2020

Capacity Maximized Linear Precoder Design for Spatial-Multiplexing MIMO VLC Systems

Yanrong Zhai

Hao Chi

Jun Tong
University of Wollongong, jtong@uow.edu.au

Jiangtao Xi
University of Wollongong, jiangtao@uow.edu.au

Abstract

© 2013 IEEE. This paper proposes a novel linear precoder design based on the singular value decomposition (SVD) for multi-input multi-output visible light communications (MIMO VLC). We provide an analytical expression on power allocation subject to the function of maximizing the lower bound of capacity according to the optical wireless communication channel model. The expression is rather different from the radio frequency (RF) communications due to the non-negativity of the transmitted signals in VLC. Furthermore, we design an adaptive bit loading scheme for sub-streams with consideration of the tremendous gain difference among subchannels. Performances of the proposed adaptive power and bits allocation strategy are evaluated in two traditional MIMO VLC scenarios, i.e., a practical 2× 2 indoor scenario and a classical 4×4 system that is generated according to the MIMO model. In simulations, the techniques of unipolar M-level pulse amplitude modulation (M-PAM) and spatial-multiplexing (SMP) are employed, and the performance comparison with other SVD-based linear precoders is also given. Simulation results show that the proposed approach can effectively improve the spectral efficiency and guarantee the bit error rate (BER) performance under the same constraints of aggregate optical power budget and non-negativity included by the intensity modulation. It indicates that the strategy of uneven bits and power allocation with full consideration of the ill-conditioned characteristics of subchannels performs better than that based on equal bits transmission in VLC systems.

Received March 12, 2020, accepted March 23, 2020, date of publication March 26, 2020, date of current version April 16, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2983517

Capacity Maximized Linear Precoder Design for Spatial-Multiplexing MIMO VLC Systems

YANRONG ZHAI [1], HAO CHI [1], (Senior Member, IEEE), JUN TONG [2], (Member, IEEE), AND JIANGTAO XI [2], (Senior Member, IEEE)

[1]School of Communication Engineering, Hangzhou Dianzi University, Hangzhou 310018, China
[2]School of Electrical, Computer, and Telecommunications, University of Wollongong, Wollongong, NSW 2522, Australia

Corresponding author: Hao Chi (chihao@hdu.edu.cn)

This work was supported in part by the National Key Research and Development Program of China under Grant 2019YFB2203204, in part by the National Natural Science Foundation of China under Grant 61975048, Grant 61901148, and Grant 41905024, in part by the Zhejiang Natural Science Foundation under Grant LZ20F010003, Grant LQ18F050002, and Grant LY20F05004, in part by the Fundamental Research Funds for the Provincial Universities of Zhejiang under Grant GK199900299012-004, and in part by the General Scientific Research Project of Zhejiang Provincial Education Department under Grant Y201942025.

ABSTRACT This paper proposes a novel linear precoder design based on the singular value decomposition (SVD) for multi-input multi-output visible light communications (MIMO VLC). We provide an analytical expression on power allocation subject to the function of maximizing the lower bound of capacity according to the optical wireless communication channel model. The expression is rather different from the radio frequency (RF) communications due to the non-negativity of the transmitted signals in VLC. Furthermore, we design an adaptive bit loading scheme for sub-streams with consideration of the tremendous gain difference among subchannels. Performances of the proposed adaptive power and bits allocation strategy are evaluated in two traditional MIMO VLC scenarios, i.e., a practical 2×2 indoor scenario and a classical 4×4 system that is generated according to the MIMO model. In simulations, the techniques of unipolar M-level pulse amplitude modulation (M-PAM) and spatial-multiplexing (SMP) are employed, and the performance comparison with other SVD-based linear precoders is also given. Simulation results show that the proposed approach can effectively improve the spectral efficiency and guarantee the bit error rate (BER) performance under the same constraints of aggregate optical power budget and non-negativity included by the intensity modulation. It indicates that the strategy of uneven bits and power allocation with full consideration of the ill-conditioned characteristics of subchannels performs better than that based on equal bits transmission in VLC systems.

INDEX TERMS Visible light communication, spatial-multiplexing, precoder design, channel capacity.

I. INTRODUCTION

Due to its low cost, high power efficiency, low electromagnetic interference [1] and use of license-free spectrum [2], visible light communication (VLC) has become a potential candidate for wideband communications. As white light-emitting diode (LED) have limited modulation bandwidth (about 150 MHz [3]) and illumination devices commonly consist of multiple LEDs, multi-input multi-output (MIMO) schemes have been considered to achieve high data rates and/or high reliability without consuming extra time and spectrum resources [4], [5]. It has been shown that multi-stream transmissions with capacities up to Gbits/s [6], [7] can be achieved by MIMO VLC over line-of-sight (LOS) channels [8].

To achieve highly reliable multi-stream transmissions in MIMO VLC, the transceiver needs to be adapted to the channel state information (CSI). Precoding has been widely studied for traditional radio-frequency MIMO communications under different constraints and performance criteria. However, VLC faces an additional design constraint that the modulated signal must be non-negative as the information bits are intensity-modulated. Typically, a direct current (DC) bias is added to the modulated signal to ensure non-negativity signaling [10]. Other constraints such as illumination control [11] and power variation [12] may also be considered.

The associate editor coordinating the review of this manuscript and approving it for publication was Xingwang Li.

Channel inversion-based precoding schemes are considered for the MIMO VLC in [13]. These schemes feature low design complexity, but may lead to high power consumption when the channel matrix is ill-conditioned [10]. By contrast, the convex optimization-based designs require an iterative solution to optimization problems. Precoding based on singular value decomposition (SVD), which has been widely considered for RF communications, also attracts significant interests for point-to-point MIMO VLC [2], [14], [17]. For example, Gong *et al.* designed a bit and power allocation method for SVD-based precoding in color-division VLC systems [2], in which different transmitted colors are incorporated. Park *et al.* introduced a precoding method that maximizes the transmission rate [5], in which various modulation sizes were applied for different substreams under specific bit error rate (BER) requirements. An alternative SVD-based precoder that optimizes the capacity of the electrical channel without considering the non-negativity constraint [17]. More recently, a SVD-based precoder minimizing the total mean squared error (MSE) was designed in [14], which was not necessarily optimal for BER as the system performance is determined by the subchannel with the least gains. Besides, some other precoder designs for multiple-user downlink transmissions with decision feedback equalizer can also be found in [15], [16].

It is necessary to allocate power according to subchannel gain and reduce the effect on the subchannel in the worst condition. In this work, we design an SVD-based low-complexity scheme for point-to-point MIMO VLC and provide an analytical expression for power and bits allocation subject to the function of maximizing the lower bound of capacity. In the scheme, the optical wireless communication (OWC) channel model with intensity modulation/direct detection (IM/DD) is considered, in which the lower bound on the capacity is rather different from RF communications [18]. The scheme can improve the achievable rates under the constraints of non-negativity signaling and aggregate optical power budget. The given approach can achieve adaptive modulation for multi-stream transmissions under a given transmission rate, by allocating fewer bits to the worse subchannels and more bits to the better subchannels. Simulation results demonstrate that the proposed scheme can effectively improve the performance in terms of BER compared with some recently proposed SVD-based precoder designs.

II. SYSTEM MODEL

We consider a spatial-multiplexing (SMP) point-to-point MIMO VLC system with N_t LED emitters and N_r photodiode detectors, which is illustrated in Fig. 1.

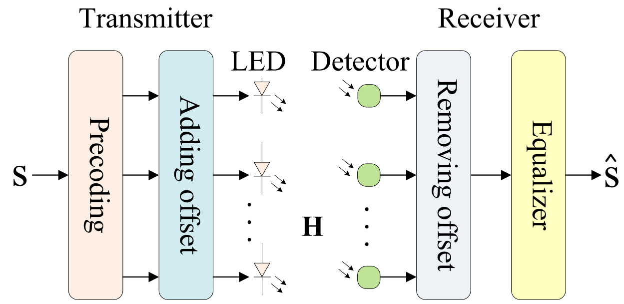


FIGURE 1. System model of MIMO VLC with linear precoding.

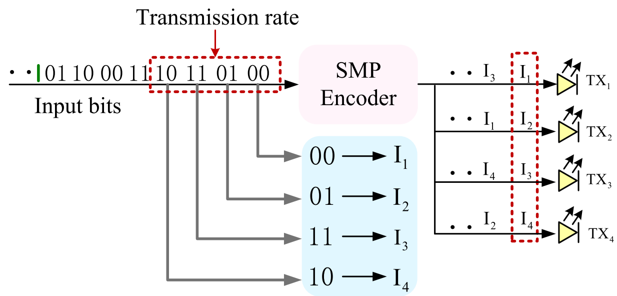


FIGURE 2. Illustration of SMP operation with $N_t = 4$ and 4-PAM. Independent data streams are transmitted simultaneously and the transmission rate is 8 bit/s/Hz.

As one of the spatial diversity MIMO techniques, SMP can effectively overcome the fading effect caused by atmospheric turbulences in VLC systems [8], [9]. With all LED emitters transmitting independent data streams simultaneously, as shown in Fig.2, SMP provides higher spectral efficiency in comparison to Repetition Coding (RC) and Spatial Modulation (SM). In SMP, N_t LED emitters transmit N_t independent data streams simultaneously. Spectral efficiency of $N_t \times log_2(M)$ bit/s/ Hz can be obtained which is better than SM of $log_2(N_t) + log_2(M)$ bit/s/Hz and RC of $log_2(M)$ bit/s/Hz.

The optical channel with IM/DD is assumed. A $N_t \times 1$ transmitted signal $\mathbf{x} = [x_1, x_2, \cdots, x_{N_t}]^T$ is written as

$$\mathbf{x} = \mathbf{d} + \mathbf{F}\mathbf{s}, \tag{1}$$

where $\mathbf{F} \in C^{N_t \times N_t}$ is the precoding matrix, $\mathbf{s} = [s_1, s_2, \cdots, s_{N_t}]^T$ consists of N_t independent, modulated symbols with zero mean and a variance of σ_s^2, and $\mathbf{d}$ is a positive offset to guarantee the non-negativity of the intensity-modulated signal. We assume an M-level pulse amplitude modulation (M-PAM) with Gray mapping is employed, in which the symbols are uniformly distributed in the range of $[-\Delta, \Delta]$ with discrete values as $\frac{\Delta(2i-1-M)}{M-1}$, $i = 1, 2, \cdots, M$, where Δ denotes half of the maximum distance between constellation points.

The following two constraints are considered for designing $\mathbf{F}$ and $\mathbf{d}$ in the MIMO VLC system:

- *Non-negativity of the transmitted signal*: This requires $\mathbf{x} \geq \mathbf{0}$, $\forall \mathbf{x}$, i.e.,

$$\mathbf{d} + \mathbf{F}\mathbf{s} \geq \mathbf{0}, \quad \forall \mathbf{s} \tag{2}$$

- *Total power constraint*: Let $p_i = \mathrm{E}[x_i]$ be the average optical power of the i-th LED transmitter, where $\mathrm{E}[\cdot]$ denotes the mathematical expectation. Given the total transmission power P_t, we have $\sum_{i=1}^{N_t} p_i \leq P_t$. Since s has a zero mean and $p_i = d_i$, the total power constraint can be written as

$$\mathbf{1}^T\mathbf{d} \leq P_t. \tag{3}$$

Let $\boldsymbol{\Delta} = [\Delta, \Delta, \cdots, \Delta]^T$, the non-negativity constraint can be rewritten as [5]

$$\mathbf{d} - \text{abs}(\mathbf{F})\boldsymbol{\Delta} \geq \mathbf{0}, \tag{4}$$

where abs$(\cdot)$ denotes taking the entry-wise absolute value. In order to minimize the total transmission power, $\mathbf{d}$ should satisfy

$$\mathbf{d} = \text{abs}(\mathbf{F})\boldsymbol{\Delta}, \tag{5}$$

which shows that the offset $\mathbf{d}$ is determined only by $\mathbf{F}$ and Δ. As such, the average power constraint can be written as

$$\mathbf{1}^T\text{abs}(\mathbf{F})\boldsymbol{\Delta} \leq P_t. \tag{6}$$

Typically, LEDs are installed in close proximity and can be jointly driven by a same baseband hardware and electronic driver. The path differences among multiple links are only some centimeters, and the temporal delays are just several nanoseconds. Consequently, the time dispersion between multiple transmission paths is negligible. In addition, the links are generally static or slow time variation under the indoor scenarios. Therefore, we assume perfect knowledge of the channel in the model.

Given the channel matrix $\mathbf{H} \in C^{N_r \times N_t}$ with $N_r \geq N_t$, the received signal can be represented as

$$\mathbf{y_r} = \mathbf{Hx} + \mathbf{n}. \tag{7}$$

The noise vector $\mathbf{n} \in C^{N_r \times 1}$ denoting the ambient shot light noise and thermal noise can be modeled as an additive white Gaussian process with zero mean and variance σ_n^2, which is independent of the signals and assumed as the primary noise impairment. Furthermore, the intensity of the first-order reflections on the surfaces (walls) is in the range of $10^{(-10)}$I (assuming Lambertian reflectors with reflectivity of 1), and the path loss of higher-order is even more significant. Therefore, the diffuse transmission portion induced by reflected links is ignored, and only line-of-sight (LOS) paths are considered. The $N_r \times N_t$ channel matrix $\mathbf{H}$ is given by

$$\mathbf{H} = \begin{pmatrix} h_{11} & \cdots & h_{1N_t} \\ \vdots & \vdots & \vdots \\ h_{N_r1} & \cdots & h_{N_rN_t} \end{pmatrix}, \tag{8}$$

where $h_{n_rn_t}$ denotes the wireless link between the emitter n_t and the receiver n_r. Each LED has an average power of several tens of mW and is concentrated within a semiangle of 15°-30°. At the receiver, a silicon positive-intrinsic-negative (PIN) photodiode is employed to detect the signal, whose responsibility peak lies between 380 nm and 780 nm. A variety of practical LOS paths can be modeled reasonably with a generalized Lambertian radiant intensity [8]. It has been shown in [1] that the rate of the reflected light is low enough compared with the LOS light, and the performance of the system is mainly depends on the LOS light. Hence, the gain of link h_{n_t,n_r} in channel matrix $\mathbf{H}$ can be expressed as [1], [8]

$$h_{n_t,n_r} = \begin{cases} \dfrac{(\kappa+1)A}{2\pi d^2} cos^{\kappa}(\phi)\, cos(\psi) & 0 \leq \psi \leq \Psi_{\frac{1}{2}} \\ 0 & \psi \geq \Psi_{\frac{1}{2}}, \end{cases} \tag{9}$$

where ϕ denotes the angle of emergence to the emitter axis, and ψ is the angle of incidence to the receiver axis. Besides, d represents the distance between the emitter and detector. A is the detection area and the coefficient κ is $\kappa = \frac{-ln(2)}{ln\left(cos\left(\Phi_{\frac{1}{2}}\right)\right)}$. For example, $\Phi_{\frac{1}{2}} = 60°$ (Lambertian transmitter) corresponds to $\kappa = 1$, while $\Phi_{\frac{1}{2}} = 15°$ corresponds to $\kappa = 20$. $\Phi_{\frac{1}{2}}$ and $\Psi_{\frac{1}{2}}$ denotes the semiangle of the transmitter and the field-of-view (FOV) semiangle of the receiver, respectively. The channel gain $h_{n_rn_t}$ depends on the geometric position of transmitter and receiver. If the emitter or detector is not in each other's FOV, the path gain is zero.

Assuming that the offset $\mathbf{d}$ is known at the receiver, equalization can be performed after removing the offset from the received signal, i.e.,

$$\mathbf{y} = \mathbf{y_r} - \mathbf{Hd} = \mathbf{HFs} + \mathbf{n}. \tag{10}$$

At the receiver, the maximum-likelihood (ML) detection is considered. Thus, the decoder decides the constellation vector $\mathbf{s}$ that with the least Euclidean distance between the actual received signal vector and all potential received signals, that is

$$\hat{\mathbf{s}} = arg \max_{\mathbf{s}} p_{\mathbf{y}}(\mathbf{y}|\mathbf{s}, \mathbf{H}) = arg \min_{\mathbf{s}} \|\mathbf{y} - \mathbf{HFs}\|_F^2, \tag{11}$$

where $p_{\mathbf{y}}$ is the probability density function of $\mathbf{y}$ conditioned on signal $\mathbf{s}$ and channel $\mathbf{H}$. $\|.\|_F$ represents the Frobenius norm.

A. SVD-BASED PRECODER DESIGN

Similar to RF communications, various precoders can be applied to MIMO VLC. In this section, we present a SVD-based precoder for MIMO VLC that incorporates the non-negativity constraint of the transmitted signal and optimizes the lower bound of the achievable capacity. We then propose an adaptive bit loading scheme for minimizing the error rate for fixed-rate uncoded PAM transmissions. In the following analysis, both the linear equalization and perfect knowledge of the channel matrix $\mathbf{H}$ at the transmitter and receiver are assumed.

Let the SVD of the channel matrix $\mathbf{H}$ be

$$\mathbf{H} = \mathbf{U}\Lambda\mathbf{V}^T, \tag{12}$$

where $\mathbf{U} \in \mathbb{R}^{N_r \times N_r}$ and $\mathbf{V} \in \mathbb{R}^{N_t \times N_t}$ are the left and right singular vector matrix, respectively, and the $N_r \times N_t$ diagonal matrix $\boldsymbol{\Lambda} = diag(\lambda_1, \lambda_2, \cdots, \lambda_{N_t})$ consists of singular values.

We assume that the precoder matrix $\mathbf{F} = [\mathbf{f}_1, \mathbf{f}_2, \cdots, \mathbf{f}_{N_t}]$ follows the structure

$$\mathbf{F} = \mathbf{V}\Phi, \tag{13}$$

where $\Phi = diag(\phi_1, \phi_2, \cdots, \phi_{N_t})$ is a diagonal matrix. The received signal $\mathbf{y}$ is first preprocessed by a linear operator $\mathbf{U}$, yielding

$$\mathbf{y}' = \mathbf{U}^T\mathbf{y} = \mathbf{U}^T\mathbf{HFs} + \mathbf{U}^T\mathbf{n} = \Lambda\Phi\mathbf{s} + \mathbf{n}'. \tag{14}$$

where $\mathbf{n}' \triangleq \mathbf{U}^T\mathbf{n}$ follows the same distribution as $\mathbf{n}$. As $\Lambda\Phi$ is a diagonal matrix, the mutual interferences between the different transmitted symbols in $\mathbf{s}$ are eliminated. Therefore, single-tap equalization can be used to recover $\mathbf{s}$.

B. PRECODER DESIGN

The precoder design aims to optimize the performance under the constraints of the aggregate power budget and the non-negativity of the modulated signal. Applying the structure in (13) on the precoder may lead to a suboptimal solution but also reduces the design complexity. Assuming $N_r = N_t$ for simplicity, the system in (14) is equivalent to N_t parallel, scalar subchannels as

$$y'_k = \lambda_k\phi_k s_k + n'_k, \quad k = 1, 2, \cdots, N_t. \tag{15}$$

Clearly, the scaling factors ϕ_k in the precoder design influences the effective signal-to-noise ratio (SNR) in the corresponding subchannel and can be viewed as the power allocation factors.

We assume that the input to each subchannel s_k is uniformly distributed in $[-\Delta, \Delta]$. Without loss of generality, let $\Delta = 1$ for notational simplicity. Then for the k-th subchannel, a lower bound on the capacity is given by [18]

$$C_{k\,VLC} = \frac{1}{2}\log\left(1 + \frac{\lambda_k^2\phi_k^2}{2\pi e\sigma_n^2}\right), \tag{16}$$

where e is the natural number. The constraint on the total power is $\mathbf{1}^T abs(\mathbf{V}\Phi)\mathbf{1} = P_t$, which depends on the singular vector matrix.

As the average transmitted optical power of P_t in VLC is given by

$$P_t = \lim_{T\to\infty}\frac{1}{2T}\int_T^{-T} x(t)\,dt, \tag{17}$$

not the typical time average of $|x(t)|^2$ in radio frequency (RF) communications. The difference results in dissimilar power constraints $tr(\mathbf{\Phi}\mathbf{\Phi}^T) = P_t$ and power allocation (Equ.18) in comparison with RF systems.

$$C_{k_{RF}} = \log\left(1 + \frac{\lambda_k^2\phi_k\sigma_x^2}{\sigma_n^2}\right). \tag{18}$$

We propose to maximize the total capacity under the total power constraint as

$$\max_{\{\phi_k\}} \frac{1}{2}\sum_{k=1}^{N_t}\log\left(1 + \frac{\lambda_k^2\phi_k^2}{2\pi e\sigma_n^2}\right)$$
$$\textit{subject to } \mathbf{1}^T abs(\mathbf{V}\Phi)\mathbf{1} = P_t. \tag{19}$$

Define

$$\nu_k \triangleq \sum_{j=1}^{N_t}|\nu_{jk}|, \quad \varepsilon = \frac{1}{2\pi e\sigma_n^2},$$

where ν_{jk} is the (j,k)-th entry of $\mathbf{V}$. In order to find the optimized power allocation, we resort to the Lagrangian method. Define

$$\mathcal{L}(\phi_k, \eta) = \frac{1}{2}\sum_{k=1}^{N_t}\log(1 + \varepsilon\lambda_k^2\phi_k^2) - \eta\Big(\sum_{k=1}^{N_t}\nu_k\phi_k - P_t\Big), \tag{20}$$

where η is the Lagrange multiplier. Letting $\frac{\partial\mathcal{L}(\{\phi_k\},\eta)}{\partial\phi_k} = 0$, the extreme value points satisfy

$$\frac{\varepsilon\lambda_k^2\phi_k ln2}{1 + \varepsilon\lambda_k^2\phi_k^2} - \eta\nu_k = 0, \quad k = 1, 2, \cdots, N_t. \tag{21}$$

There are two solutions to (21), which correspond to the extreme points of the power allocation. It can be easily seen that if we choose the solution

$$\phi_k = \frac{1}{\mu\nu_k}\left(1 - \sqrt{1 - \frac{\mu^2\nu_k^2}{\varepsilon\lambda_k^2}}\right), \tag{22}$$

where $\mu \triangleq \frac{2\eta}{ln2}$, the allocated power ϕ_k decreases as λ_k increases, in contrast to the common waterfilling solutions. We choose the other solution in our power allocation. By solving the above equation, we propose the following power allocation scheme

$$\phi_k = \begin{cases} \frac{1}{\mu\nu_k}\left(1 + \sqrt{1 - \frac{\mu^2\nu_k^2}{\varepsilon\lambda_k^2}}\right), & \lambda_k \geq \frac{\mu\nu_k}{\sqrt{\varepsilon}} \\ 0, & \textit{otherwise}, \end{cases}$$
$$k = 1, 2, \cdots, N_t, \tag{23}$$

where μ is chosen such that the total power constraint is satisfied, i.e.,

$$\sum_{k=1}^{N_t}\nu_k\phi_k = P_t. \tag{24}$$

Thus, the power allocation can be obtained by (23).

C. ADAPTIVE MODULATION

In order to evaluate the effectiveness of the proposed design, we consider a scenario with uncoded transmissions with PAM modulations and a given total transmission rate of B_T bits/symbol. The order 2^{b_k} of the PAM modulation for each data stream is determined according to the lower bounds C_k of the achievable capacities in (16). This can be done by using the Algorithm 1 given in the table, where b_k denotes the transmission rate of the stream k, $\lfloor\cdot\rfloor$ denotes taking the integer part of a number, and the vector $\mathbf{j}$ records the indexes of the sorted entries.

Algorithm 1 Bit Allocation

Initialization: $b_k = B_T \frac{C_k}{\sum_{i=1}^{N_t} C_i}$, $\mathbf{b} = [b_1, b_2, \cdots, b_{N_t}]$
$i = 1$;
while $\sum_{k=1}^{N_t} \lfloor b_k \rfloor < B_T$ **do**
    $[j] = sort(\mathbf{b} - \lfloor \mathbf{b} \rfloor, 'descend')$;
    $b_{j(i)} = b_{j(i)} + 1$;
    $i = i + 1$;
end while
$\mathbf{b} = \lfloor \mathbf{b} \rfloor$;
Output: $\mathbf{b}$

III. SIMULATION RESULTS

The performance of the proposed capacity maximized strategy is demonstrated in this section. The Monte Carlo method is used to evaluate the performance in terms of BER and capacity. Several hundreds of thousands of bits are transmitted under different channel conditions, and the BER is calculated by evaluating the practical error bits received at the detectors. The capacity depends on actual achieved spectral efficiency as well, which not only relies on the precoder design, spatial diversity scheme, but also is influenced by the noise variance, subchannel gains, and transmission rate. Furthermore, results for comparison with that of schemes in [5], [14], [16] are given, and differences between the strategies are also analyzed.

It has been found that several LED arrays would result in channel matrices with unacceptably high condition numbers even in massive 16 × 16 MIMO VLC systems (which is considered "massive" in VLC [19]). Hence, we focus on the traditional MIMO VLC system with 2 × 2 and 4 × 4 scenarios. Noting that dealing with high spatial channel correlation and inter-channel interference (ICI) will inevitably increase the system complexity. Here, we still consider the classical precoder and receiver design for traditional MIMO VLC scenarios.

As LED arrays are typically installed in a compact type and can be driven by a same baseband and electronic hardware, we assume the system in exact synchronization. In addition, the intensity of the first-order reflections on the surfaces (walls) is in the range of 10^{-10}I (assuming Lambertian transmitters with reflectivity of 1). The path loss of higher-order reflections is even larger. Therefore, the diffuse transmission portion induced by reflected links is ignored. In simulations, the LEDs are oriented down-towards, and the detectors are oriented up-towards.

Performance of a practical symmetrical 2×2 indoor MIMO VLC communication and an asymmetrical 4×4 scenarios are evaluated. Without loss of generality, in the 4 × 4 system, the channel matrix is generated according to the MIMO model used in [5], [10].

In a room size of 3 m × 3 m × 2.5 m, we established a 2 × 2 ($N_r = 2$ and $N_t = 2$) MIMO VLC scenario. The LED arrays are centered in the middle of the room and oriented down-towards at the height of $z = 2.5$ m, and the detectors are located on a table (height of 0.75 m) and oriented up-towards. In the static setup, the transmitters are spaced at every 0.4 m and the receivers are spaced at every 0.2 m. The coordinates of the LEDs are (−0.2, 0, 2.5) and (0.2, 0, 2.5). Detectors are positioned at (−0.1, 0, 0.75) and (0.1, 0, 0.75). According to a practical LOS OWC system implemented within the European Union (EU) project OMEGA [21], [22], the transmitter semiangle at half of power is assumed to be 15°, and FOV semiangle of the receiver is assumed to be 15°. The simulation parameters are listed in Tab. 1.

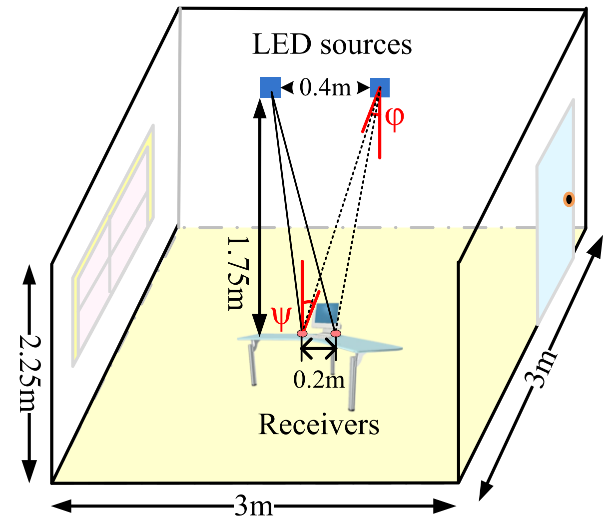


FIGURE 3. Illustration of the 2 × 2 practical MIMO VLC scenario.

TABLE 1. Simulation patameters of the 2 × 2 indoor MIMO VLC scenario.

Parameters	Values
room size	$3.0m \times 3.0m \times 2.5m$
LEDs array	10×10
single LED power	20mW/30mW
LED semiangle ($\Phi_{\frac{1}{2}}$)	15°
FOV semiangle ($\Psi_{\frac{1}{2}}$)	15°
detection area (A)	$1cm^2$

The channel gain of each LOS link is calculated according to Equ.9, which is given by

$$\mathbf{H}_2 = 10^{-4} \times \begin{bmatrix} 1.05 & 0.78 \\ 0.78 & 1.05 \end{bmatrix}. \tag{25}$$

The BER and capacity of the 2 × 2 MIMO VLC system is shown in Fig. 4 and Fig.5, respectively. By employing M-PAM and SMP, 4 bits/symbol transmission rate is obtained in the system. From Fig. 4, it can be obviously found that the proposed scheme achieves the best bit transmission accuracy, whereas the method in [16] obtains the largest number of error bits. In addition, when the noise variance becomes smaller, the gap between different schemes gets narrower. This indicates that system performance is significantly influenced by the SNR. Hence, it is vital to allocate power appropriately at the transmitter. In the SVD-based scheme [14] and the geometric mean decomposition (GMD) [16],

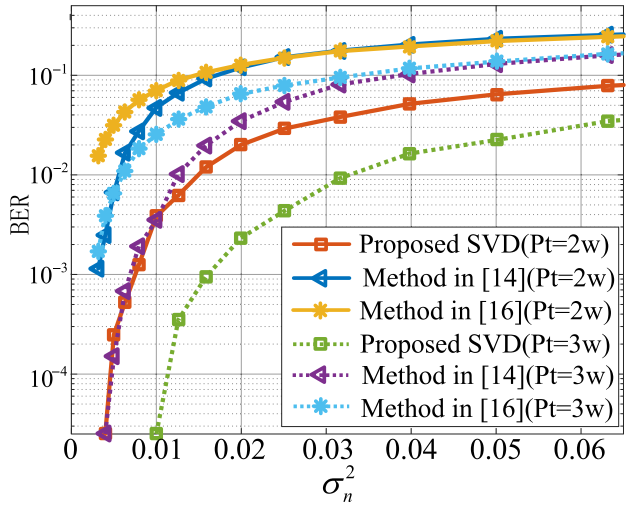


FIGURE 4. Comparison of BER for the 2 × 2 MIMO VLC system with $P_t = 2, 3$ W and different noise power. The total transmission rate is 4 bits/symbol.

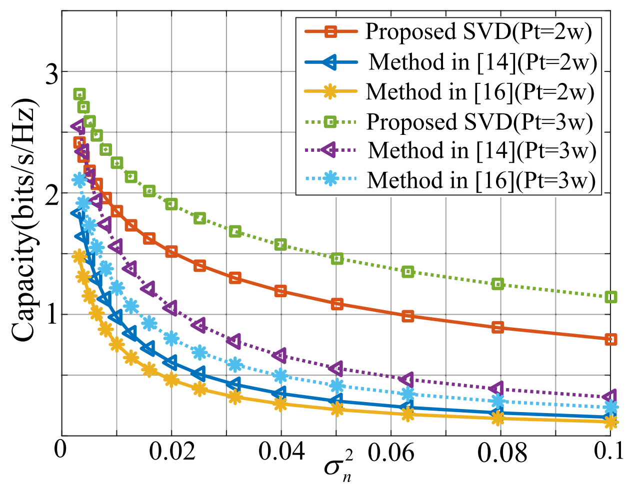


FIGURE 5. Lower bounds on the capacity with different precoding schemes in 2 × 2 system.

equal bit loading among all subchannels is applied. This is in contrast to the proposed precoder, in which different amounts of bits are allocated to substreams with given total transmission bits. Combined with the bit allocation in our scheme, the subchannel with smaller gain will be allocated less power, or even no power when the gain is extremely small under the ill-conditioned scenarios. Thus, better performance can be achieved by fully considering the subchannel conditions.

Besides, at $\sigma_n = 0.01$ and $P_t = 3$ W, BER of the proposed design is 2.5×10^{-5}, which is lower than 2.54×10^{-2} in [14] and 3.5×10^{-3} in [16]. Whereas with $P_t = 2$ W, BER of the proposed method is 3.9×10^{-3}, and the gap between the other two designs is narrower. It shows that performance superiority becomes more evident due to the higher transmission power.

From the capacity comparison in Fig. 5, it can be seen that the given strategy achieves better channel capacity under various noise situations. Besides, the same trend as BER

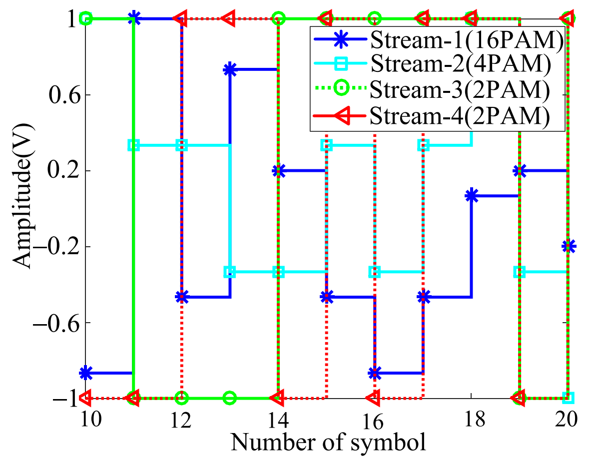


FIGURE 6. Example information-carrying symbols s in a 4 × 4 MIMO VLC system with Δ = 1. The total transmission rate is 8 bits/symbol.

can be found that the performance difference gets more obvious when the aggregate power increases. In addition, the three methods have nearly the same capacity when the noise variance is sufficiently low. This suggests the proposed scheme may perform better when combining with the capacity-approaching error control codes.

We also evaluate the performance of a system with larger asymmetrical antennas. In a 4 × 4 MIMO VLC system, we compare the proposed method with the SVD-based design in [14] and [5], which was also designed based on the SVD precoding and adaptive modulation size for subchannels. Without loss of generality, the channel matrix is generated according to the MIMO model in [10], which can also be calculated with the geometric position of transceiver. The generated channel matrix is expressed as

$$\mathbf{H}_4 = 10^{(-4)} \times \begin{bmatrix} 1.3060 & 0.1122 & 0.6696 & 1.4911 \\ 1.0030 & 0.7189 & 0.7195 & 0.0920 \\ 0.8754 & 0.9745 & 0.2235 & 0.6634 \\ 0.5553 & 0.3450 & 1.0194 & 1.6516 \end{bmatrix}. \quad (26)$$

As stated before, the imbalanced bit allocation is employed in the design. Fig. 6 illustrates the modulated symbols of each stream with rates allocated as [4, 2, 1, 1]. It is found that different streams have various modulation sizes in the proposed scheme. Fig. 7 shows the transmitted signals after precoding and adding a DC offset, which is non-negative and could be transmitted in optical channels with IM/DD.

The performances of the uncoded BER and lower bounds on capacity with different noise variances and transmission powers are investigated. The results of a 4 × 4 MIMO VLC system with a total transmission rate of $B_T = 8$ bits/symbol are shown in Fig. 8 and Fig. 9. It is found that the proposed scheme outperforms the SVD-based design in [14] under the same total power budget.

With $P_t = 10$ W, as shown in Fig. 8, the BER of the proposed design is 4.9×10^{-4}, which is about 2.7 times better than the design in [14] when $\sigma_n^2 = 0.02$. In terms of the achievable capacity (Fig. 9), it also outperforms the SVD-based scheme. At the point of $\sigma_n^2 = 0.04$, the capacity of the

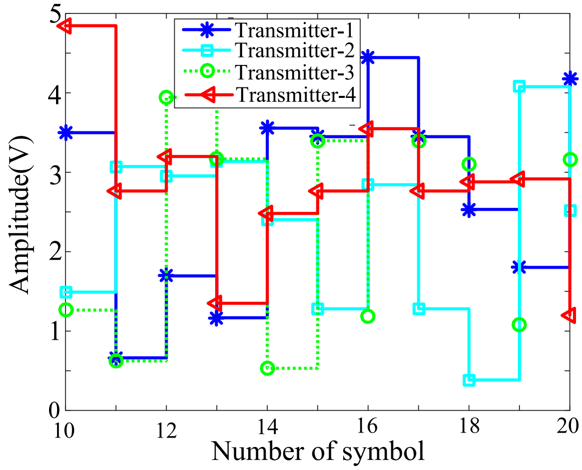


FIGURE 7. The transmitted signal x after applying precoding and adding the offset to the signal s in Figure 2. The average transmission power is $P_t = 10$ W and $\sigma_n^2 = 0.01$.

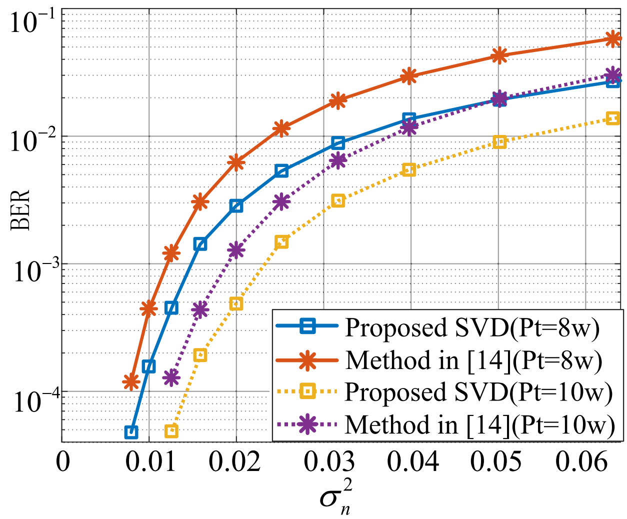


FIGURE 8. Comparison of BER versus different noise variance in the 4 × 4 MIMO VLC system with $P_t = 8, 10$ W. The total transmission rate is 8 bits/symbol.

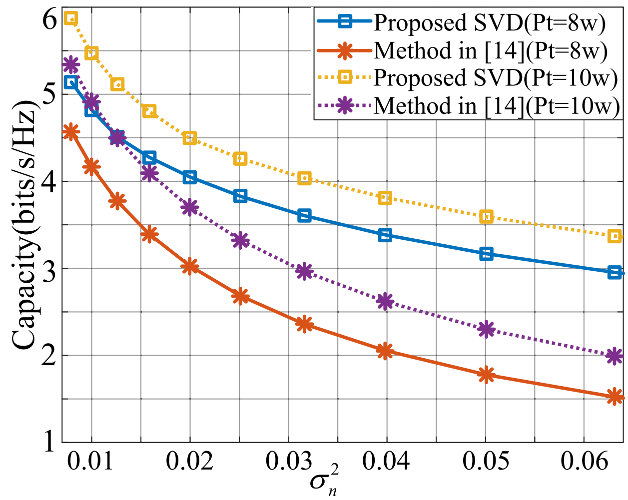


FIGURE 9. Lower bounds on the capacity with different precoding schemes.

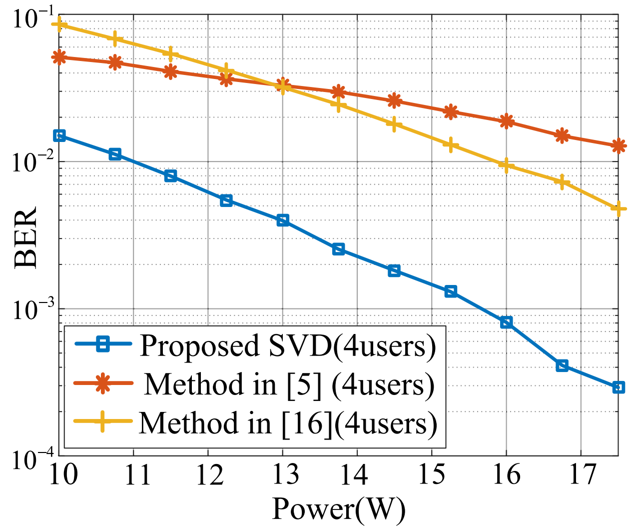


FIGURE 10. Comparison of BER for the 2 × 2 and 4 × 4 MIMO VLC system with different transmit power.

proposed scheme is about 1.5 times of that in [14]. And with the decrease of the noise variance, the capacity gap between the two schemes becomes narrower.

Generally, it is essential to apply adaptive modulation sizes in subchannels according to their channel conditions. Thus, the spectral efficiency can be improved by making full use of channel gains when compared with the schemes based on equal loading among all subchannels. Note that in [5], the rate maximization problem under specific BER requirement is formulated with a SVD precoding method and adaptive modulation size. Performance comparisons are also implemented for a 4×2 channel matrix considered in [5] with a total transmission rate of $B_T = 8$ bits/symbol.

Fig. 10 presents the comparison results among the proposed scheme and the precoding designs in [5], [16]. With the same total transmission bits and $\sigma_n = 1$, BER performance versus various power of these methods is given. In the simulation, both the methods in our design and [5], the adaptive modulation are applied according to the difference of subchannel conditions. In contrast, equal bits are allocated for all subchannels in [16]. BER is calculated according to the error bits obtained at the receiver. From Fig. 10, we can see that even though the strategies in the proposed design and [5] apply the same adaptive bit loading technique, the proposed precoding achieves better BER performance under different aggregate powers, which is due to the different target functions and bit allocation methods. In [5], the power allocation aims at minimum the mean square error (MMSE). In contrast, power is allocated for achieving the maximum capacity in the proposed method, and the modulation size of each subchannel is proportional to the square of the singular value rather than the singular value in [5]. In the VLC system, the channel condition number is typically large [19], [20], which makes a significant difference in gain among subchannels. In the proposed scheme, the performance is improved by avoiding the negative influence of the ill-conditioned subchannel and fully utilizing the subchannels with larger channel gain.

IV. CONCLUSION

We have proposed a novel linear precoder design based on SVD of the channel matrix for the spatial-multiplexing MIMO VLC system. Under the constraints of the total power budget and positive transmission signal, a power allocation scheme that maximizes the capacity is designed, which realizes adaptive PAM transmissions on different subchannels. Simulation results demonstrate that the proposed scheme can effectively improve the performance in terms of BER and the channel capacity. Furthermore, it is vital to pay attention to the property of the large condition number of VLC channels, which means a tremendous difference in gain among subchannels. In addition, applying adaptive modulation size according to subchannel gain can significantly improve the spectral efficiency. However, employing adaptive modulation will inevitably increase the system complexity, especially in a massive MIMO scenario, which should be further investigated in future research.

REFERENCES

[1] T. Komine and M. Nakagawa, "Fundamental analysis for visible-light communication system using LED lights," *IEEE Trans. Consum. Electron.*, vol. 50, no. 1, pp. 100–107, Feb. 2004.

[2] C. Gong, S. Li, Q. Gao, and Z. Xu, "Power and rate optimization for visible light communication system with lighting constraint," *IEEE Trans. Sig. Process.*, vol. 63, no. 16, pp. 4245–4256, Aug. 2015.

[3] H. Li, X. Chen, B. Huang, D. Tang, and H. Chen, "High bandwidth visible light communications based on a post-equalization circuit," *IEEE Photon. Technol. Lett.*, vol. 26, no. 2, pp. 119–122, Jan. 2014.

[4] Y. Hou, S. Xiao, M. Bi, Y. Xue, W. Pan, and W. Hu, "Single LED beacon-based 3-D indoor positioning using off-the-shelf devices," *IEEE Photon. J.*, vol. 8, no. 6, Dec. 2016, Art. no. 6806211.

[5] K.-H. Park, Y.-C. Ko, and M. Alouini, "On the power and offset allocation for rate adaptation of spatial multiplexing in optical wireless MIMO channels," *IEEE Trans. Commun.*, vol. 61, no. 4, pp. 1535–1543, Apr. 2013.

[6] M. Schuppert and C.-A. Bunge, "5 Gb/s eye-safe LED-based Si-POF transmission with equalization of transmitter nonlinearities," *IEEE Photon. Technol. Lett.*, vol. 28, no. 23, pp. 2732–2735, Dec. 1, 2016.

[7] A. H. Azhar, T.-A. Tran, and D. O'Brien, "A Gigabit/s indoor wireless transmission using MIMO-OFDM visible-light communications," *IEEE Photon. Technol. Lett.*, vol. 25, no. 2, pp. 171–174, Jan. 2013.

[8] T. Fath and H. Haas, "Performance comparison of MIMO techniques for optical wireless communications in indoor environments," *IEEE Trans. Commun.*, vol. 61, no. 2, pp. 733–742, Feb. 2013.

[9] S. Navidpour, M. Uysal, and M. Kavehrad, "BER performance of free-space optical transmission with spatial diversity," *IEEE Trans. Wireless Commun.*, vol. 6, no. 8, pp. 2813–2819, Aug. 2007.

[10] K. Ying, H. Qian, R. J. Baxley, and S. Yao, "Joint optimization of precoder and equalizer in MIMO VLC systems," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 9, pp. 1949–1958, Sep. 2015.

[11] J. Fang, M. Bi, S. Xiao, G. Yang, L. Liu, Y. Zhang, and W. Hu, "Polar-coded MIMO FSO communication system over gamma-gamma turbulence channel with spatially correlated fading," *J. Opt. Commun. Netw.*, vol. 10, no. 11, pp. 915–923, Nov. 2018.

[12] B. Li, J. Wang, R. Zhang, H. Shen, C. Zhao, and L. Hanzo, "Multiuser MISO transceiver design for indoor downlink visible light communication under per-LED optical power constraints," *IEEE Photon. J.*, vol. 7, no. 4, Aug. 2015, Art. no. 7201415.

[13] L. Zeng, D. O'Brien, H. Minh, G. Faulkner, K. Lee, D. Jung, Y. Oh, and E. Won, "High data rate multiple input multiple output (MIMO) optical wireless communications using white led lighting," *IEEE J. Sel. Areas Commun.*, vol. 27, no. 9, pp. 1654–1662, Dec. 2009.

[14] R. Wang, Q. Gao, J. You, E. Liu, P. Wang, Z. Xu, and Y. Hua, "Linear transceiver designs for MIMO indoor visible light communications under lighting constraints," *IEEE Trans. Commun.*, vol. 65, no. 6, pp. 2494–2508, Jun. 2017.

[15] H. Shen, Y. Deng, W. Xu, and C. Zhao, "Rate-maximized zero-forcing beamforming for VLC multiuser MISO downlinks," *IEEE Photon. J.*, vol. 8, no. 1, Feb. 2016, Art. no. 7901913.

[16] Y. Zhai, J. Tong, and J. Xi, "Precoder design for MIMO visible light communications with decision-feedback receivers," *IEEE Photon. Technol. Lett.*, vol. 31, no. 7, pp. 521–524, Apr. 2019.

[17] P. M. Butala, H. Elgala, and T. D. C. Little, "SVD-VLC: A novel capacity maximizing VLC MIMO system architecture under illumination constraints," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2013, pp. 1087–1092.

[18] A. Lapidoth, S. M. Moser, and M. A. Wigger, "On the capacity of free-space optical intensity channels," *IEEE Trans. Inf. Theory*, vol. 55, no. 10, pp. 4449–4461, Oct. 2009.

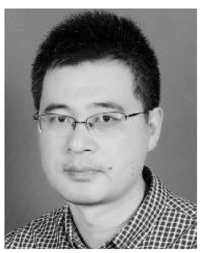
[19] K. Xu, H. Yu, and Y.-J. Zhu, "Channel-adapted spatial modulation for massive MIMO visible light communications," *IEEE Photon. Technol. Lett.*, vol. 28, no. 23, pp. 2693–2696, Dec. 2016.

[20] R. Mitra and V. Bhatia, "Precoding technique for ill-conditioned massive MIMO-VLC system," in *Proc. IEEE 87th Veh. Technol. Conf. (VTC Spring)*, Jun. 2018, pp. 1–5.

[21] O. Bouchet, G. Faulkner, L. Grobe, E. Gueutier, K.-D. Langer, S. Nerreter, D. O'Brien, R. Turnbull, J. Vucic, J. Walewski, and M. Wolf, "Deliverable D4. 2b physical layer design and specification," 7th Franmework Programme Inf. Commu. Technol., Tech. Rep., Feb. 2011, pp. 1–57. Accessed: Jul. 18, 2012. [Online]. Available: http://www.ict-omega.eu

[22] D. C. O'Brien, G. Faulkner, H. L. Minh, O. Bouchet, M. El Tabach, M. Wolf, J. W. Walewski, S. Randel, S. Nerreter, M. Franke, K.-D. Langer, J. Grubor, and T. Kamalakis, "Home access networks using optical wireless transmission," in *Proc. IEEE 19th Int. Symp. Pers., Indoor Mobile Radio Commun.*, Sep. 2008, pp. 1–5.

YANRONG ZHAI received the B.E. degree in electronic and communication engineering from Weifang University, Weifang, Shangdong, China, in 2011, and the Ph.D. degree in information and communication engineering from the China University of Mining and Technology, Xuzhou, Jiangsu, China, in 2018. She is currently a Lecturer with the School of Communication Engineering, Hangzhou Dianzi University, China. Her research interest includes visible light communication and Talbot effect in microwave photonic signal processing.



HAO CHI (Senior Member, IEEE) received the B.S. degree in applied physics from Xi'an Jiaotong University, Xi'an, China, in 1994, and the Ph.D. degree in electronic engineering from Zhejiang University, Hangzhou, China, in 2001.

From 2000 to 2001, he was a Research Assistant with The Hong Kong Polytechnic University, Hong Kong. From 2001 to 2003, he was a Postdoctoral Research Fellow with the Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai, China. From 2003 to 2018, he was with the College of Information Science and Electronic Engineering, Zhejiang University, where he became a Full Professor, in 2008. He is currently a Professor with the School of Communication Engineering, Hangzhou Dianzi University, Hangzhou. He has authored or coauthored more than 100 articles in international academic journals. His research interests include microwave photonics, optical signal processing, and optical communications.

Dr. Chi has been serving as an Associate Editor for the IEEE Photonics Technology Letters.

JUN TONG (Member, IEEE) received the B.E. and M.E. degrees from the University of Electronic Science and Technology of China (UESTC) and the Ph.D. degree in electronic engineering from the City University of Hong Kong. He is currently a Senior Lecturer with the School of Electrical, Computer, and Telecommunications Engineering, University of Wollongong, Wollongong, NSW, Australia. His research interest includes signal processing and its applications to communication systems.

JIANGTAO XI (Senior Member, IEEE) received the B.E. degree from the Beijing Institute of Technology, Beijing, China, in 1982, the M.E. degree from Tsinghua University, Beijing, in 1985, and the Ph.D. degree from the University of Wollongong, Wollongong, NSW, Australia, in 1996, all in electrical engineering. He was a Postdoctoral Fellow with the Communications Research Laboratory, McMaster University, Hamilton, ON, Canada, from 1995 to 1996, and a Member of Technical Staff with Bell Laboratories, Lucent Technologies Inc., Murray Hill, NJ, USA, from 1996 to 1998. From 2000 to 2002, he was the Chief Technical Officer with TCL IT Group Company, China. In 2003, he rejoined the University of Wollongong, as a Senior Lecturer, where he is currently a Professor and the Head of the School of Electrical, Computer, and Telecommunications Engineering. His research interest includes signal processing and its applications in various areas, such as optoelectronics, instrumentation and measurement, and telecommunications.