---|
| SMP | 47 dB | 49.4 dB |
| GSM | 39.5 dB | 45.6 dB |
| SM | 12 dB | 17.3 dB |

TABLE II
SNR GAIN FOR MIMO SCHEMES WITH DIAGONAL AND OPTIMAL PRECODERS FOR $d_{tx} = 0.6$ METERS.

Similarly, let $d^{opt}_{min,\mathbf{H}}$ and $d^{D}_{min,\mathbf{H}}$ denote the minimum euclidean distance in the received signal set for the optimal and diagonal precoders, respectively. Since the BER at high SNRs mostly depends on $d_{min,\mathbf{H}}$, we get the SNR gap in dB as

$$\text{SNR}_{D,\text{dB}} - \text{SNR}_{opt,\text{dB}} = 20\log(\tilde{d}^{opt}_{min1,\mathbf{H}}/\tilde{d}^{D}_{min1,\mathbf{H}}), \quad (16)$$

where $\tilde{d}^{opt}_{min,\mathbf{H}} = \frac{d^{opt}_{min,\mathbf{H}}}{\sqrt{P^{opt}_r}}$ and $\tilde{d}^{D}_{min,\mathbf{H}} = \frac{d^{D}_{min,\mathbf{H}}}{\sqrt{P^{D}_r}}$ are the normalized minimum euclidean distances in the received signal set for the optimal and diagonal precoders, respectively, $P^{opt}_r = \frac{1}{N_r}\mathbb{E}[||\mathbf{H}\mathbf{W}_{opt}\mathbf{s}||^2]$, and $P^{D}_r = \frac{1}{N_r}\mathbb{E}[||\mathbf{H}\mathbf{W}_{D}\mathbf{s}||^2]$. The normalized minimum euclidean distances for SMP are $\tilde{d}^{opt}_{min,\mathbf{H}} = 0.0516$ and $\tilde{d}^{D}_{min,\mathbf{H}} = 0.0295$. Substituting these values of $\tilde{d}^{opt}_{min,\mathbf{H}}$ and $\tilde{d}^{D}_{min,\mathbf{H}}$ in (16), we get the SNR gap equal to 2.4 dB, which is approximately equal to the one obtained through simulations (i.e., from Fig. 4). The normalized minimum euclidean distances for GSM are $\tilde{d}^{opt}_{min,\mathbf{H}} = 0.0113$ and $\tilde{d}^{D}_{min,\mathbf{H}} = 0.0027$. The normalized minimum euclidean distances for SM are $\tilde{d}^{opt}_{min,\mathbf{H}} = 0.0127$ and $\tilde{d}^{D}_{min,\mathbf{H}} = 0.0048$. In Table II, we present the SNR gains for diagonal and optimal precoders compared to the without precoder for $d_{tx} = 0.6$m.

Figure 7 shows the BER performance comparison between SMP, GSM, and SM schemes with optimal precoder, diagonal precoder, and no precoder. All the schemes use $d_{tx} = 3$m and 4 bpcu. The schemes considered are: *i)* SMP: $M = 2$, *ii)* GSM: $N_a = 2, M = 2$, and *iii)* SM: $M = 4$. It can be seen that SMP with optimal precoder outperforms both GSM and SM with optimal precoder. For example, at a BER of $10^{-4}$, SMP with optimal precoder gives an SNR advantage of 4 dB over SM and GSM with optimal precoder. This is because of

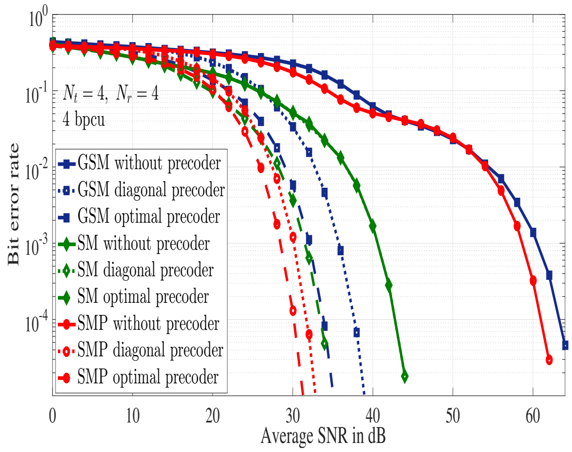


Fig. 7. BER performance comparison of SMP, GSM, and SM with optimal and diagonal precoders in VLC system with $d_{tx} = 3$m and 4 bpcu.

| Modulation Scheme | SNR gain with diagonal precoder | SNR gain with optimal precoder |
|---|---|---|
| SMP | 30.7 dB | 32.2 dB |
| GSM | 26.9 dB | 30.9 dB |
| SM | 0 dB | 9.7 dB |

TABLE III
SNR GAIN FOR MIMO SCHEMES WITH DIAGONAL AND OPTIMAL PRECODERS FOR $d_{tx} = 3$ METERS.

the better normalized minimum euclidean distance between the received points in SMP with optimal precoder. The minimum distances between the received points for SMP, GSM, and SM are 0.0516, 0.0201, and 0.0206, respectively. We also see that SMP with diagonal precoder outperforms both GSM and SM with diagonal precoder. For example, to achieve $10^{-4}$ BER, SMP with diagonal precoder requires about 6 dB and 12 dB less SNR when compared to GSM and SM, respectively, with diagonal precoder. It is further observed that SM with diagonal precoder performs almost same as SM without precoder. This indicates that diagonal precoding for SM does not improve the BER performance when the channel correlation is low. In the case of SMP and GSM, the performance of diagonal precoder is quite good. This suggests that diagonal precoder is a good suboptimal solution for improving the BER performance of the SMP and GSM. In Table III, we present the SNR gains for diagonal and optimal precoders for $d_{tx} = 3$m.

In Fig. 8, we present the BER performance of SMP with optimal precoder, diagonal precoder, and no precoder as a function of $d_{tx}$ with $M = 2$ and 4 bpcu. It can be seen that, SMP with or without precoder achieves the best BER performance at some optimum value of $d_{tx}$. This is because, as the $d_{tx}$ increases, the channel correlation decreases which leads to improvement in the BER performance. On the other hand, the channel gains decrease as $d_{tx}$ increases, which leads to degradation in BER performance. This results in an optimum spacing because of the opposing effects of channel correlation and channel gains with $d_{tx}$. We can also see that, SMP with optimal precoder clearly outperforms SMP with diagonal and no precoder. For example, at 30 dB, the optimal precoder achieves a BER of order $10^{-4}$, whereas SMP with diagonal precoder and no precoder achieve only a BER of order $10^{-3}$ and $10^{-1}$, respectively.

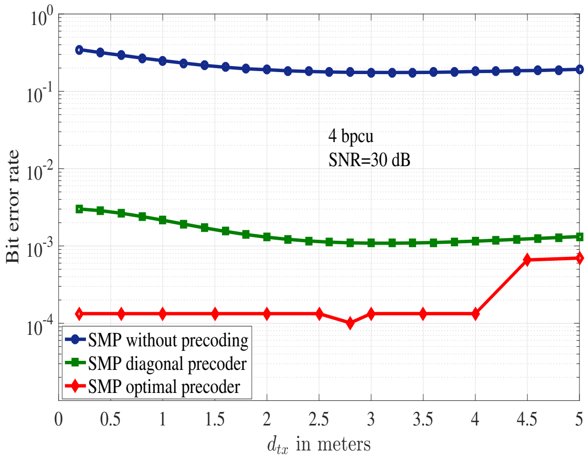


Fig. 8. BER performance of optimal and diagonal precoders as a function of $d_{tx}$ in VLC system using SMP with $N_t = 4,\ N_a = 4,\ N_r = 4$, and 4 bpcu.

## V. CONCLUSIONS

We proposed two precoders, namely, an optimal precoder and a diagonal precoder for MIMO schemes in the context of indoor wireless VLC systems. The optimal precoder maximized the minimum euclidean distance of the received signal set under non-negativity and maximum power constraints. The diagonal precoder induced transmit power imbalance to achieve improved performance. Our simulation results showed that MIMO schemes with precoder outperform the MIMO schemes without precoder. Among the considered MIMO schemes with precoding, SMP outperformed GSM and SM.

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