Journal of Southeast University (English Edition) Vol. 31, No. 2, pp. 175 – 180 June 2015 ISSN 1003—7985

Adaptive modulation in MIMO optical wireless communication systems

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Abstract: In the intensity modulation and direct detection (IM/DD) multiple-input multiple-output (MIMO) optical wireless communication systems, a direct-current-biased adaptive modulation scheme is proposed to guarantee the nonnegative property of transmitted signals, and the MIMO channel is converted to a parallel channel by using a singular value decomposition. Besides, a QR decomposition and successive interference cancellation based adaptive modulation scheme is proposed, and the MIMO channel can be simplified to a parallel channel under the bit error ratio (BER) target constraint. The power is optimally allocated to each sub-channel to maximize the data rate. Simulation results show that the proposed adaptive modulation schemes can effectively improve the transmission rate of the systems under the BER target and constant optical power constraints. The proposed adaptive modulation schemes make use of the multiplexing gain of the MIMO techniques, and can further improve the spectrum efficiency of optical wireless systems.

Key words: optical wireless communication; multiple input and multiple output (MIMO); adaptive modulation

doi: 10.3969/j. issn. 1003 – 7985. 2015. 02. 003

In the multiple-input and multiple-output (MIMO) radio frequency wireless communication system[1-2], precoding and successive interference cancellation are two of the most commonly used techniques to curb the inter-symbol interference. When applying precoding techniques[3], the transmitter needs to know the channel status information through the feedback of the receiver. In a practical system, the channel status information must be quantified by a limited number of bits in order to be sent back to the transmitter[4]. A practical method based on the QR decomposition and successive interference cancellation can be easily realized and applied in many areas[5].

The system spectrum efficiency can be enhanced by adaptive modulation and power allocation schemes[6]. The adaptive technique also requires the feedback information. In an adaptive modulation system based on precoding, channel state information which includes the precoding matrix must be sent back to the transmitter. In a practical system, the perfect channel state information cannot be acquired, an adaptive algorithm based on the error channel state information[7] is analyzed. Zhou et al.[8] studied the adaptive technique based on the mean value feedback. In Ref. [9], a method using the outdated channel state information was proposed. Park et al.[10] proposed an enhanced precoding scheme with limited-rate imperfect feedback.

By utilizing MIMO techniques, the anti-fading characteristics and spectrum efficiency of a system can be enhanced, and adaptive modulation can further improve the spectrum efficiency while still ensuring system performance. However, adaptive techniques in radio frequency wireless communications cannot be directly applied to optical wireless communication systems because of the intensity modulation and direct detection (IM/DD), which means that the transmitted signal must be nonnegative. Besides, few studies have been conducted on the adaptive modulation techniques in MIMO optical wireless communication systems. In this paper, we focus on the adaptive modulation techniques applicable to the IM/DD MIMO optical wireless communication system. Two adaptive modulation schemes are proposed for the IM/DD optical wireless communication system in flat fading channels. DC bias and singular value decomposition (SVD) are applied in the first proposed scheme, and the second scheme is based on successive interference cancellation. Simulation results show that the proposed schemes work well under the bit error ratio (BER) target and constant transmit power constraints.

1 System Model of MIMO Optical Wireless Communications

A point to point un-imaged MIMO optical wireless communication system is considered in this paper[11]. It is assumed that a transmitter consists of n_t light-emitting diodes (LEDs) and a receiver consists of n_r photodiodes (PDs). The block diagram of the MIMO optical wireless system is shown in Fig. 1. The channel of MIMO optical wireless communication can be expressed by a $n_r \times n_t$ matrix $\boldsymbol{H}$, where the (i, j)-th component of $\boldsymbol{H}$ is $h_{i,j}$, which is the channel coefficient from the j-th LED to the i-th

Received 2014-10-23.

Biographies: Wu Bin (1974—), male, graduate; Zou Cairong (corresponding author), male, doctor, professor, zoucairong@seu.edu.cn.

Foundation items: The National High Technology Research and Development Program of China (863 Program) (No. 2013AA013601), the National Science and Technology Major Project of China (No. 2015ZX03004009).

Citation: Wu Bin, Wu Liang, Zou Cairong. Adaptive modulation in MIMO optical wireless communication systems[J]. Journal of Southeast University (English Edition), 2015, 31(2): 175 – 180. [doi: 10.3969/j. issn. 1003 – 7985. 2015. 02. 003]

PD. In line of sight (LOS) links, $h_{i,j}$ can be expressed as[12]

$$h_{i,j}=\begin{cases}\dfrac{(m+1)A_r}{2\pi D_{i,j}^2}\cos^m(\varphi_{i,j})\cos(\phi_{i,j}) & \phi_{i,j}<\Psi_{c,i}\\ 0 & \phi_{i,j}>\Psi_{c,i}\end{cases} \quad (1)$$

where m is the order of Lambertian emission, $m=-\ln 2/\ln(\cos\Phi_{1/2})$; $\Phi_{1/2}$ is the semiangle at half-power of the transmitting LED; A_r is the receiving area of PD; $D_{i,j}$ and $\phi_{i,j}$ are the distance and angle of incidence from the j-th LED to the i-th PD, respectively; $\Psi_{c,i}$ is the field of view (FOV) of the i-th PD.

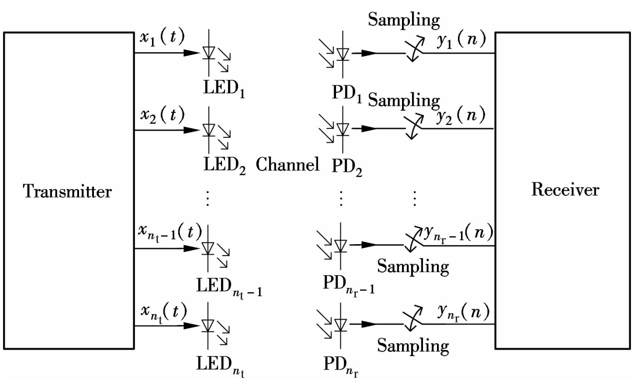

Fig. 1 Block diagram of a MIMO optical wireless communication system

The received signal takes the form as

$$\boldsymbol{y}=\boldsymbol{H}\boldsymbol{x}+\boldsymbol{n} \quad (2)$$

where $\boldsymbol{x}$ is a $n_t\times 1$ transmit vector; $\boldsymbol{n}$ is an additive Gaussian noise vector; and each component of $\boldsymbol{n}$ is a Gaussian random variable with zero mean and variance σ_n^2.

2 Adaptive Modulation Scheme based on DC-Bias and SVD

In radio frequency (RF) MIMO communication systems, the optimal precoding matrix is

$$\boldsymbol{U}_P=\boldsymbol{U}_H \quad (3)$$

where $\boldsymbol{U}_H$ is the right singular matrix of channel matrix $\boldsymbol{H}$, $\boldsymbol{H}=\boldsymbol{V}_H\boldsymbol{\Lambda}\boldsymbol{U}_H^H$, and $\boldsymbol{\Lambda}$ is a diagonal matrix with the components $\lambda_1\geqslant\lambda_2\geqslant\ldots\geqslant\lambda_r>0$, where r is the rank of $\boldsymbol{H}$. After precoding, the transmitted signal takes the form as

$$\boldsymbol{t}=\boldsymbol{U}_P\boldsymbol{s} \quad (4)$$

where $\boldsymbol{s}$ is the information vector. However, it cannot be guaranteed that all the components of $\boldsymbol{t}$ are nonnegative, and a DC bias is required. It is assumed that the k-th element of $\boldsymbol{s}$ is a zero mean and variance $\sigma_{s,k}^2$ Gaussian random variable, and all the elements are independent. Therefore, the k-th element of $\boldsymbol{t}$ is with zero mean and variance $\sigma_{t,k}^2=\sum_{i=1}^{n_t}(\boldsymbol{U}_P)_{k,i}^2\sigma_{s,i}^2$, where $(\boldsymbol{U}_P)_{k,i}$ is the (k,i)-th component of the precoding matrix $\boldsymbol{U}_P$.

For a Gaussian random variable ν with zero mean and variance σ_ν^2, the probability that ν lies in $[-2\sigma_\nu, 2\sigma_\nu]$ is 95.6 %; therefore, it has[13]

$$\Pr(\nu+2\sigma_\nu>0)\approx 97.8\% \quad (5)$$

which is very close to 1.

Define a vector $\boldsymbol{\kappa}$ and its k-th component is $\boldsymbol{\kappa}_k=2\sigma_{t,k}$. By adding a DC bias, the transmitted signal can be expressed as

$$\boldsymbol{x}=\boldsymbol{U}_P\boldsymbol{s}+\boldsymbol{\kappa} \quad (6)$$

Therefore, each component of $\boldsymbol{x}$ is greater than zero with a probability 97.8%, and the expectation of $\boldsymbol{x}$ is $E[\boldsymbol{x}]=\boldsymbol{\kappa}$. At the receiver, the received vector is multiplied by $\boldsymbol{V}_H^H$, and the derived signal is

$$\tilde{\boldsymbol{y}}=\boldsymbol{V}_H^H\boldsymbol{y}=\boldsymbol{\Lambda}(\boldsymbol{s}+\boldsymbol{U}_H^H\boldsymbol{\kappa})+\boldsymbol{V}_H^H\boldsymbol{n}=\boldsymbol{\Lambda}(\boldsymbol{s}+\boldsymbol{U}_H^H\boldsymbol{\kappa})+\tilde{\boldsymbol{n}} \quad (7)$$

After subtracting the DC bias component, the signal becomes

$$\tilde{\tilde{\boldsymbol{y}}}=\tilde{\boldsymbol{y}}-\boldsymbol{\Lambda}\boldsymbol{U}_H^H\boldsymbol{\kappa}=\boldsymbol{\Lambda}\boldsymbol{s}+\tilde{\boldsymbol{n}} \quad (8)$$

In the practical communication system, each component of information vector $\boldsymbol{s}$ employs a traditional pulse amplitude modulation (PAM) scheme, and the modulation order is chosen adaptively. It is assumed that the maximum value of the k-th spatial subchannel is Z_k. Therefore, the k-th component of the DC bias vector $\boldsymbol{\kappa}$ is

$$\boldsymbol{\kappa}_k=\sum_{i=1}^{n_t}|(\boldsymbol{U}_P)_{k,i}|Z_i \quad (9)$$

When the average transmit optical power is p_a, the corresponding constraint is

$$\sum_{k=1}^{n_t}\sum_{i=1}^{n_t}|(\boldsymbol{U}_P)_{k,i}|Z_i\leqslant p_a \quad (10)$$

The Euclidean distance between the adjacent points in the PAM scheme is $d_{k,M}=\dfrac{2Z_k}{M-1}$. When Gray coding is applied, the bit error ratio (BER) of the k-th date stream can be expressed as[14]

$$\mathrm{BER}_{k,M}\approx\frac{2(M-1)}{M\log_2 M}Q\left(\frac{Z_k\lambda_k}{(M-1)\sigma_n}\right) \quad (11)$$

where $Q(x)=\int_x^{+\infty}\frac{1}{\sqrt{2\pi}}\exp\left(-\frac{u^2}{2}\right)\mathrm{d}u$ is the Q-function. It is assumed that the BER target is BER_t, which means that BER should satisfy $\mathrm{BER}_{k,M}\leqslant\mathrm{BER}_t$. The modulation threshold can be derived as

$$\mathrm{Th}_{k,i}=\left(\frac{Z_k}{\sigma_n}\right)_i=\frac{M-1}{\lambda_k}Q^{-1}\left(\mathrm{BER}_t\frac{M\log_2 M}{2(M-1)}\right)$$
$$M=2^i;\ i=1,2,\ldots,6 \quad (12)$$

where $Q^{-1}(\cdot)$ is the inverse function of the Q-function, and it has

$$\mathrm{Th}_{k,1} \leqslant \mathrm{Th}_{k,2} \leqslant \ldots \leqslant \mathrm{Th}_{k,6} \quad (13)$$

The modulation order can be decided according to the following criteria:

$$M = \begin{cases} 0 & \dfrac{Z_k}{\sigma_n} < \mathrm{Th}_{k,1} \\ 2^i & \mathrm{Th}_{k,i} \leqslant \dfrac{Z_k}{\sigma_n} < \mathrm{Th}_{k,i+1};\ i = 1, 2, \ldots, 5 \\ 64 & \mathrm{Th}_{k,6} \leqslant \dfrac{Z_k}{\sigma_n} \end{cases} \quad (14)$$

The transmission rate of the k-th data stream is

$$R_k = \sum_{i=1}^{6} U\left(\frac{Z_k}{\sigma_n} - \mathrm{Th}_{k,i}\right) \quad (15)$$

where $U(\cdot)$ is the step function. Under the constant power and BER target constraints, the adaptive modulation scheme can be expressed as the following optimization problem:

$$\max_{Z_k}\left\{\sum_{k=1}^{n_t}\sum_{i=1}^{6} U\left(\frac{Z_k}{\sigma_n} - \mathrm{Th}_{k,i}\right)\right\} \quad (16)$$

$$\text{s. t.} \quad \sum_{k=1}^{n_t}\sum_{i=1}^{n_t} |(\boldsymbol{U}_{\mathrm{P}})_{k,i}| Z_i \leqslant p_{\mathrm{a}} \quad (17)$$

To optimize the power allocation, The maximum value Z_k of the k-th data stream should satisfy

$$Z_k \in \{\mathrm{ThP}_{k,i} = \mathrm{Th}_{k,i}\sigma_n,\ i = 1, 2, \ldots, 6\} \quad (18)$$

Define the incremental power as

$$\Delta_{k,i}^{\mathrm{P}} = \begin{cases} \mathrm{ThP}_{k,1} & i = 1 \\ \mathrm{ThP}_{k,i} - \mathrm{ThP}_{k,i-1} & i = 2, 3, \ldots, 6 \end{cases} \quad (19)$$

It has $\Delta_{k,i}^{\mathrm{P}} \leqslant \Delta_{k,i+1}^{\mathrm{P}}$ for each data stream.

When the k-th spatial subchannel employs the 2^{m_k}-PAM scheme, the corresponding maximum value is $Z_k = \sum_{i=1}^{m_k} \Delta_{k,i}^{\mathrm{P}}$. The optimization problem becomes

$$\max_{m_k}\left\{R_{\text{achieve}} = \sum_{k=1}^{n_t} m_k\right\} \quad (20)$$

$$\text{s. t.} \quad \sum_{k=1}^{r}\sum_{j=1}^{n_t} |(U_{\mathrm{P}})_{k,j}| \sum_{i=1}^{m_j} \Delta_{j,i}^{\mathrm{P}} \leqslant p_{\mathrm{a}} \quad (21)$$

The problem can be solved by the following two steps[15]:

1) Sort the $6r$ values of $\sum_{j=1}^{n_t} |(U_{\mathrm{P}})_{j,k}| \Delta_{k,i}^{\mathrm{P}}$ in an ascending order $Y_1 \leqslant Y_2 \leqslant \ldots \leqslant Y_{6r}$;

2) Find the maximum value of R_{achieve}, subject to $\sum_{i=1}^{R_{\text{achieve}}} Y_i \leqslant p_{\mathrm{a}}$.

If the optimal modulation scheme of the k-th spatial sub-stream is $2^{m_{k,\mathrm{opt}}}$-PAM, the power allocation is

$$p_{k,\mathrm{avg}}^{\mathrm{opt}} = \begin{cases} \sum_{i=1}^{m_{k,\mathrm{opt}}} Y_{k,i}^{\mathrm{P}} & m_{k,\mathrm{opt}} \geqslant 1 \\ 0 & m_{k,\mathrm{opt}} = 0 \end{cases} \quad (22)$$

When the transmit optical power p_{a} is a constant and $\sum_{k=1}^{r} p_{k,\mathrm{avg}}^{\mathrm{opt}} < p_{\mathrm{a}}$, the remaining power can be equally allocated to the spatial sub-streams to further improve the BER performance.

3 Adaptive Modulation Scheme based on QR Decomposition and Successive Interference Cancellation

3.1 The principle of QR decomposition and successive interference cancellation

It is assumed that the QR decomposition of channel matrix $\boldsymbol{H}$ is

$$\boldsymbol{H} = \boldsymbol{U}_{\mathrm{Q}}\boldsymbol{G} \quad (23)$$

where $\boldsymbol{U}_{\mathrm{Q}}$ is an unitary matrix and $\boldsymbol{G}$ is an upper triangle matrix. At the receiver, the received signal is multiplied by the conjugate and transpose of matrix $\boldsymbol{U}_{\mathrm{Q}}$, such that the signal can be expressed as

$$\hat{\boldsymbol{y}} = \boldsymbol{U}_{\mathrm{Q}}^{\mathrm{H}}\boldsymbol{y} = \boldsymbol{G}x + \boldsymbol{U}_{\mathrm{Q}}^{\mathrm{H}}\boldsymbol{n} = \boldsymbol{G}\boldsymbol{x} + \hat{\boldsymbol{n}} \quad (24)$$

where $\hat{\boldsymbol{n}} = \boldsymbol{U}_{\mathrm{Q}}^{\mathrm{H}}\boldsymbol{n}$ is a Gaussian random vector, and each component is with zero mean and variance σ_n^2. Since $\boldsymbol{G}$ is an upper triangle matrix, the successive interference cancellation can be applied to detect the data. It is assumed that the (i, j)-th component of $\boldsymbol{G}$ is $g_{i,j}$. Each spatial transmitted information stream employs DC bias pulse amplitude modulation (PAM), and it is assumed that the average optical power of the k-th spatial sub-stream is $p_{k,\mathrm{avg}}$.

Theorem 1 In optical wireless communication systems, the optical domain signal to noise ratio (SNR) of the k-th spatial sub-channel is dominated by $\dfrac{|g_{k,k}| p_{k,\mathrm{avg}}}{\sigma_n}$, when QR decomposition and the successive interference cancellation based adaptive modulation is applied.

The proof is as follows: The BER target in the uncoded adaptive modulation system is usually less than 10^{-3}. In the optical domain, SNR is defined as

$$\mathrm{SNR} = \frac{p_{\mathrm{a}}}{\sigma_n} \quad (25)$$

where p_{a} is the optical power.

Therefore, the average SNR of the k-th spatial sub-channel is

$$E[\vartheta_k] = \sum_{i=0}^{k-1}\binom{k-1}{i}(1 - \mathrm{BER}_{\mathrm{t}})^{k-1-i}(\mathrm{BER}_{\mathrm{t}})^{i}\vartheta_{k,i} \quad (26)$$

where $\vartheta_{k,i}$ is the SNR of the k-th spatial sub-stream when suffering the interference from i data streams, and it is assumed that $\vartheta_{k,i}$ are in the same order with the same i. Besides, in the practical environment, it has $n_{\mathrm{t}} < 10$ and $n_{\mathrm{r}} < 10$. Therefore,

$$E[\vartheta_k] \approx (1 - \mathrm{BER}_{\mathrm{t}})^{k-1}\vartheta_{k,0} \approx \vartheta_{k,0} = \frac{|g_{k,k}| p_{k,\mathrm{avg}}}{\sigma_n} \quad (27)$$

The QR decomposition and successive interference cancellation based adaptively modulated optical wireless communication system can be viewed as adaptive modulation in parallel channels.

3.2 QR decomposition and successive interference cancellation based adaptive modulation scheme

In the MIMO optical wireless system, the DC-bias PAM scheme is employed for each sub-channel. The BER performance of the DC bias PAM scheme takes the form as[14]

$$\mathrm{BER}_M \approx \frac{2(M-1)}{M\log_2 M} Q\left(\frac{\mathrm{SNR}}{M-1}\right) \tag{28}$$

where SNR is in the optical domain as Eq. (25). The SNR threshold is defined as

$$\mathrm{ThO}_i = (2^i - 1) Q^{-1}\left(\mathrm{BER}_t \frac{i2^i}{2(2^i-1)}\right) \qquad i = 1, 2, \ldots, 6 \tag{29}$$

where $\mathrm{ThO}_1 \leqslant \mathrm{ThO}_2 \leqslant \ldots \leqslant \mathrm{ThO}_6$.

When the transmit power is a constant and the BER target is set, the power is optimally allocated such that the achieved data rate is maximized. The optimization problem can be expressed as

$$\max_{p_{k,\mathrm{avg}}} \left\{ \sum_{k=1}^{r} \sum_{i=1}^{6} U\left(\frac{|g_{k,k}| p_{k,\mathrm{avg}}}{\sigma_n} - \mathrm{ThO}_i \right) \right\} \tag{30}$$

$$\text{s.t.} \quad \sum_{k=1}^{r} p_{k,\mathrm{avg}} = p_a, \quad p_{k,\mathrm{avg}} \geqslant 0 \tag{31}$$

According to the SNR threshold, the power allocated to the k-th spatial sub-stream needs to satisfy

$$p_{k,\mathrm{avg}} \in \left\{ \mathrm{ThOP}_{k,i} = \frac{\mathrm{ThO}_i}{|g_{k,k}|}\sigma_n \qquad i = 1, 2, \ldots, 6 \right\} \tag{32}$$

which can achieve the maximum spectrum.

The incremental optical power is defined as

$$\Phi^{\mathrm{P}}_{k,i} = \begin{cases} \mathrm{ThOP}_{k,1} & i = 1 \\ \mathrm{ThOP}_{k,i} - \mathrm{ThOP}_{k,i-1} & i = 2, 3, \ldots, 6 \end{cases} \tag{33}$$

It has $\Phi^{\mathrm{P}}_{k,i} \leqslant \Phi^{\mathrm{P}}_{k,i+1}$ for each sub-channel.

When 2^{m_k}-PAM scheme is employed in the k-th spatial sub-channel, the optical power allocated to the k-th spatial sub-channel is $p_{k,\mathrm{avg}} = \sum_{i=1}^{m_k} \Phi^{\mathrm{P}}_{k,i}$. The previous optimization problem is equivalent to the following problem:

$$\max_{m_k} \left\{ R_{\mathrm{achieve}} = \sum_{k=1}^{n_t} m_k \right\} \tag{34}$$

$$\text{s.t.} \quad \sum_{k=1}^{r} \sum_{i=1}^{m_k} \Phi^{\mathrm{P}}_{k,i} \leqslant p_a \tag{35}$$

The problem can be solved by the following two steps[15]:

1) Sort the $6r$ values of $\Phi^{\mathrm{P}}_{k,i}$ in ascending order expressed $\Theta_1 \leqslant \Theta_2 \leqslant \ldots \leqslant \Theta_{6r}$

2) Find the maximum value of R_{achieve}, subject to $\sum_{i=1}^{R_{\mathrm{achieve}}} \Theta_i \leqslant p_a$.

If the optimal modulation scheme of the k-th spatial sub-stream is $2^{m_{k,\mathrm{opt}}}$-PAM, the power allocation is

$$p^{\mathrm{opt}}_{k,\mathrm{avg}} = \begin{cases} \sum_{i=1}^{m_{k,\mathrm{opt}}} \Phi^{\mathrm{P}}_{k,i} & m_{k,\mathrm{opt}} \geqslant 1 \\ 0 & m_{k,\mathrm{opt}} = 0 \end{cases} \tag{36}$$

When the transmit optical power p_a is a constant and $\sum_{k=1}^{r} p^{\mathrm{opt}}_{k,\mathrm{avg}} < p_a$, the remaining power can be equally allocated to the spatial sub-streams. Define

$$\Omega_{\mathrm{p}} = p_a - \sum_{k=1}^{r} p^{\mathrm{opt}}_{k,\mathrm{avg}} \tag{37}$$

The achieved data rate of the proposed adaptive modulation is

$$R_{\mathrm{achieve}} = \sum_{k=1}^{r} \sum_{i=1}^{6} U\left(\frac{|g_{k,k}| (p^{\mathrm{opt}}_{k,\mathrm{avg}} + \Omega_{\mathrm{p}}/r)}{\sigma_n} - \mathrm{ThO}_i \right) \tag{38}$$

If q bits are used to quantize the proportion of the power allocated for each spatial sub-stream to the total transmitted power, the total number of feedback bits are $(q+3)r$, where $3r$ bits are used to send the modulation order.

4 Simulation Results

In the simulation, the channel coefficient $h_{i,j}$ is set to be $h_{i,j} = \sqrt{\pi/2}\,|\omega_{i,j}|$, where $\omega_{i,j}$ is a Gaussian random variable with zero mean and variance 1. Therefore, it has $E[\eta_{i,j}] = 1$. Besides, it is assumed that the spatial sub-channels are independent, and variance of noise is $\sigma_n^2 = 1$. The BER target is $\mathrm{BER}_t = 10^{-3}$.

Figs. 2 and 3 depict the performance of the DC bias and SVD-based adaptive modulation scheme. Fig. 2 shows the achieved data rate with different LED and PD configurations. It can be seen from Fig. 2 that the achieved data rate is linearly proportional to n_t when $n_t = n_r$. Fig. 3 shows the simulated BER performance. It can be seen that the BER target is satisfied in all the conditions. The trend of the BER performance changes when SNR becomes great, that is because the remaining power, which can further improve the BER performance, changes with a different SNR. For example, when $n_t = n_r = 8$, the BER at SNR = 8 dB is worse than that at SNR = 6 dB. The achieved data rate at SNR = 8 dB is higher than that at SNR = 6 dB, which means that the modulation order at SNR = 8 dB is higher than that at SNR = 6 dB. Besides, according to Eq. (37), the remaining power at SNR = 8 dB may be less than that at SNR = 6 dB. Therefore, BER at SNR = 8 dB is worse than that at SNR = 6 dB, even if the transmit power at SNR = 8 dB is higher than that at SNR = 6 dB. But the BER is below the BER target in all SNR regions.

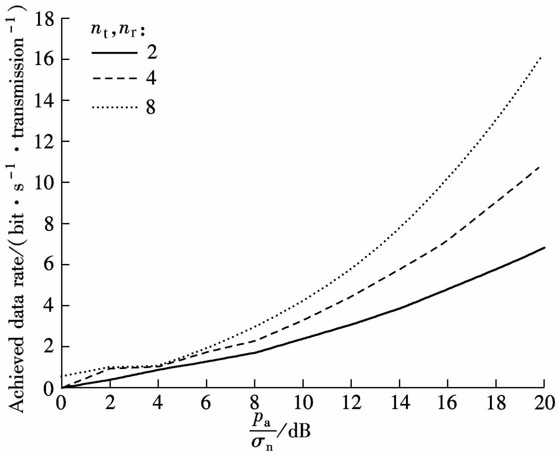

Fig. 2 Achieved data rate of the DC bias and SVD based adaptive modulation scheme with different LED and PD configurations

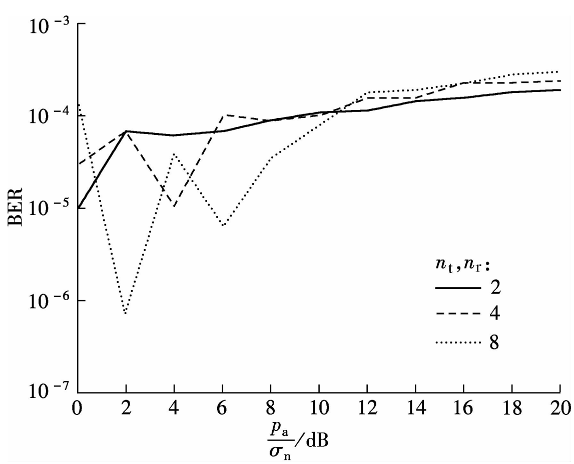

Fig. 3 Simulated BER performance of DC-bias and SVD based adaptive modulation scheme with different LED and PD configurations

Fig. 4 shows the achieved data rate of the QR decomposition and successive interference cancellation based adaptive modulation scheme with different quantization bits, where $n_t = n_r = 4$. It can be seen from Fig. 4 that the effect of quantization bits is small in the low SNR region; when SNR is larger than 14 dB, the effect of quantization bits becomes large. Besides, the gap between $q = 4$ and $q = \infty$ is very small, which mean that 4 bits are enough to quantize the power allocation strategy. For comparison, the achieved data rate of the DC bias adaptive modulation scheme with $n_t = n_r = 4$ is also plotted. It can be seen that the achieved data rate of the QR based scheme is improved, when the number of quantization bits is no less than 2.

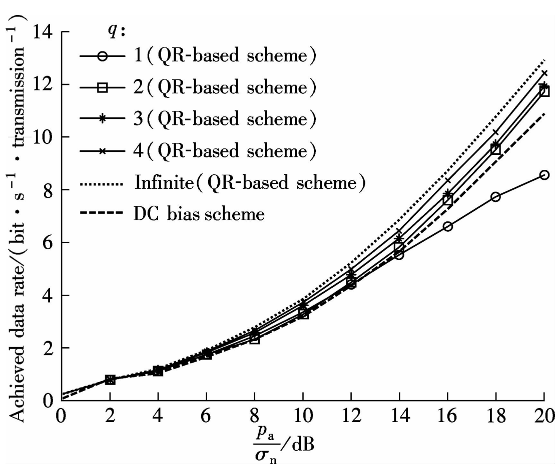

Fig. 4 Achieved data rate of QR decomposition and successive interference cancellation based adaptive modulation scheme with different quantization bits and $n_t = n_r = 4$

Fig. 5 depicts the BER performance. It can be seen that BER performances with different quantization bits are below the BER target. When the SNR becomes high, the trend of BER performance changes as shown in Fig. 3, and it is caused by the same reason.

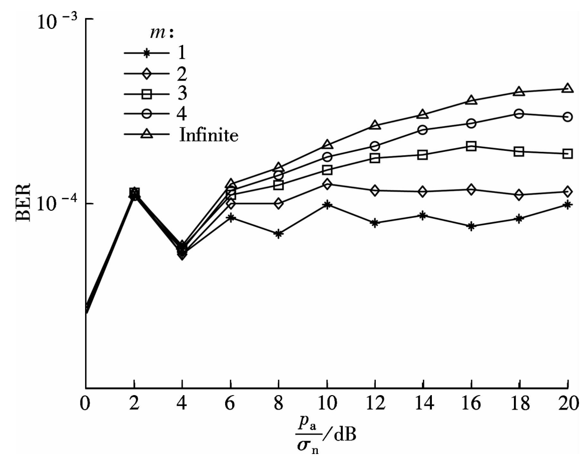

Fig. 5 Simulated BER performance of QR decomposition and successive interference cancellation based adaptive modulation scheme with different quantization bits and $n_t = n_r = 4$.

5 Conclusion

Spatial multiplexing gain in the MIMO technique can effectively improve the spectrum efficiency of the system, while the adaptive modulation techniques under certain specified constraints can further enhance the system performance. In this paper, adaptive modulation schemes in IM/DD MIMO optical wireless communication systems are studied. Two adaptive modulation techniques are proposed. The first scheme is based on DC-bias and SVD, and the second scheme is based on QR decomposition and successive interference cancellation. The first scheme is a straightforward scheme, and the achieved data rate of the second scheme is higher when the number of quantization bits is no less than 2. The maximum data rate and achieved BER performance under a given BER target and constant transmit power constraint are analyzed. Besides, the second proposed adaptive modulation technique can achieve the specified performance using finite rate feedback. The feasibility of the proposed adaptive modulation techniques are verified by the simulation results.

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多输入多输出无线光通信系统中的自适应调制技术

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摘要:在基于强度调制、直接检测的多输入多输出无线光通信系统中,为了保证发射信号非负特性,提出一种基于直流偏置的自适应调制技术,并且利用奇异值分解将多输入多输出信道转换为并行信道. 此外,提出一种基于 QR 分解、逐次干扰消除的自适应调制技术. 在目标误比特率性能条件下,利用 QR 分解、逐次干扰消除的特性将多输入多输出信道等效为并行信道. 根据最大化可达速率的优化目标,最优地给各个子信道分配功率. 仿真结果表明所提出的 2 种自适应调制方法在保证误比特率性能和平均发射光功率恒定的前提下,有效地提高了系统的传输速率. 这 2 种自适应调制技术在利用多输入多输出技术空分复用增益的同时,进一步提高了无线光通信系统的频谱利用率.

关键词:可见光通信; 多输入多输出; 自适应调制

中图分类号:TN92