IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 5, Number 4, August 2013

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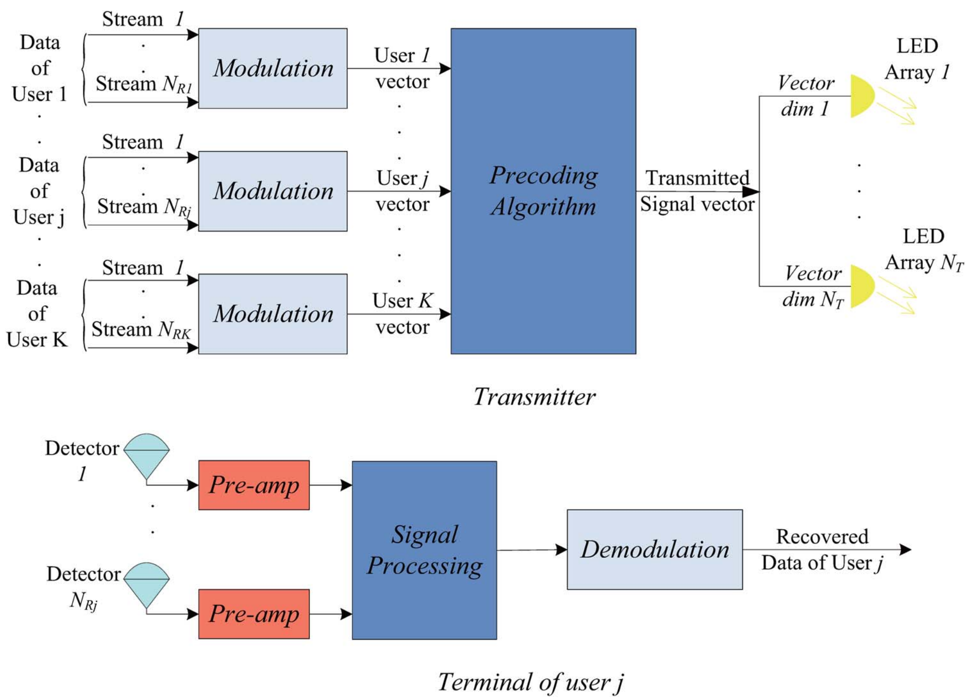

DOI: 10.1109/JPHOT.2013.2274766
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Performance of a Precoding MIMO System for Decentralized Multiuser Indoor Visible Light Communications

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DOI: 10.1109/JPHOT.2013.2274766

Manuscript received May 28, 2013; revised July 16, 2013; accepted July 17, 2013. Date of publication July 25, 2013; date of current version August 6, 2013. This work was supported by the National Natural Science Foundation of China under Grant 61271239. Corresponding author: J. Chen (e-mail: chenjian@njupt.edu.cn).

Abstract: This paper investigates the performance of our recently proposed precoding multiuser (MU) MIMO system in indoor visible light communications (VLC). The transmitted data of decentralized users are transmitted by light-emitting-diode (LED) arrays after precoding in a transmitter, by which the MU interference is eliminated. Thus, the complexity of user terminals could be reduced, which results in the reduction of power consumption. The limitation of block diagonalization precoding algorithm in VLC systems is investigated. The corresponding solution by utilizing optical detectors with different fields of view (FOV) is derived, and the impact of FOV to the proposed system is also analyzed. In this paper, we focus on BER and signal-to-noise-ratio performances of the proposed system with the consideration of the mobility of user terminals. Simulation results show that the majority of the indoor region can achieve 100 Mb/s at a BER of 10^{-6} when single LED chip's power is larger than 10 mW.

Index Terms: Visible light communication (VLC), multi-user (MU) MIMO, precoding, light-emitting diode (LED).

1. Introduction

Light-emitting diodes (LED) are expected to be the substitute of conventional incandescent and fluorescent lamp due to its lower power consumption, high efficiency and longer lifetime [1], [2], [3]. Since it is possible to modulate electric signals to visible lightwave, the indoor visible light communication (VLC) utilizing white LED has attracted many researchers' interests. However, achieving high data rate is challenging for the VLC system due to the limited bandwidth of white LED, which is typically several MHz [4]. For a typical indoor environment, multiple LED sources are commonly employed by the reason that the optimum illuminance should be 300 to 1500 lx for sufficient illumination [2]. Therefore, multiple input and multiple output (MIMO) technique appears attractive to improve data rate, for a very high signal to noise ratio (SNR) is available in VLC systems [5], [6]. There have been some reports about MIMO technique in VLC. Non-imaging and imaging optical MIMO approaches are introduced and simulation results are presented in [5], but the system does not work in the central area, which is unacceptable in a practical indoor VLC system. The experimental demonstration of an indoor optical wireless MIMO system with an imaging receiver is reported and simulation results show that the system performs well at certain positions [7], however, the proposed system can not provide sufficient illuminance for indoor area. An experimental demonstration of a 4×9 optimized MIMO system, which enables indoor gigabit/s VLC transmission is reported in [8], but the proposed system has limited range and coverage in a typical indoor environment. Besides, a power allocation method for an arbitrary number of transmit and receive antennas for optical wireless MIMO systems is derived in [9], simulation results show that the proposed allocation method gives a better spectral efficiency at the expense of an increased computational complexity.

However, only the scenario that all receivers belong to the same user terminal (single user) is considered in these works. For a practical indoor environment, multiple user terminals are likely deployed in VLC system. Consequently, the study of multi-user MIMO VLC system has emerged recently as an important research topic. A novel LED lamp arrangement is proposed for multi-user VLC systems to reduce SNR fluctuation [10]. Report shows an optical code-division multiple access (OCDMA) system for multi-user VLC which utilizes random optical codes (ROCs) as coding sequences [11] and a new indoor VLC system which supports multiple access under line-of-sight (LOS) constraints is investigated [12]. Nevertheless, these complicated systems have high requirement for terminal's signal processing ability.

We have recently proposed a precoding MU-MIMO indoor VLC system [13]. Since the main difficulty for transmission is the separation of received data for different user terminal [14], [15], i.e., multi-user interference (MUI), block diagonalization (BD) precoding algorithm [15] is adopted in the proposed system to eliminate MUI in transmitter by pre-processing the data of each user terminal. Thus the complexity of user terminal could be reduced, which results in the reduction of power consumption. We investigated the limitation of BD precoding algorithm in the proposed VLC systems. The corresponding solution by utilizing optical detectors with different field of view (FOV) is derived and the influence of FOV to the proposed system is analyzed. In this paper, we focus on BER and SNR performances of the proposed system, in addition, the mobility of user terminal to the proposed system is also considered.

The rest of this paper is organized as follows. The principle of BD precoding algorithm is described in Section II. Section III shows the precoding MU-MIMO VLC system. The BER and SNR performances of 100-Mbit/s bipolar OOK signal together with the impact of user terminal mobility are given in Section IV. Section V shows the conclusion.

2. Principle of Block Diagonalization Algorithm

Consider a precoding MIMO indoor VLC system with K user terminals. The number of LED array (transmitter) is N_T and the j-th user terminal has N_{Rj} optical receivers. The total number of optical receivers is defined to be $N_R = \Sigma\, N_{Rj}$. After BD precoding [15], the signal vector is given by

$$f(t) = (f_1(t), \ldots, f_{N_T}(t))^H = (F_1, \ldots, F_K)(u_1(t), \ldots, u_K(t))^H = \sum_{j=1}^{K} F_j u_j(t) \tag{1}$$

where $(\cdot)^H$ denotes the Hermitian transpose, F_j is the precoding matrix corresponding to the j-th user data symbol vector $u_j(t)$. In order to eliminate MUI, BD algorithm pre-processes each user with a precoding matrix, i.e., matrix F_j, which lies in the null space of the other users' channel matrices [15], such that

$$H_i F_j = 0 \quad \textit{for all} \quad i \neq j \quad \textit{and} \quad 1 \leq i,\ j \leq K \tag{2}$$

where H_i is the channel matrix of the i-th user terminal. Hence, the received signal at the j-th user terminal can be calculated as

$$y_j(t) = \sum_{i=1}^{K} H_j F_i u_i(t) + n_j(t) = H_j F_j u_j(t) + \sum_{i=1, i\neq j}^{K} H_j F_i u_i(t) + n_j(t) = H_j F_j u_j(t) + n_j(t) \tag{3}$$

where $n_j(t)$ represent the $N_{Rj} \times 1$ noise vector for user j. The solving process of BD precoding matrix can be summarized as follows [15].

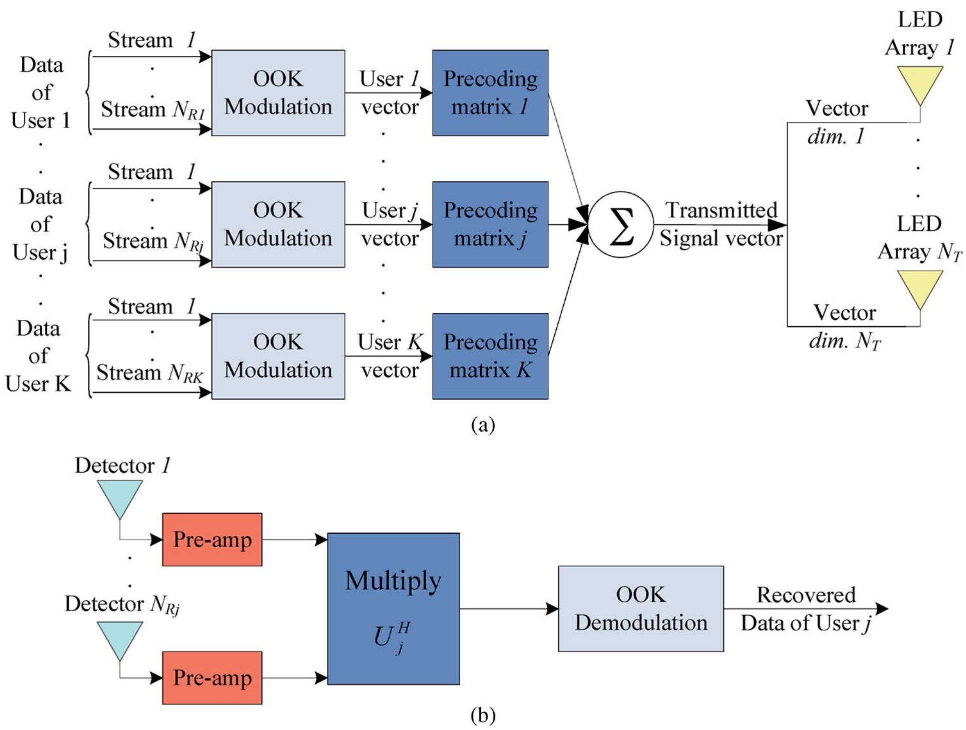

Fig. 1. Schematic of the precoding multi-user MIMO indoor VLC system. (a) Transmitter. (b) Terminal of user j.

First, define matrix $\widetilde{H}_j = (H_1^H, \ldots H_{j-1}^H, H_{j+1}^H, \ldots H_K^H)^H$, which contains all channel matrices except the j-th user.

Second, let $\widetilde{L}_j = rank(\widetilde{H}_j)$ and define singular value decomposition (SVD) [16] of

$$\widetilde{H}_j = \widetilde{U}_j \begin{pmatrix} \widetilde{\Sigma}_j & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} \widetilde{V}_j^{(1)} & \widetilde{V}_j^{(0)} \end{pmatrix}^H \tag{4}$$

where $\widetilde{V}_j^{(1)}$ holds the first $\widetilde{L}_j$ right singular vectors and $\widetilde{V}_j^{(0)}$ holds the last $N_T - \widetilde{L}_j$ right singular vectors. Thus $\widetilde{V}_j^{(0)}$ forms an orthogonal basis for the null space of $\widetilde{H}_j$ and its columns are, thus, candidates for the precoding matrix F_j of user j.

Third, we define equivalent channel matrix of user j, i.e., $\overline{H}_j = H_j \widetilde{V}_j^{(0)}$. Let $L_j = rank(\overline{H}_j)$ and calculate the SVD

$$\overline{H}_j = H_j \cdot \widetilde{V}_j^{(0)} = U_j \begin{pmatrix} \Sigma_j & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} V_j^{(1)} & V_j^{(0)} \end{pmatrix}^H \tag{5}$$

where $V_j^{(1)}$ holds the first L_j singular vectors and forms the orthogonal basis of $\overline{H}_j$.

Finally, we define the BD precoding matrix as [15],

$$F_j = \widetilde{V}_j^{(0)} V_j^{(1)}. \tag{6}$$

As mentioned above, MUI is completely eliminated in transmitter. At user terminal, the data vector can be easily restored after demodulation without much complicated processing. Thus, the complexity of user terminal can be significantly reduced.

3. Modeling of Precoding MU-MIMO Indoor VLC System

Fig. 1 shows the schematic of our proposed precoding MU-MIMO indoor VLC system, and each of the components is described as follows.

3.1. Transmitter

The modulating bipolar NRZ on-off keying (OOK) signal is given by $u(t) = (u_1(t), \ldots, u_K(t))^H$, $u_j(t)$ is a $N_{Rj} \times 1$ data vector of the j-th user terminal. After BD precoding, the signal vector is given by Eq. (1), and the optical signal at output of LED arrays is given by

$$x(t) = (x_1(t), \ldots, x_{N_T}(t))^H = \sum_{n=1}^{LEDs} P_{LED} * p(t) = \sum_{n=1}^{LEDs} P_{LED} * (1 + m_I * f(t)) \tag{7}$$

where m_I is modulation index [17]; LEDs is the number of LED per array; P_{LED} is single LED chip's power.

3.2. Channel Matrix

The optical detectors receive optical signal propagated from each LED. And generally, there are two types of propagation: (1) line of sight (LOS) (propagates to the receiver directly), (2) non-LOS (due to reflections from the surfaces within indoor environment). As revealed in [2], for the designed indoor environment which is adopted in this work, the proportion of LOS is more than 95% of the light collected by optical receiver. Therefore, we assume that the reflection of walls, ceiling and floor is so faint that DC gain [18] is used to describe the channel matrix (A similar approach is taken in [5], [10]). For further discussion, the non-LOS effect will be taken into account. The channel coefficient h_{ji}, defined as the DC gain [18] between transmitter i and receiver j, is given by

$$h_{ji} = \begin{cases} \sum_{k=1}^{LEDs} \frac{A}{d_{jik}^2} R_0(\phi_{jik}) T_s(\psi_{jik}) g(\psi_{jik}) \cos\psi_{jik} & 0 \le \psi_{jik} \le \psi_c \\ 0 & \psi_{jik} > \psi_c \end{cases} \tag{8}$$

where A is the physical area of photo-detector, d_{jik} is the distance between the k-th LED (in the i-th LED array) to the j-th optical detector, ψ_c denotes the optical receiver FOV (semi-angle), ϕ_{jik} is the emission angle, ψ_{jik} is the angle of incidence. $T_s(\psi)$ is the gain of an optical filter and $g(\psi)$ is the gain of an optical contractor. $R_0(\phi_{jik})$ denotes the Lambertian radiant intensity, which is given by

$$R_0(\phi_{jik}) = \frac{(m+1)}{2\pi} \cos^m(\phi_{jik}) \tag{9}$$

where m is the order of Lambertian emission, which is related to $\phi_{1/2}$, the LED's semi-angle at half power, by $m = -\ln(2)/\ln(\cos(\phi_{1/2}))$.

3.3. Receiver

After transmission in visible light channel, the average received optical power at the j-th optical detector is

$$r_j(t) = \sum_{i=1}^{N_T} h_{ji}(P_{LED} * (1 + m * f_i(t))) \tag{10}$$

where $f_i(t)$ is the signal emitted from the i-th LED array. After the DC component is blocked, the signal can be described as

$$r'_j(t) = m * P_{LED} * \sum_{i=1}^{N_T} h_{ji} f_i(t). \tag{11}$$

Thus the received electrical signal on the j-th optical detector is described by

$$y_j(t) = \gamma * r'_j(t) + n_j(t) = \gamma * m * P_{LED} * \sum_{i=1}^{N_T} h_{ji} f_i(t) + \sqrt{i_{n,j}^2(t)} \tag{12}$$

where $\overline{i_{n,j}^2(t)}$ is mean square noise current, containing shot noise and thermal noise, which is given by

$$\overline{i_{n,j}^2} = \sigma_{total}^2 = \sigma_{shot}^2 + \sigma_{thermal}^2 \tag{13}$$

where σ_{shot}^2 is the variance of shot noise and $\sigma_{thermal}^2$ is the variance of the thermal noise, the parameters to determine them are the same as in [2]. Note that the background noise, which is dominant in VLC systems, is included in the above mentioned shot noise. Hence, SNR of the output recovered electrical signal at j-th optical detector is given by

$$SNR = \frac{\left(\gamma * r_j'\right)^2}{\overline{i_{n,j}^2}} = \frac{\left(\gamma * r_j'\right)^2}{\sigma_{shot}^2 + \sigma_{thermal}^2}. \tag{14}$$

At output of pre-amplifier, the signal vector is multiplied with Hermitian transpose of matrix U_j, the data vector can be restored after demodulation without the more complicated processing. For a portable terminal in VLC system, the ability to process high speed signal is normally limited and complicated processing in the user terminal is supposed to cause battery drain problem. Therefore, the reduction of complexity and cost of signal processing at user terminals by applying the precoding technique at transmitter (LED) will decrease the computational burden of user terminal, leading to lower energy consumption.

3.4. Illumination With White-Light LEDs

As for the indoor environment lighting, consideration of sufficient brightness at receiving plane is required. The illuminance expresses the brightness of an illuminated surface. According to [2], the horizontal illuminance at a desk surface is defined as

$$E_h(x, y) = \sum_{LEDs} \frac{I_0 \cos^m(\phi)}{d^2} \cos(\psi) \tag{15}$$

where I_0 is the center luminous intensity of the LED, ϕ is the angle of irradiance, ψ is the angle of incidence, d is the distance between an LED and optical receiver and m is the order of Lambertian emission.

4. Numerical Results and Discussion

The setup of the precoding indoor VLC system is shown in Fig. 2, where four LED arrays locate on the ceiling (as arranged in [5]) and two terminals, each with two optical receivers, is assumed to compose a 4 $\times$ [2, 2] MU-MIMO system. The receiving plane is $h = 2.15$ m away from ceiling. The center of the room is selected as the origin of coordinate and the other parameters of the proposed system are listed in Table 1.

Without loss of generality, we assume two typical scenarios to simulate BER and SNR performance of the system by considering the diversity of user terminals' distribution. And then, the impact of user terminal's mobility to the proposed system is investigated. The location of decentralized users is listed in Table 2. In scenario 1, both of the users locate near the LED array. In scenario 2, one user is close to the LED array and the other one is fixed in the corner of the room.

Fig. 3 shows the distribution of horizontal illuminance at the receiving plane (0.85 m). Note that LED arrays is arranged in the ceiling, which is 2.15 m away from the receiving plane. From this figure, the sufficient illuminance, i.e., 300 to 1500 lx by ISO, is obtained in the indoor area.

The result of Fig. 3 shows that the LED array arrangement satisfies lighting requirement for indoor environment. Next, we will discuss the performance of the proposed system in detail. Fig. 4 shows the relation between single LED power and BER of user terminal.

Due to factors such as size and volume, the receiver pitch is generally limited to 0.1 m for user terminal. The range for optical receiver to receive optical signal is derived as $r = d \cdot tan(FOV)$,

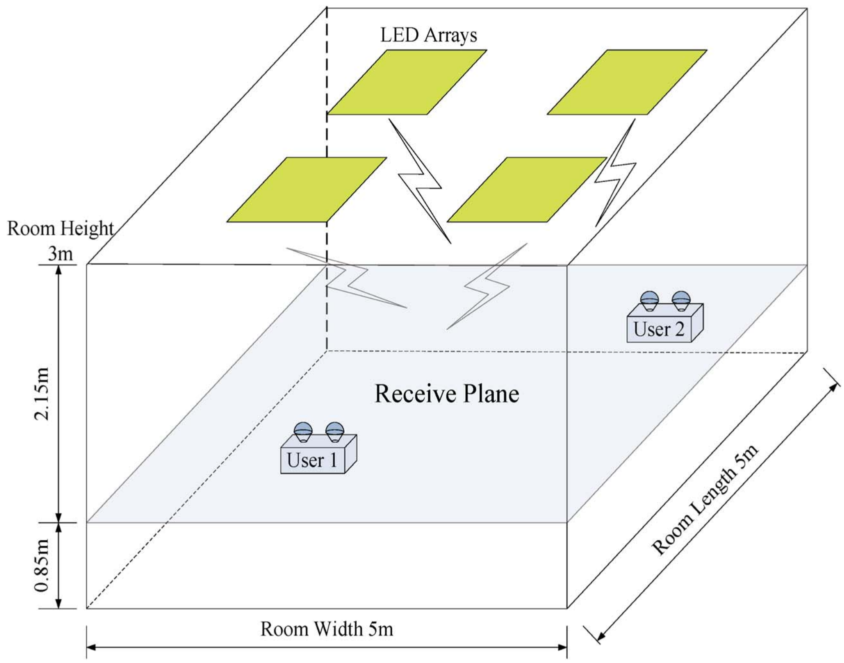

Fig. 2. Model of the precoding MU-MIMO indoor VLC system.

TABLE 1

Parameters of precoding MU-MIMO indoor VLC system

Parameters	Values	Parameters	Values
Room size $(W \times L \times H)$	$5m \times 5m \times 3m$	PD Responsivity	$0.4\ A/W$
Detector physical area of a PD	$1.0\ cm^2$	Receiver pitch	$0.1\ m$
Number of LEDs per array	$3600\ (60 \times 60)$	Gain of optical filter	1.0
Center luminous intensity	$0.73\ cd$	Size of LED array	$0.59m \times 0.59m$
Background light current	$5100\ \mu A$	Modulation Index	0.2
Refractive index n	1.5	LED pitch	$0.01\ m$
Transmitter semi-angle	$60\ deg$	Data Rate	$100\ Mbit/s$

TABLE 2

Location of the decentralized user terminals

Scenario	$\mathbf{Receiver1\&2(UserTerminal1)}$	$\mathbf{Receiver1\&2(UserTerminal2)}$
1	$[-1, -1, 0.85][-1.1, -1, 0.85]$	$[-0.5, 0.5, 0.85][-0.6, 0.5, 0.85]$
2	$[-1, -1, 0.85][-1.1, -1, 0.85]$	$[1.3, 2.3, 0.85][1.4, 2.3, 0.85]$

where d denotes the vertical distance from ceiling to receiving plane. For receivers belonging to the same user, the ranges to receive the optical signal for them are almost identical when they have the same FOV, e.g., 70 deg in this work, which leads to high correlation between the channel matrices belong to one user. As for BD algorithm, when detectors of the terminal have high correlation with

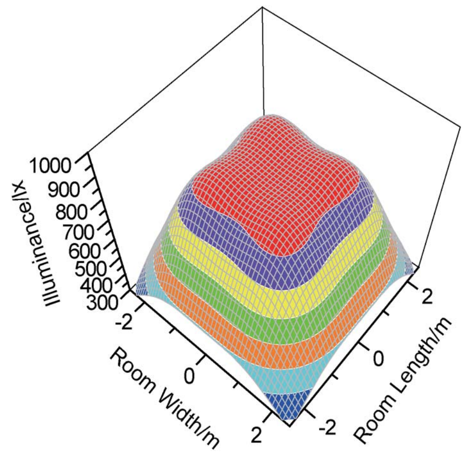

Fig. 3. The distribution of illuminance at the receiving plane.

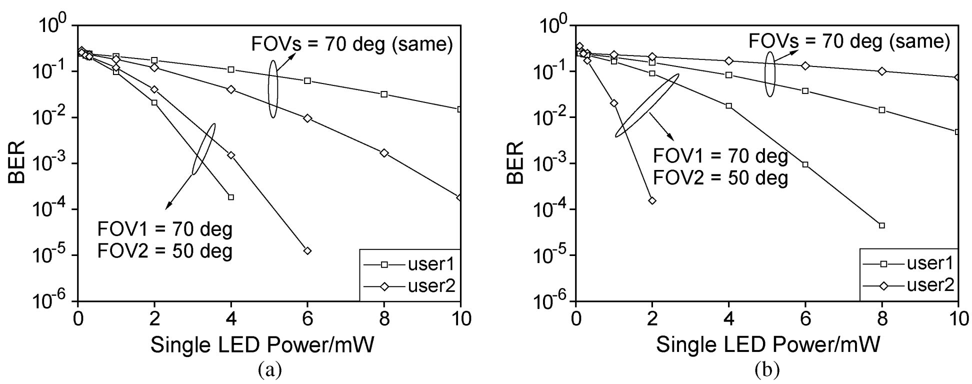

Fig. 4. BER performance of user terminals. (a) Scenario 1. (b) Scenario 2 (in Table 2).

each other, the singular values of terminal, i.e., equivalent channel gains, are much dissimilar after singular value decomposition of the channel matrix. Hence, the terminals' performance decreases significantly. As is depicted in Fig. 4, the user terminals perform poor. The BER of the terminal is still about 10^{-2} even when the single LED's power is $\sim$10 mW in both scenarios. Therefore, the limitation of BD algorithm in VLC system lies in the fact that closely spaced optical detectors have high correlation with each other.

In order to improve BER performance of user terminals, we then propose a scheme to weaken the correlation between the receivers by utilizing different FOV for the same user terminal, which is shown in Fig. 5.

As is shown in Fig. 4, the BER performance is significantly improved in both scenarios by the proposed scheme. When the single LED power is 10 mW, both of the terminals' BER are smaller than 10^{-6}. Note that the performance of user terminal is affected by its mobility, which will be discussed later in this paper. Hence, the performance of user terminals varies in different scenarios.

Now we consider SNR performance of the system. Fig. 6 shows the relation between single LED power and SNR of the output detected signal when FOVs of single user terminal (with two optical receivers) are all 70 deg. From Fig. 6 we find that, the SNR performance is almost the same for optical receivers which belong to the same user terminal. For different user terminals, the difference of SNR performance is not significant as depicted Fig. 6(a) while SNR of user 1 is about 5 dB larger than the other user terminal, which is shown in Fig. 6(b).

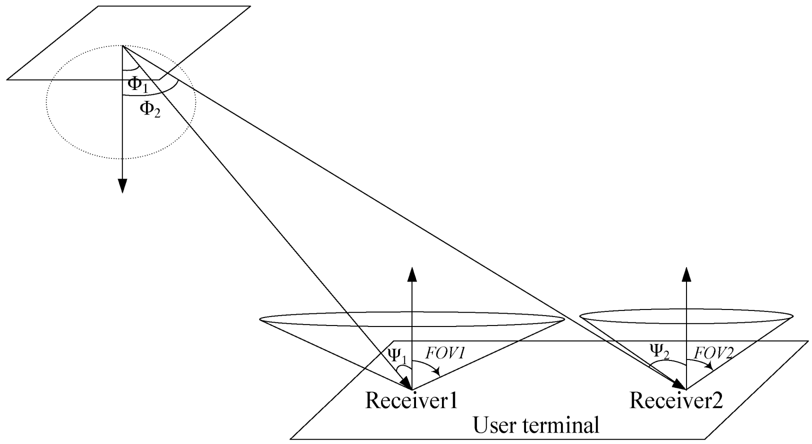

Fig. 5. Schematic diagram of the user terminal with different FOV.

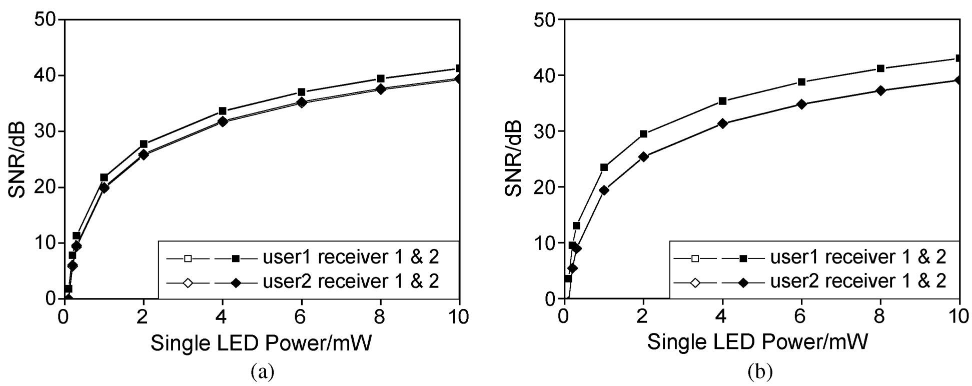

Fig. 6. Relations between single LED power and SNR of the output detected signal when the FOV of single user terminal (with two optical receivers) are all 70 deg. (a) Scenario 1. (b) Scenario 2 (in Table 2).

From Fig. 7, we see that FOV at an optical receiver has strong influence on the SNR performance of the system. The difference of SNR for optical receivers which belong to the same user terminal is about 5 dB as shown in Fig. 7. For the situation where user terminals are fixed in different location in comparison to LED array (scenario 2), SNR of the terminal, which is close to the LED array, is about 15 dB larger than the one which is located in the corner, as depicted in Fig. 7(b).

We then step further to investigate the impact of FOV at an optical receiver to the system when single LED power is 10 mW, and simulation results are shown in Figs. 8 and 9.

From Figs. 8 and 9 we find that, the larger the difference between FOV at optical receivers which belongs to the same user terminal, the larger the disparity of SNR at the output of optical receivers will be, as shown in Fig. 8, and basically the better BER performance will the two user terminals achieve, as depicted in Fig. 9. Note that the discontinuous points, i.e., 35 to $\sim$50 deg, in Fig. 9 denote that the BER of user terminal is smaller than 10^{-6}. For an optical detector, the lower FOV value it has, the less optical signal it can collect. Hence, the SNR will decrease, leading to poor BER performance at terminal. As for a terminal with multiple optical detectors, the detectors should be decorrelated in order to achieve good performance. Basically, the more difference between the value of detector's FOV is, the better performance user terminal will achieve. However, as for a typical indoor environment, the illuminance is inhomogeneous. A small FOV value goes against achieving good performance in most indoor area. By comprehensive consideration of the two

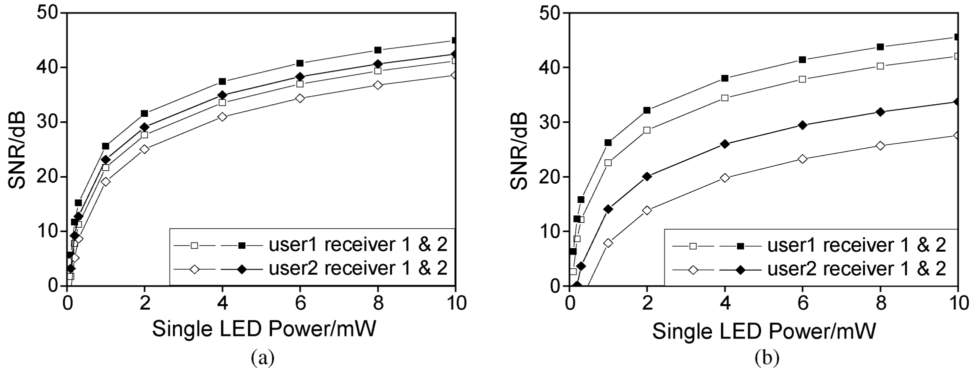

Fig. 7. Relations between single LED power and SNR of the output detected signal when the FOV of single user terminal (with two optical receivers) are 70 deg and 50 deg. (a) Scenario 1. (b) Scenario 2 (in Table 2).

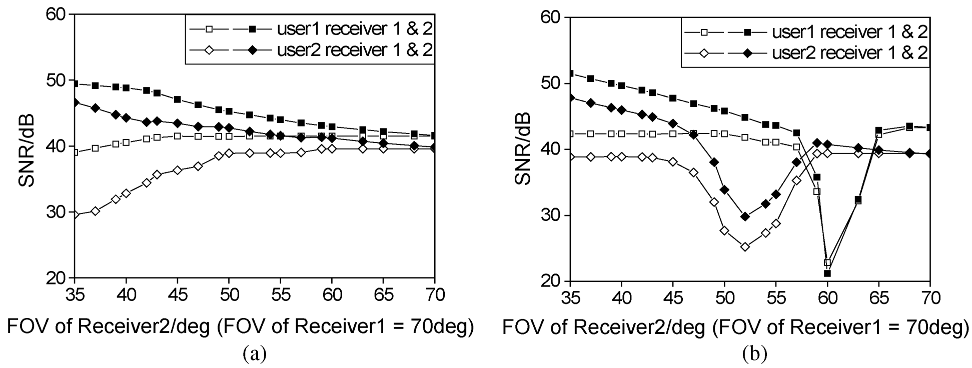

Fig. 8. Relations between FOV at the receiver and SNR of the output detected signal. (a) Scenario 1. (b) Scenario 2 (in Table 2).

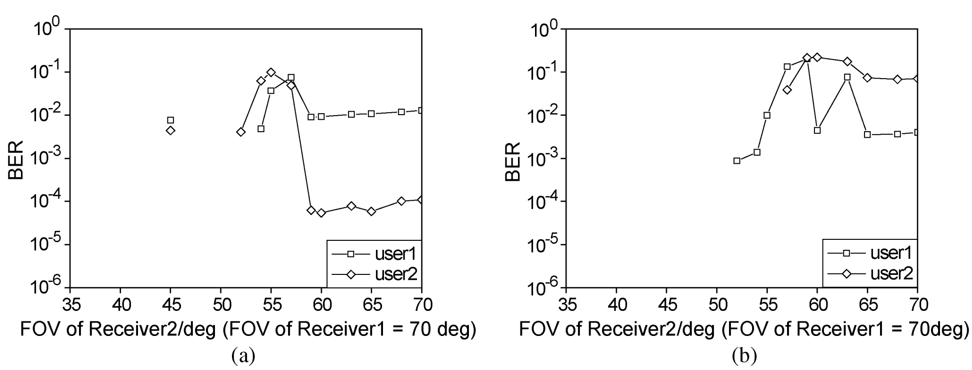

Fig. 9. Relations between FOV at the receiver and BER of the user terminals. (a) Scenario 1. (b) Scenario 2 (in Table 2).

factors, it is an optimum choice for a user terminal to adopt 70 deg and 50 deg as the FOVs for the optical receivers. What deserves mention here is that the scheme by using different FOV is not the only solution to improve the performance of the system. This is worthy of further investigation, as it is an open question as to what scheme creates the best precoding MU-MIMO VLC system. Further

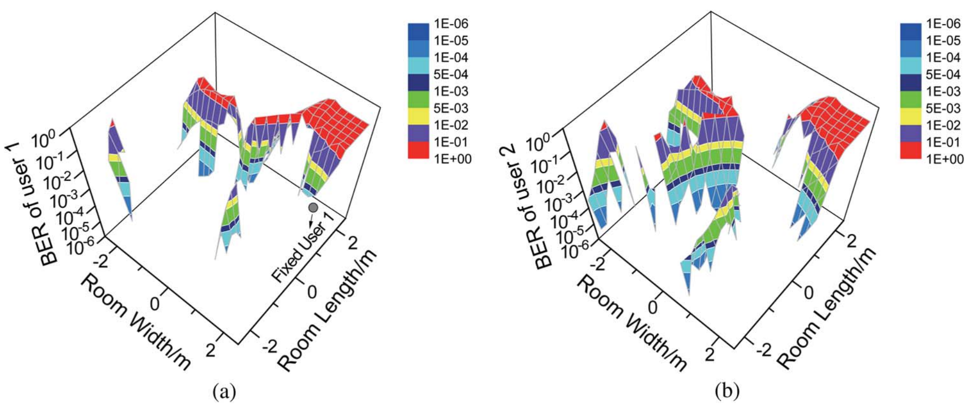

Fig. 10. The impact of user 2's mobility to the BER of user terminals. (a) User terminal 1. (b) User terminal 2.

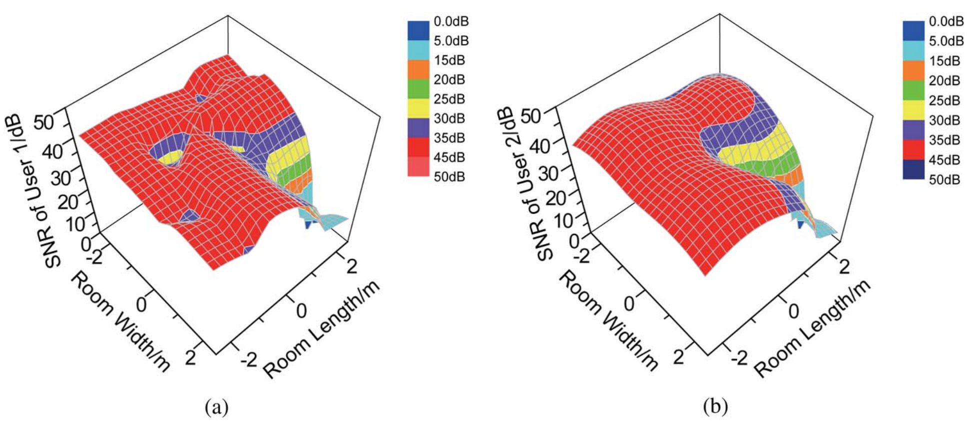

Fig. 11. The impact of user 2's mobility to the average SNR of user terminals. (a) User terminal 1. (b) User terminal 2.

optimization of terminals' performance is required and these are expected to the other methods, e.g., detectors with angle diversity, which will be discussed extensively in our following work.

Now we consider the impact of the user's mobility to the system. The data rate is 100 Mbit/s while single LED's power is 10 mW. We assume that user terminal 1 is fixed in a certain position while user terminal 2 moves around in the room and more complex scenarios will be discussed extensively in the following work. Figs. 10 and 11 show the impact of user 2's mobility to BER and average SNR performance of both terminals when the two optical receivers of user 1 are located in [1.3, 2.3, 0.85] and [1.4, 2.3, 0.85], respectively, as marked in Fig. 10(a).

As depicted in Figs. 10 and 11, user 2's mobility has an effect on both terminals' BER and SNR performance. Generally, the BER performance of user terminal 1 and user terminal 2 are similar, while the moving user terminal 2 performs a little worse, as is shown in Fig. 10. The user terminals could achieve a high SNR in the most regions, as shown in Fig. 11. Both user terminals in the precoding MU-MIMO indoor VLC system trend to perform worse when the moving user 2 is in the vicinity of the fixed user 1, accompanied by the significant decrease of the terminals' average SNR. Note that the discontinuous points in Fig. 10 indicate that the BER of user terminal is lower than 10^{-6}. Therefore, the majority of the indoor area can achieve 100 Mb/s at a BER of 10^{-6} when single LED's power is $\sim$10 mW.

5. Conclusion

We have investigated BER and SNR performances of our recently proposed precoding MIMO indoor VLC system for decentralized multi-user. The multi-user interference is eliminated in transmitter by BD precoding algorithm. Under this scheme, the power consumption and complexity of user terminals are reduced. A method to improve the system performance by utilizing different FOV is analyzed. Simulation results have shown a high SNR communication channel, which is up to 40 dB. When the single LED's power exceeds 10 mW, the system can achieve 100 Mb/s at a BER of 10^{-6} while 70 deg and 50 deg are adopted as FOVs for the optical receivers which belong to single user terminal.

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