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Research Article

Switching MIMO System with Adaptive OFDM Modulation for Indoor Visible Light Communication

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In this paper, we propose and experimentally demonstrate a switching multiple input and multiple output (MIMO) system combining with adaptive orthogonal frequency division multiplexing (OFDM) modulation for high-speed indoor visible light communications. The adaptive OFDM modulation, which is realized by power and bit allocation on OFDM subchannels, is utilized to achieve the maximum channel capacity under a given target bit error rate (BER). Meanwhile, the MIMO mode switches between spatial multiplexing and transmit diversity adapting to the channel correlation, where the modulation order solved by adaptive OFDM modulation is chosen as the switching criterion. Experimental results validate data rates improvement over the pure spatial multiplexing and the pure transmit diversity system, where BERs are all below the 7% preforward error correction (pre-FEC) threshold of 3.8×10^{-3} in experiments.

1. Introduction

Recently, light-emitting diode- (LED-) based visible light communication (VLC) has become a major candidate for future wireless communication. As a compelling wireless communication technology beyond traditional radio frequency (RF) communications, VLC offers several advantages such as low cost, no need for a license, immunity to electromagnetic interference, and high security [1, 2]. Meanwhile, compared with the subterahertz communication system, which has also been proposed to overcome the shortcomings of RF communication systems effectively [3], VLC system benefits from its simple system structure and much lower cost. Due to the combination of illumination and communication, a large number of investigations have been focused on indoor high-speed transmission in VLC applications [4–6]. However, the limited modulation bandwidth of commercial LEDs constrains the transmission data rate, where signals modulated at high frequencies are seriously attenuated because of the physical property of LEDs [7]. As a result, it is vital to employ spectral-efficient techniques to achieve high data rate for indoor VLC system.

Among the approaches reported in previous works, orthogonal frequency division multiplexing (OFDM) and multiple input and multiple output (MIMO) techniques have been considered particularly promising in achieving high data rate, which can even be combined together in the VLC system [8–10]. Through OFDM modulation, channel is decomposed into multiple frequency-flat channels and the intersymbol interference (ISI) can be eliminated, while MIMO scheme boosts the channel capacity and improves the reliability based on the simple idea of transmitting multiple data streams simultaneously on multiple LEDs.

However, one major limitation on MIMO performance is the correlation of the MIMO VLC channel [4]. Traditional spatial multiplexing MIMO scheme, which transmits independent data streams simultaneously on multiple LEDs, has been proved to be only useful with low channel correlation. Once the channel is highly correlated, i.e., channel gains between different transmitters and receivers are similar to each other, it would be difficult for the receiver to separate the single data streams [11]. Hence, another popular MIMO scheme transmit diversity is proposed to apply to the high channel correlation environment. As same information-bearing signals are sent from multiple LEDs in transmit diversity MIMO scheme, they benefit the high reliability and insensitivity to channel correlation but lack multiplexing gains [12]. Recently, a more intelligent MIMO scheme has

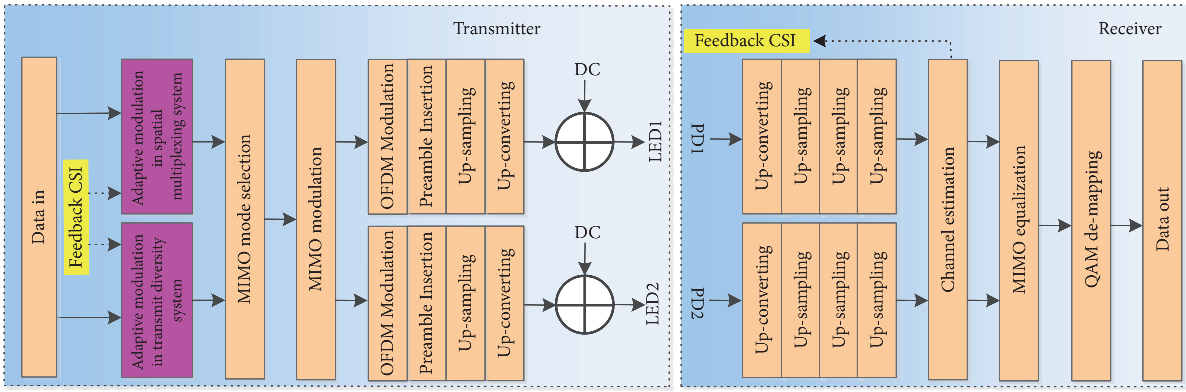


FIGURE 1: Block diagram of the switching MIMO VLC system with adaptive OFDM modulation.

been proposed in [13], where MIMO mode switches between spatial multiplexing and transmit diversity adapting to the channel correlation. In such a way, we can take advantages of both MIMO schemes. However, the switching MIMO scheme is proposed in a fixed-rate MIMO OFDM system, where modulation orders are constant on all OFDM subchannels. Therefore, the transmit diversity scheme has to use a larger signal constellation size to support a high data rate, resulting in worse bit error rate (BER) performance. Otherwise, only low data rate can be reached to ensure the BER under certain threshold.

In this paper, we extend the idea of switching MIMO scheme to a variable-rate MIMO OFDM system. The contribution of this work is to build a switching MIMO VLC system combining with adaptive OFDM modulation for the first time. Firstly, adaptive OFDM modulation is utilized to achieve the maximum channel capacity through power and bit allocation under the constraint of a target BER. Then, the MIMO mode is switched between spatial multiplexing and transmit diversity to adapt to the channel correlation. Specifically, the modulation order solved by adaptive OFDM modulation is chosen as the switching criterion, where the MIMO scheme with higher modulation order is more preferred. Finally, experimental demonstration is set up to investigate the performance of the proposed system, which is compared with the pure spatial multiplexing and the pure transmit diversity system. Experimental results confirm that data rates are improved significantly under the condition of different channel correlations and different locations of transmitters and receivers, where BERs are all below the 7% preforward error correction (pre-FEC) threshold of 3.8×10^{-3}.

The rest of the paper is organized as follows. Section 2 provides the description of the switching MIMO VLC system with adaptive OFDM modulation and the detailed algorithm. In Section 3, experimental demonstration is set up and the discussions of experimental results are given. Finally, we come to the conclusion in Section 4.

2. Principle

2.1. System Description. The block diagram of the switching MIMO VLC system with adaptive OFDM modulation is shown in Figure 1, where the detailed signal processing at transmitter and receiver is presented. In the system, the vertical Bell laboratories layered space-time (V-BLAST) architecture [14] and the Alamouti coding [15] are chosen as the mechanisms to realize spatial multiplexing and transmit diversity, respectively. Without loss of generality, a simple MIMO configuration with two LEDs and two photodiodes (PDs) is considered as an example in the paper.

At the transmitter, adaptive modulation is separately implemented on OFDM subchannels in V-BLAST system and Alamouti coding system according to the channel state information (CSI) fed back from the receiver, where power and bits are allocated based on the idea of maximizing the channel capacity. Then MIMO scheme with higher modulation order is determined as the proper one. After MIMO modulation, single data stream is mapped into two parallel data streams as two transmitters are assumed. The OFDM modulation is performed on each data stream, which is realized by inverse fast Fourier transform (IFFT) with cyclic prefix (CP) attached to each OFDM symbol to overcome the ISI. Preambles are inserted orthogonally in front of the two data streams, which are required for synchronization and channel estimation at the receiver. Afterwards, two data streams are upsampled and upconverted to the same carrier, where complex-to-real-value conversion is applied to achieve the real-value OFDM symbols [16]. Finally, by means of adding direct current (DC) offset, positive, and real-valued signals are transmitted through two LEDs in the form of optical power.

At the receiver, optical signals entering two PDs are converted into electrical signals. Note that crosstalk exists in the MIMO channel, since light from a single LED falls on multiple PDs. The demodulation is the inverse process of the modulation at the transmitter. After removing DC from received signals, downconverting and downsampling are performed. Frame synchronization is realized by the special designed preambles. OFDM is demodulated by the fast Fourier transform (FFT) after CP removal. Then, CSI is estimated based on the simple least square algorithm by preambles, which is required for adaptive modulation and MIMO equalization. Finally, channel crosstalk is eliminated by MIMO equalization and QAM demapping is carried out to recover the original signals.

2.2. Algorithm Description. We establish the MIMO switching criterion based on the modulation order, where the higher modulation order that can be supported by V-BLAST or Alamouti coding is chosen as the proper MIMO scheme. Compared with the switching criterion based on BER bounds in fixed-rate system, it is obvious that wrong switching can be avoided as the modulation order actually represents the data rate of the current system. Besides, it is natural to utilize such switching criterion, since the modulation order is the ready-made solution of adaptive OFDM modulation. In the following, adaptive OFDM modulation for V-BLAST and Alamouti coding systems are described, respectively.

Because crosstalk exists among colocated channels, MIMO channel should be decorrelated into parallel single-input single-output (SISO) channels, and then each SISO channel is further divided into multiple subchannels by using OFDM modulation.

In the V-BLAST system, two symbols are transmitted from two LEDs simultaneously over one symbol period. Hence, the MIMO channel is decorrelated by zero-forcing (ZF) algorithm, which is expressed as

$$\mathbf{W}[k]\,\mathbf{Y}[k] = \mathbf{X}[k] + \mathbf{W}[k]\,\mathbf{N}[k], \quad k = 1, \cdots, M \tag{1}$$

where k is the index of the subchannel, M is the number of subchannels, $\mathbf{W}[k]=\mathbf{H}^{-1}[k]$ and $(\cdot)^{-1}$ denotes the matrix inversion, and $\mathbf{Y}[k]$, $\mathbf{X}[k]$, and $\mathbf{N}[k]$ represent the vectors of received signals, transmitted signals, and noise, respectively. $\mathbf{H}[k] = \begin{bmatrix} h_{11}[k] & h_{12}[k] \\ h_{21}[k] & h_{22}[k] \end{bmatrix}$ is the MIMO channel matrix of kth subchannel, where $h_{ij}[k]$ stands for the channel gain between the ith LED and the jth PD.

Afterwards, the channel capacity of V-BLAST system can be maximized by allocating the power on all the subchannels from different decorrelated SISO channels under the power constraint, which is formulated as the following optimization problem:

$$\begin{aligned}\max_{P_i[k]} \quad & \sum_{i=1}^{2}\sum_{k=1}^{M} C_i[k] \\ & = \max_{P_i[k]} \sum_{i=1}^{2}\sum_{k=1}^{M} \log\left(1 + P_i[k]\, SNR_i[k]\right)\end{aligned} \tag{2}$$

$$\text{Subject to} \quad \sum_{i=1}^{2}\sum_{k=1}^{M} P_i[k] = 2M, \quad P_i \geq 0 \tag{3}$$

where $P_i[k]$, $SNR_i[k]$, and $C_i[k]$ denote the power, the signal-to-noise ratio (SNR), and the channel capacity on the kth subchannel of the ith SISO channel, respectively, where SNR can be easily calculated with the help of feedback CSI according to (1). We solve the optimized power allocated coefficients based on the classic water-filling algorithm.

Then bits are allocated to subchannels to realize the maximum channel capacity under the constraint of a given target BER, which are solved by [17]

$$Q_i[k] = 1 - \frac{1.5 P_i[k]\, SNR_i[k]}{\log\left(5 BER_{\mathrm{T}}\right)} \tag{4}$$

where $Q_i[k]$ is the modulation order on the kth subchannel of the ith SISO channel and BER_{T} is the given target BER. Note that modulation orders should be further rounded down to the nearest integer which is the powers of 2.

Finally, the supported modulation order for V-BLAST system is obtained by summing bits over all subchannels of decorrelated SISO channels.

In the Alamouti coding system, two symbols are transmitted from two LEDs over two symbol periods. So the MIMO channel can easily be decorrelated through matrix transformation by combining signals from different receivers with signals from different symbol periods, which can be denoted as [12]

$$\begin{aligned}&\mathbf{H}_1^{\mathrm{H}}[k]\,\mathbf{Y}_1[k] + \mathbf{H}_2^{\mathrm{H}}[k]\,\mathbf{Y}_2[k] \\ &\quad = \left(\mathbf{H}_1^{\mathrm{H}}[k]\,\mathbf{H}_1[k] + \mathbf{H}_2^{\mathrm{H}}[k]\,\mathbf{H}_2[k]\right)\mathbf{X}[k] \\ &\qquad + \mathbf{H}_1^{\mathrm{H}}[k]\,\mathbf{N}_1[k] + \mathbf{H}_2^{\mathrm{H}}[k]\,\mathbf{N}_2[k], \\ &\qquad\qquad k = 1, \cdots, M\end{aligned} \tag{5}$$

where $\mathbf{Y}_j[k]$ and $\mathbf{N}_j[k]$ denote the vectors of received signals and noise from two symbol periods on kth subchannel at the jth receiver. $\mathbf{H}_j[k] = \begin{bmatrix} h_{1j}^*[k] & h_{2j}[k] \\ h_{2j}^*[k] & -h_{1j}[k] \end{bmatrix}$ stands for the orthogonal channel matrix corresponding to the jth receiver. $(\cdot)^{\mathrm{H}}$ and $(\cdot)^*$ express the matrix Hermitian transpose and conjugation, respectively. Obviously, the result of $\mathbf{H}_j^{\mathrm{H}}[k]\mathbf{H}_j[k]$ is diagonal.

According to (5), we find that SNRs on the corresponding subchannels from two decorrelated SISO channel are the same as each other. Moreover, the Alamouti coding system cannot enjoy the multiplexing gain as only one symbol is actually transmitted over one symbol period. Thus, the maximum channel capacity of Alamouti coding system is equivalent to allocate the power on subchannels of one decorrelated SISO channel, which is given by

$$\begin{aligned}\max_{P_i[k]} \quad & \sum_{k=1}^{M} C_i[k] \\ & = \max_{P_i[k]} \sum_{k=1}^{M} \log\left(1 + P_i[k]\, SNR_i[k]\right)\end{aligned} \tag{6}$$

$$\text{Subject to} \quad \sum_{k=1}^{M} P_i[k] = M, \quad P_i \geq 0 \tag{7}$$

After bit allocation based on (4), the supported modulation order for Alamouti coding system is calculated by summing bits over subchannels of one SISO channel.

It is worth noting that the switching criterion in variable-rate system is still related to the channel correlation. When the channel correlation is low, the modulation order of V-BLAST is higher than Alamouti coding system for its multiplexing gains. However, once the channel is highly correlated, noise would be enhanced by ZF algorithm. Thus, less bits can be allocated because of the worse SNR in V-BLAST system. Nevertheless, SNR performance of Alamouti coding system remains almost the same, since the SNR value

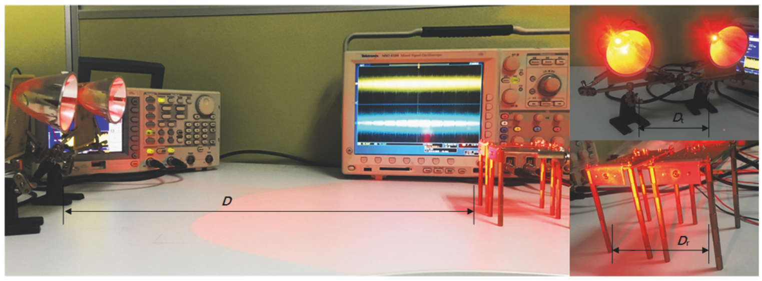
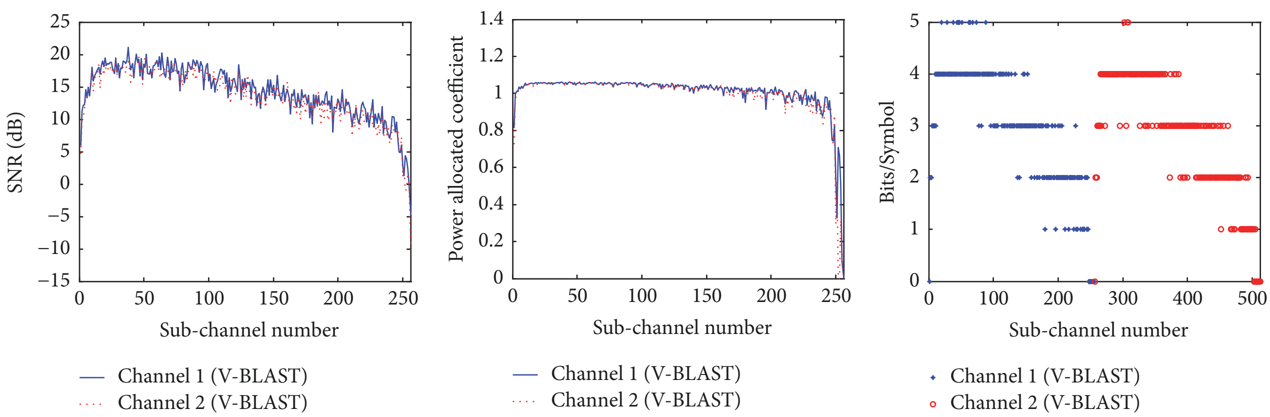


Figure 2: Experimental setup of the switching MIMO VLC system with adaptive OFDM modulation.



(a) (b) (c)

Figure 3: Power and bit allocation results for V-BLAST system (K=2.2805, BER_T=0.003).

of Alamouti coding system depends on the 2-norm of channel matrix. As a result, it is considered as a better choice then.

3. Experimental Results

Experimentally, demonstration is set up to examine the performance of the switching MIMO VLC system with adaptive OFDM modulation, as shown in Figure 2. In the experiment, signals are generated by an arbitrary function generator (AFG: Tektronix AFG3252C), which also supplies the DC offset to ensure the positivity of transmitted signals. The signal peak-to-peak voltage is set to 2.0 V with 2.0 V DC offset so that LEDs may work in the linear region. At the receiver, optical signals are focused on the PDs and converted into electrical signals, which are recorded by a high-speed digital oscilloscope (OSC: Tektronix MSO4104). We use two commercial red light LEDs (Cree XLamp XP-E) as transmitters. We use two PD modules (Hamamatsu C12702-11) as receivers. The rest of system parameters used in experiments are set as follows: the occupied modulation bandwidth is ranged from 0 to 12.5MHz and the upconverted frequency is 6.25MHz; the IFFT/FFT point is 256 with the length of CP equal to 16.

As discussed above, channel correlation is considered an important indicator in MIMO VLC system, which reflects the similarity of channel gains between transmitters and receivers. To quantify the similarity, we use the condition number of the channel matrix to measure the channel correlation [18], which is defined as

$$k = \frac{\lambda_{\max}(\mathbf{H})}{\lambda_{\min}(\mathbf{H})} \tag{8}$$

where $\lambda_{\max}(\mathbf{H})$ and $\lambda_{\min}(\mathbf{H})$ represent the maximum and minimal singular values of the channel matrix $\mathbf{H}$. When channel gains between transmitters and receivers are more similar, the singular values of the channel matrix would be spread out more widely. Thus, less multiplexing gains can be achieved [19] and, obviously, the value of the condition number becomes larger, indicating that the channel correlation gets higher.

Note that MIMO channel is divided into subchannels by OFDM modulation in our system. Therefore, the channel correlation indicator K in the paper is calculated by averaging the channel matrix condition numbers over all subchannels.

Figures 3 and 4 show the power and bit allocation results for V-BLAST system with different channel correlations. In the figures, Channel 1 and Channel 2 denote the two decorrelated SISO channels, each of which is divided into 256 subchannels. In order to display the bit allocation results more clearly, subchannels numbered from 1 to 256 corresponded to Channel 1 and subchannels numbered from 257 to 512 represent subchannels in Channel 2 in Figures 3(c) and 4(c). As can be seen, the SNRs of Channel 1 and Channel 2 are different, which both decreases dramatically with the

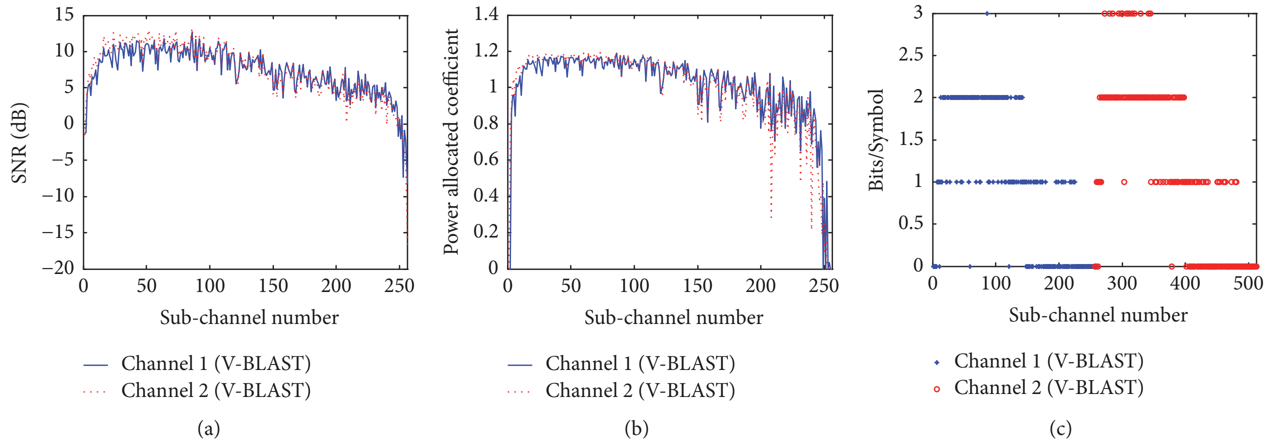


FIGURE 4: Power and bit allocation results for V-BLAST system (K=5.4985, BER_T=0.003).

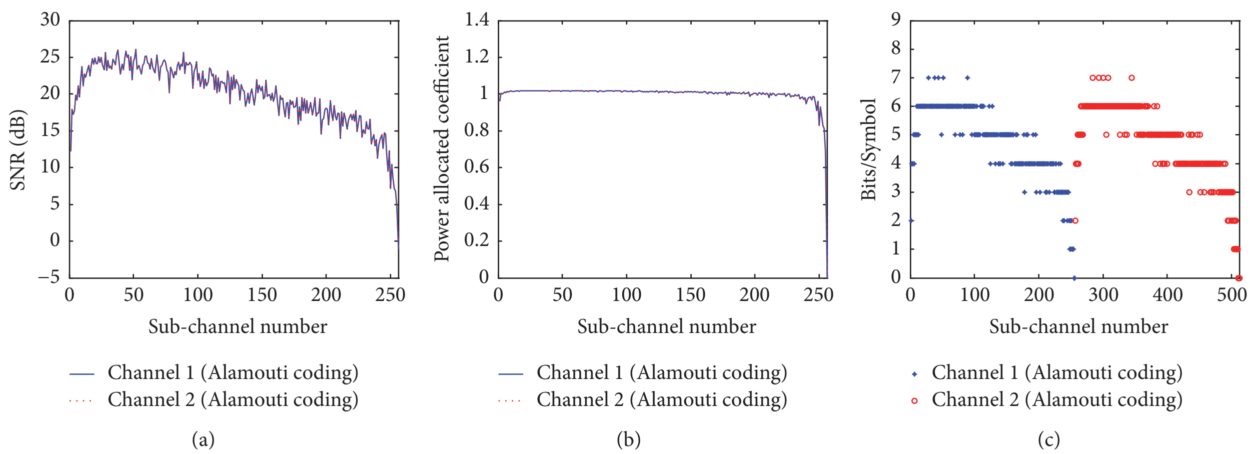


FIGURE 5: Power and bit allocation results for Alamouti coding system (K=2.2805, BER_T=0.003).

frequency growing due to the physical property of LEDs. Hence, power and bit allocation results are also different, where more power and bits are allocated to the subchannels with larger SNRs under the constraint of a given target BER. Comparing Figure 3 with Figure 4, we find that SNRs are reduced obviously when channel correlation increases. As a result, less bits are allocated on the subchannels in order to maintain the same target BER.

In Figures 5 and 6, experimental results of power and bit allocation for Alamouti coding system are given. Experimental results prove that SNRs of Channel 1 and Channel 2 are the same in Alamouti coding system, leading to the same power and bit allocation results. Moreover, the experimental results are quite similar to different channel correlations as shown in Figures 5 and 6, which indicate that the Alamouti coding system is robust to the channel correlation.

To validate the system performance improvement, data rates of the switching MIMO system are compared with the pure V-BLAST system and the pure Alamouti coding system in Figures 7, where adaptive OFDM modulation is implemented in all the systems. Considering the 7% pre-FEC limit of 3.8×10^{-3}, target BERs are set as 0.001 and 0.003 in experiments. Benefitting from the multiplexing gain, data rates of V-BLAST system are higher than Alamouti coding system when the channel correlation is low. However, they decrease quickly with the channel correlation growing. As for the Alamouti coding system, data rates remain about the same when the channel correlation increases. Thereby, it is more preferred in the high channel correlation environment. Experimental results also verify that the exact switching can always be achieved based on the proposed switching criterion, even around the switching threshold. Besides, compared Figure 7(a) with Figure 7(b), it can be seen that data rates are growing with higher target BER, where the switching threshold of the channel matrix condition number increases as well.

Furthermore, data rates of the switching MIMO system are also evaluated in terms of the distance between LEDs, the distance between PDs, and the distance between the LED plane and the PD plane, which are denoted as D_t, D_r, and D, respectively, as shown in Figure 2. In the experiments, LEDs and PDs should be placed symmetrically; meanwhile, the LED plane and the PD plane are parallel. The target BER is set as 0.003. As shown in Figures 8(a) and 8(b), the MIMO mode

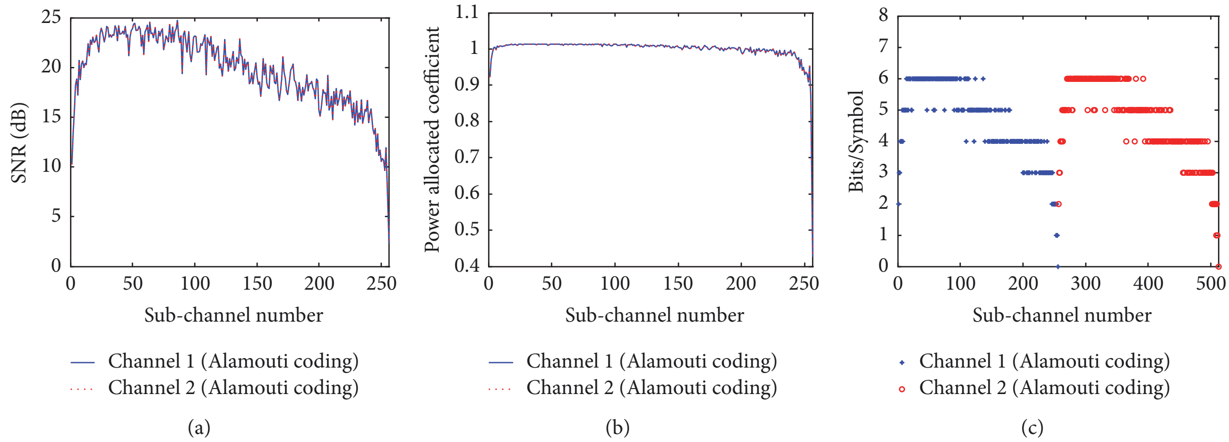


FIGURE 6: Power and bit allocation results for Alamouti coding system (K=5.4985, BER_T=0.003).

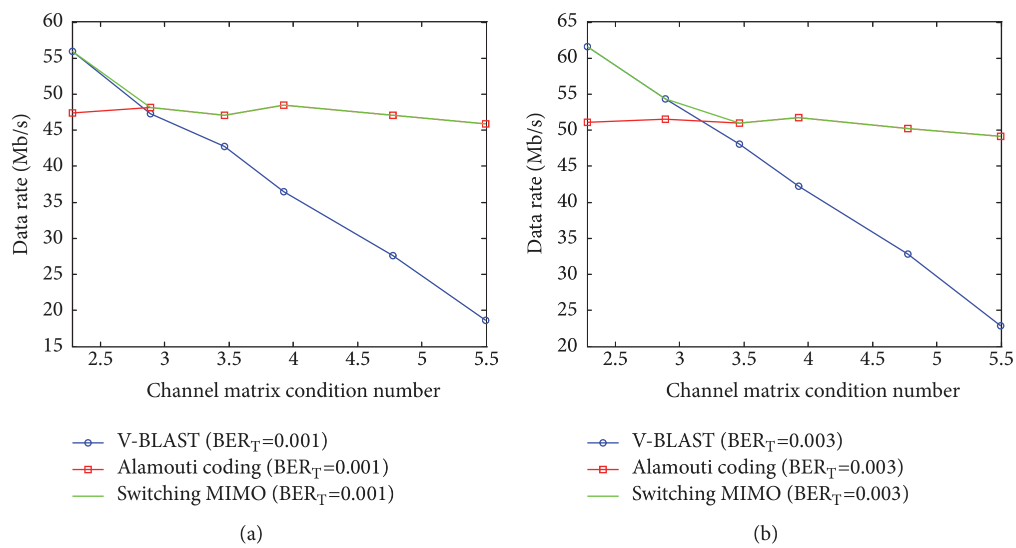


FIGURE 7: Data rate versus channel matrix condition number: (a) BER_T=0.001; (b) BER_T=0.003.

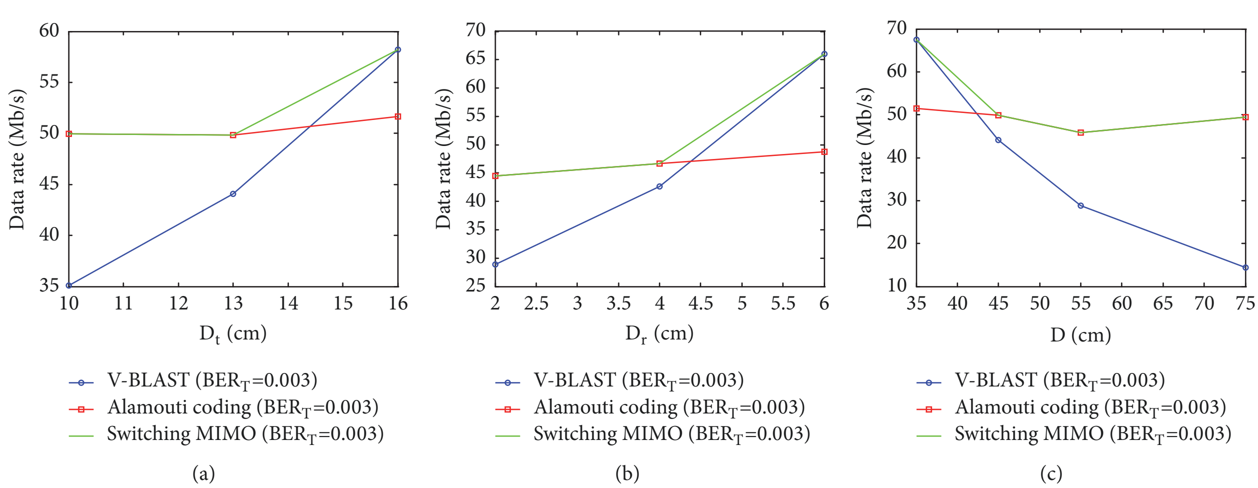


FIGURE 8: Data rate versus (a) distance between LEDs, (b) distance between PDs, and (c) distance between LED plane and the PD plane.

is switched to V-BLAST with D_t or D_r growing. The result is straightforward as the channel correlation decreases when the distance between LEDs or PDs becomes farther. However, the MIMO mode is switched to Alamouti coding when D increases in Figure 8(c). The reason is that differences among distances between the ith LED and jth PD would become smaller with the increase of D, leading to more similar link gains of the channel matrix.

4. Conclusion

In conclusion, we propose and experimentally demonstrate a switching MIMO scheme combining with adaptive OFDM modulation for indoor VLC system. In the system, adaptive OFDM modulation is utilized to maximize the data rate, which is realized by power and bit allocation under the constraint of a given target BER. Meanwhile, MIMO mode is switched between V-BLAST and Alamouti coding to adapt to the channel correlation, where the modulation order solved by adaptive OFDM modulation is chosen as the switching criterion. Experimental results validate the performance improvement over the pure V-BLAST system and the pure Alamouti coding system, where the exact switching can always be achieved with different channel correlations. In this work, we assume that accurate CSI can be obtained at the transmitter, resulting in overloaded feedback in the system. Future work may focus on the study of the limited feedback of the switching MIMO system to achieve the tradeoff between the feedback quantity and the performance loss.

Data Availability

The BERs data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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References

[1] N. Chi, H. Haas, M. Kavehrad et al., “Visible light communications: Demand factors, benefits and opportunities,” *IEEE Wireless Communications Magazine*, vol. 22, no. 2, pp. 5–7, 2015.

[2] A. Jovicic, J. Li, and T. Richardson, “Visible light communication: opportunities, challenges and the path to market,” *IEEE Communications Magazine*, vol. 51, no. 12, pp. 26–32, 2013.

[3] S. Chen, Z. Xie, J. Liu et al., “Effective generation of milliwatt-level sub-terahertz wave for nonlinear response measurement of two-dimensional material by optical heterodyne technique,” *Advances in Condensed Matter Physics*, vol. 2017, Article ID 1704374, 9 pages, 2017.

[4] A. Nuwanpriya, S.-W. Ho, and C. S. Chen, “Indoor MIMO Visible Light Communications: Novel Angle Diversity Receivers for Mobile Users,” *IEEE Journal on Selected Areas in Communications*, vol. 33, no. 9, pp. 1780–1792, 2015.

[5] J. Lian and M. Brandt-Pearce, “Multiuser MIMO Indoor Visible Light Communication System Using Spatial Multiplexing,” *Journal of Lightwave Technology*, vol. 35, no. 23, pp. 5024–5033, 2017.

[6] F. Zafar, M. Bakaul, and R. Parthiban, “Laser-diode-based visible light communication: Toward gigabit class communication,” *IEEE Communications Magazine*, vol. 55, no. 2, pp. 144–151, 2017.

[7] N. Chi, Y. Zhou, S. Liang, F. Wang, J. Li, and Y. Wang, “Enabling Technologies for High-Speed Visible Light Communication Employing CAP Modulation,” *Journal of Lightwave Technology*, vol. 36, no. 2, pp. 510–518, 2018.

[8] A. H. Azhar, T.-A. Tran, and D. O’Brien, “A gigabit/s indoor wireless transmission using MIMO-OFDM visible-light communications,” *IEEE Photonics Technology Letters*, vol. 25, no. 2, pp. 171–174, 2013.

[9] Y. Hong, T. Wu, and L.-K. Chen, “On the Performance of Adaptive MIMO-OFDM Indoor Visible Light Communications,” *IEEE Photonics Technology Letters*, vol. 28, no. 8, pp. 907–910, 2016.

[10] C. Wei, F. Wu, Z. Chen et al., “Indoor VLC system with multiple LEDs of different path lengths employing space-time block-coded DMT/CAP modulation,” *IEEE/OSA Journal of Optical Communications Networking*, vol. 7, no. 3, pp. A459–A466, 2015.

[11] T. Fath and H. Haas, “Performance comparison of MIMO techniques for optical wireless communications in indoor environments,” *IEEE Transactions on Communications*, vol. 61, no. 2, pp. 733–742, 2013.

[12] X. Guo, S. Li, and Y. Guo, “Adaptive STBC MIMO-OFDM system design for indoor visible communications,” *Infrared and Laser Engineering*, vol. 47, no. 2, pp. 0222001-1–0222001-8, 2018.

[13] X. Guo, X. Li, and R. Huang, “Adaptive multiple-input multiple-output mode switching for indoor visible light communication system with orthogonal frequency division multiplexing modulation,” *Chinese Optics Letters*, vol. 15, no. 11, pp. 24–29, 2017.

[14] P. W. Wolniansky, G. J. Foschini, G. D. Golden, and R. A. Valenzuela, “V-BLAST: an architecture for realizing very high data rates over the rich-scattering wireless channel,” in *Proceedings of the 1998 URSI International Symposium on Signals, Systems, and Electronics (ISSSE ’98)*, pp. 295–300, IEEE, Pisa, Italy, 1998.

[15] S. M. Alamouti, “A simple transmit diversity technique for wireless communications,” *IEEE Journal on Selected Areas in Communications*, vol. 16, no. 8, pp. 1451–1458, 1998.

[16] Y. Wang, Y. Wang, and N. Chi, “Experimental verification of performance improvement for a gigabit wavelength division multiplexing visible light communication system utilizing asymmetrically clipped optical orthogonal frequency division multiplexing,” *Photonics Research*, vol. 2, no. 5, pp. 138–142, 2014.

[17] A. J. Goldsmith and S. G. Chua, “Variable-rate variable-power MQAM for fading channels,” *IEEE Transactions on Communications*, vol. 45, no. 10, pp. 1218–1230, 1997.

[18] A. Kumar and S. K. Ghorai, “BER performance analysis of indoor MIMO-VLC system for multipath reflection,” in *Proceedings of the 2018 Technologies for Smart-City Energy Security and Power (ICSESP ’18)*, pp. 1–5, Bhubaneswar, India, 2018.

[19] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*, Cambridge University Press, Cambridge, UK, 2005.