Front. Electr. Electron. Eng. China 2008, 3(2): 145–149
DOI 10.1007/s11460-008-0024-4

RESEARCH ARTICLE

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A PO-CI/MC-CDMA scheme for high modulation styles

Abstract Through analyzing the theoretical spreading principle, it has been proved in this paper that the benefit of pseudo-orthogonal carrier interferometry (PO-CI) spreading code is not supported when complex signal modulation (e.g., quadrature phase-shift keying (QPSK) and quadrature amplitude modulation (QAM)) types are employed. On this basis, a novel and feasible structure for this problem is brought forward. Within the structure mentioned, instead of complex modulation patterns, pulse amplitude modulation (PAM) combined with PO-CI spreading code is utilized. This allows us to maintain the throughput increase of a multi-carrier code division multiple access (MC-CDMA) system with minimal loss in performance and no bandwidth expansion.

Keywords pseudo-orthogonal carrier interferometry, pulse amplitude modulation, spreading/de-spreading, multi-carrier code division multiple access, doubled throughput

1 Introduction

Carrier interferometry (CI)/multi-carrier code division multiple access (MC-CDMA) [1] replaces the traditional Hadamard sequences by CI codes [2] to obtain a number of promising advantages. In CI/MC-CDMA systems, first, the spreading codes can be constituted by any length N. Second, the peak-to-average power ratio (PAPR) of the systems could be remarkably decreased compared with traditional MC-CDMA [3,4].

Based on CI/MC-CDMA, MC-CDMA or orthogonal frequency division multiplexing (OFDM) with pseudo-orthogonal carrier interferometry (PO-CI) codes was introduced by Zhiqiang Wu and his partners. With this novel code of length N, MC-CDMA can support $2N$ users, which can double the system throughput simultaneously. Since PO-CI/MC-CDMA systems own the novel characteristics above, a lot of communication methods have been researched and proposed based on PO-CI sequences, which have been analyzed in Refs. [5–9] in an OFDM system. In Ref. [10], PO-CI sequences are combined with time division multiple access (TDMA). However, without expanding to high rank modulation types, the existing literatures about theoretical derivation and performance analysis of PO-CI spreading codes are only grounded on binary phase shift keying (BPSK) modulation. It is mainly due to that in the existing literature analysis, high rank modulation types always employ complex phase modulations, such as quadrature phase-shift keying (QPSK) and quadrature amplitude modulation (QAM). As will be mentioned in the succeeding sections, PO-CI/MC-CDMA systems cannot be de-spread thoroughly with these modulation types and the performance deterioration is totally unacceptable. However, from another point of view, to enhance the frequency efficiency and data throughput, high rank modulation types are indispensable in wireless communication systems with high velocity. Through the analysis above, it is proved that the performance analysis of Refs. [3,5] is severely limited in the practical wireless communication systems. Therefore, the de-spreading principle of PO-CI spreading codes and the system performance analysis of PO-CI/MC-CDMA systems in different modulation types, except BPSK, are essential. Besides, it is necessary to find a suitable modulation type for PO-CI spreading codes to satisfy the requirements of wireless communication with high velocity.

In consequence, the performance of PO-CI/MC-CDMA systems with several different modulation types is analyzed in this paper, and a novel modulation and spreading combination scheme suitable for PO-CI spreading sequences is proposed based on the comparison. From the analysis, it is proved that since the cross correlation

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Translated from *Journal of Beijing University of Posts and Telecommunications*, 2007, 30(4): 14–18 [译自: 北京邮电大学学报]

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between different pseudo-orthogonal codes is not forced to zero, when high rank modulation types are employed and the user number is larger than the sub-carrier number, the inter-user interference resulting from code cross correlation characteristic is so serious that the system performance is catastrophically destroyed. Nevertheless, because of the specialty of its constellation, BPSK modulation can avoid this kind of code interference. In the proposed modulation and spreading combination method, the transmitted data are modulated on pure real or pure imaginary constellation (pulse amplitude modulation (PAM) or imaginary PAM) at first, and then PO-CI spreading is undertaken. It is further demonstrated by the simulation results that the performance decrease brought by large inter-code interference of PO-CI spreading sequence can be effectively conquered by making use of this scheme.

2 PO-CI/MC-CDMA signal and transmitter model

In a PO-CI/MC-CDMA system, the transmitter spreading module of user k can be expressed as Fig. 1.

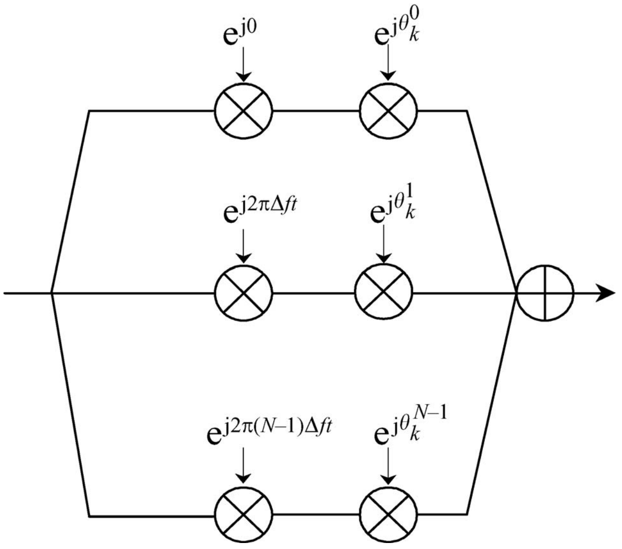

Fig. 1 Spreading module of the transmitter in PO-CI/MC-CDMA

As an orthogonal complex spreading sequence, the spreading codes of the kth user can be shown as:

$$\boldsymbol{c_k}(t) = \sum_{i=0}^{N-1} \beta_k^i e^{j2\pi i \Delta ft}, \tag{1}$$

where $(\beta_k^0, \cdots, \beta_k^i, \cdots, \beta_k^{N-1}) = \left(e^{j\theta_k^0}, \cdots, e^{j\theta_k^i}, \cdots, e^{j\theta_k^{N-1}}\right)$ denotes the spreading sequences. When user number K is no more than sub-carrier number N, there would not be any code interference between the data stream of every user. Therefore, the spreading sequence of user k can be depicted as:

$$\begin{aligned}&(\beta_k^0, \cdots, \beta_k^i, \cdots, \beta_k^{N-1})\\&= \left(e^{j\theta_k^0}, \cdots, e^{j\theta_k^i}, \cdots, e^{j\theta_k^{N-1}}\right)\\&= \left(e^{j(2\pi/N)\cdot 0\cdot k}, \cdots, e^{j(2\pi/N)ik}, \cdots, e^{j(2\pi/N)(N-1)k}\right).\end{aligned} \tag{2}$$

When PO-CI spreading codes are employed, MC-CDMA systems can transmit K (more than N) users' data on N sub-carriers. As depicted in Ref. [11], the characteristics of PO-CI codes are:

1) Composed of two sets of CI codes;

2) The first set of CI codes is expressed in Eq. (1);

3) The second set of CI codes should bear minimum cross correlation between the first set and itself.

Therefore, the PO-CI sequences satisfying the above restrictions [6] can be shown as:

$$\begin{aligned}&(\beta_k^0, \cdots, \beta_k^i, \cdots, \beta_k^{N-1})\\&= \left(e^{j\theta_k^0}, \cdots, e^{j\theta_k^i}, \cdots, e^{j\theta_k^{N-1}}\right)\\&= \left(e^{j(2\pi/N)\cdot 0\cdot k + 0\cdot\pi/N}, \cdots, e^{j(2\pi/N)ik + i\pi/N},\right.\\&\qquad \left.\cdots, e^{j(2\pi/N)(N-1)k + (N-1)\pi/N}\right).\end{aligned} \tag{3}$$

In a word, the spreading PO-CI codes of all K users can be expressed in matrix form as:

$$\boldsymbol{C}(t) = (\boldsymbol{c}_0(t), \cdots, \boldsymbol{c}_k(t), \cdots, \boldsymbol{c}_K(t)), \tag{4}$$

where

$$\boldsymbol{c}_k(t) = \left(\beta_k^0, \cdots, \beta_k^i, \cdots, \beta_k^{N-1}\right)^{\mathrm{T}}, \tag{5}$$

$$\begin{cases} \beta_i^k = e^{j\frac{2\pi}{N}ki}, & k \in \{0, 1, \cdots, N-1\} \\ \beta_i^k = e^{j\frac{2\pi}{N}ki + i\frac{\pi}{N}}, & k \in \{N, N+1, \cdots, 2N-1\} \end{cases}. \tag{6}$$

By utilizing PO-CI spreading codes, if code interference can be eliminated and the receiver can de-spread correctly, the user number supported by PO-CI/MC-CDMA can be doubled compared with that in MC-CDMA employing CI or other orthogonal spreading codes ($K = 2N$ v.s. $K = N$). From the analysis in Sect. 3, it can be seen that the performance of this spreading codes is closely related with the modulation type. In this paper, PO-CI/MC-CDMA systems combined with different modulation types, including BPSK, QPSK, QAM and PAM are discussed and simulated, and then the most suitable modulation type would be proposed.

The transceiver structure of PO-CI/MC-CDMA systems is shown in Fig. 2.

The main modules on the transmitter include: channel coding, modulation (PSK, QAM and PAM are optional), spreading the data of every user with PO-CI codes, transforming the frequency domain signal to time domain by

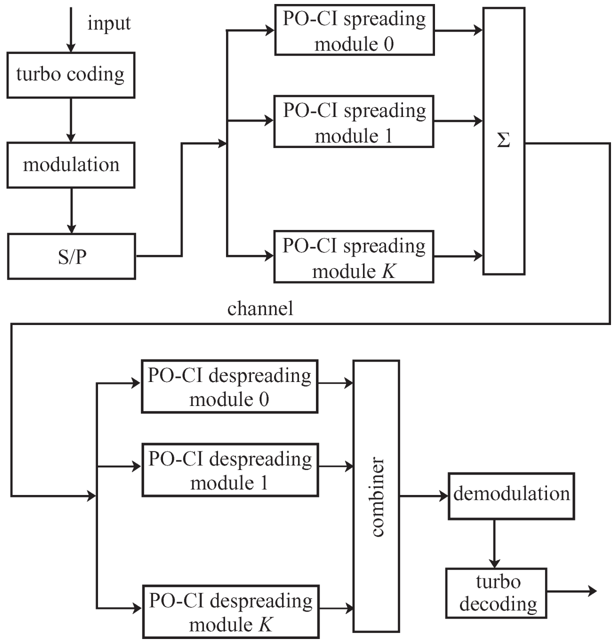

Fig. 2 Transceiver structure of PO-CI/MC-CDMA systems

inverse fast Fourier transform (IFFT) and then adding a cyclic prefix (CP) to form an OFDM symbol.

3 Receiver structure and analysis of received signal

The receiver structure of PO-CI/MC-CDMA is shown in Fig. 2. The main receiver modules are: removing CP, transforming the time domain signal to frequency domain by fast Fourier transform (FFT), conducting the de-spreading with PO-CI codes, combining (such as orthogonality restoring combining (ORC) and minimum mean square error combining (MMSEC)), demodulating and de-coding.

In an MC-CDMA system with K users, its baseband received signal can be depicted as:

$$r_i(t)=\sum_{k=1}^{K} A_i s_i(t) c_k^i(t)+n_i(t), \tag{7}$$

where A_i is the amplitude of the received signal, $s_i(t)$ represents the modulated signal on the transmitter, $c_k^i(t)$ means the spreading codes of user k and $n(t)$ denotes additive white Gaussian noise (AWGN). Perfect timing and frequency synchronization here is assumed for simplicity in presentation. In one symbol interval, the received signal can be expressed as:

$$\boldsymbol{r}(t)=\boldsymbol{A}\boldsymbol{C}\boldsymbol{s}(t)+\boldsymbol{n}, \tag{8}$$

where $\boldsymbol{s}=(s_0(t),\cdots,s_k(t),\cdots,s_K(t))^{\mathrm{T}}$ are the information vectors of all K users; $\boldsymbol{A}=\mathrm{diag}(A_1,A_2,\cdots,A_{\mathrm{k}})$ denotes the channel fading coefficient of every user; $\boldsymbol{n}$ represents the Gaussian noise vector and $\boldsymbol{C}$ means the spreading codes matrix. After de-spreading, the output vector of the received signal is:

$$y_k(t)=A_k s_k(t)\boldsymbol{c}_k(t)\boldsymbol{c}_k{}^{\mathrm{H}}(t)+n_k(t), \tag{9}$$

which could be re-written in matrix form as:

$$\boldsymbol{Y}=\boldsymbol{C}\boldsymbol{C}^{\mathrm{H}}\boldsymbol{A}\boldsymbol{s}(t)+\hat{\boldsymbol{n}}, \tag{10}$$

where $(\cdot)^H$ is the conjugate transposition.

Assuming that $\boldsymbol{c}_k$ and $\boldsymbol{c}_{k'}$ are the PO-CI spreading sequence sets of two users, $\boldsymbol{c}_k\times\boldsymbol{c}_{k'}^{\mathrm{H}}$ can be analyzed as follows:

When $k,\ k'\in\{0,\ 1,\cdots,\ N-1\}$, i.e., $\boldsymbol{c}_k=\mathrm{e}^{\mathrm{j}\frac{2\pi}{N}ki}$ and $\boldsymbol{c}_{k'}=\mathrm{e}^{\mathrm{j}\frac{2\pi}{N}k'i}$ belong to one orthogonal codes set, that is,

$$\begin{aligned}\boldsymbol{c}_k\times\boldsymbol{c}_{k'}^{\mathrm{H}}&=\sum_{i=0}^{N-1}\mathrm{e}^{\mathrm{j}\frac{2\pi}{N}ki}\mathrm{e}^{-\mathrm{j}\frac{2\pi}{N}k'i}\mathrm{e}^{\mathrm{j}2\pi i\Delta ft}\mathrm{e}^{-\mathrm{j}2\pi i\Delta ft}\\&=\sum_{i=0}^{N-1}\mathrm{e}^{\mathrm{j}\frac{2\pi}{N}(k-k')i}=\begin{cases}N, & k=k'\\0, & k\neq k'\end{cases}.\end{aligned} \tag{11}$$

When $k'\in\{N,\ N+1,\cdots,\ 2N-1\}$, $k\in\{0,\ 1,\cdots,\ N-1\}$, i.e., $\boldsymbol{c}_k=\mathrm{e}^{\mathrm{j}\frac{2\pi}{N}ki}$ and $\boldsymbol{c}_{k'}=\mathrm{e}^{\mathrm{j}\frac{2\pi}{N}k'i+i\frac{\pi}{N}}$ locate in two different spreading codes sets and are pseudo-orthogonal, the code interference is:

$$\begin{aligned}\boldsymbol{c}_k\times\boldsymbol{c}_{k'}^{\mathrm{H}}&=\sum_{i=0}^{N-1}\mathrm{e}^{\mathrm{j}\left(\frac{2\pi}{N}k-\frac{2\pi}{N}k'-\frac{\pi}{N}\right)\cdot i}=\frac{A(1-A^N)}{1-A}=\frac{2A}{1-A}\\&=\frac{2}{1-A}-2=\frac{2}{1-\cos\theta-\mathrm{j}\sin\theta}=1+\mathrm{j}\cot\frac{\theta}{2},\end{aligned} \tag{12}$$

where $A=\mathrm{e}^{\mathrm{j}\left(\frac{2\pi}{N}k-\frac{2\pi}{N}k'-\frac{\pi}{N}\right)}$, $\theta=\frac{2\pi}{N}k-\frac{2\pi}{N}k'-\frac{\pi}{N}$.

Therefore, $\boldsymbol{c}_k\times\boldsymbol{c}_{k'}^{\mathrm{H}}$ could be expressed in matrix form as:

$$\begin{pmatrix} \begin{matrix} N & \cdots & 0\\ \vdots & \ddots & \vdots\\ 0 & \cdots & N \end{matrix} & \begin{matrix} 1+\mathrm{j}\cot\frac{\theta}{2} & \cdots & 1+\mathrm{j}\cot\frac{\theta}{2}\\ \vdots & \ddots & \vdots\\ 1+\mathrm{j}\cot\frac{\theta}{2} & \cdots & 1+\mathrm{j}\cot\frac{\theta}{2} \end{matrix}\\ \begin{matrix} 1+\mathrm{j}\cot\frac{\theta}{2} & \cdots & 1+\mathrm{j}\cot\frac{\theta}{2}\\ \vdots & \ddots & \vdots\\ 1+\mathrm{j}\cot\frac{\theta}{2} & \cdots & 1+\mathrm{j}\cot\frac{\theta}{2} \end{matrix} & \begin{matrix} N & \cdots & 0\\ \vdots & \ddots & \vdots\\ 0 & \cdots & N \end{matrix} \end{pmatrix},\quad \theta=\frac{2\pi}{N}k-\frac{2\pi}{N}k'-\frac{\pi}{N}. \tag{13}$$

In consequence, the de-spreading signal of user k can be depicted as

$$\begin{aligned} y_k(t) &= s_k(t)N + \sum_{k' \neq k, k'=0}^{2N-1} s_{k'}(t)\left(1 + \mathrm{j}\cot\frac{\theta}{2}\right) \\ &= s_k(t)N + \sum_{k' \neq k, k'=0}^{2N-1} |s_{k'}(t)|(\cos\omega_{k'}(t) + \mathrm{j}\sin\omega_{k'}(t))\left(1 + \mathrm{j}\cot\frac{\theta}{2}\right) \\ &= s_k(t)N + \sum_{k' \neq k, k'=0}^{2N-1} (I_k(t) + \mathrm{j}Q_k(t)), \end{aligned} \tag{14}$$

where $s_k(t) = |s_k(t)|(\cos\omega_k(t) + \mathrm{j}\sin\omega_k(t))$ denotes the demodulated data of each user at time t, white

$$\begin{aligned} I_k(t) &= |s_{k'}(t)|\cos\omega_{k'}(t) - |s_{k'}(t)|\sin\omega_{k'}(t)\cot\left(\frac{\pi}{N}(k-k') + \frac{\pi}{2N}\right), \\ Q_k(t) &= |s_{k'}(t)|\sin\omega_{k'}(t) + |s_{k'}(t)|\cos\omega_{k'}(t)\cot\left(\frac{\pi}{N}(k-k') + \frac{\pi}{2N}\right). \end{aligned} \tag{15}$$

In Eq. (14), $s_k(t)$ is the transmitted signal of user k and $\sum_{k' \neq k, k'=0}^{2N-1} (I_k(t) + \mathrm{j}Q_k(t))$ denotes the code interference from other users.

When BPSK (2PAM) modulation is adopted, $s_k(t)$, $s_{k'}(t) \in \{-1, 1\}$ and $\sin\omega_k(t) = 0$, the code interference is

$$\sum_{k \neq k', k=0}^{2N-1} |s_k(t)|\cos\omega_k(t) = \pm \sum_{k \neq k', k=0}^{2N-1} |s_k(t)|.$$

Therefore, the received signals are $y_k(t) = Ns_k(t) \pm \sum_{k \neq k', k=0}^{2N-1} s_{k'}(t)$. Since the phase $\omega_k(t)$ of user data is random, $\left|\sum_{k \neq k', k=0}^{2N-1} s_{k'}(t)\right| \leqslant |s_k(t)N|$ and $y_k(t)$ are always in-phase with the $\left|\sum_{k \neq k', k=0}^{2N-1} s_{k'}(t)\right|$, thus resulting in no mistakes to the received signal. From the constellation of de-spread data, as shown in Fig. 3, the data transmitted as "1" are all positive in the receiver and vice versa.

When QAM modulation is applied in PO-CI/MC-CDMA systems, the received signal can be expressed as Eq. (14). In this case, $\sin\omega_k(t)$ and $\cos\omega_k(t)$ are both not equal to zero. Therefore, both real and imaginary interferences exist simultaneously, which consequently leads to incorrect system de-spreading. This character shall be proved by simulation in Sect. 4.

When high rank PAM modulation (i.e., 4PAM) is employed, similar to BPSK, the imaginary of the modulated signal will not be considered. As a result, the received signals are:

$$y_k(t) = Ns_k(t) \pm \sum_{k \neq k', k=0}^{2N-1} s_{k'}(t), \tag{16}$$

where $s_k(t), s_{k'}(t) \in \{(-3, -1, 1, 3)/\sqrt{5}\}$. If the modulated data are randomly distributed in the above set and the user number is relatively large, there will be hardly any bit error in the system. It can be seen from Fig. 4 that the

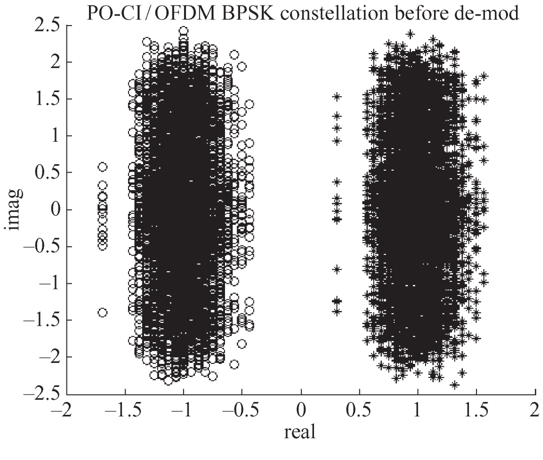

Fig. 3 Constellation of PO-CI/MC-CDMA combined with BPSK de-spreading

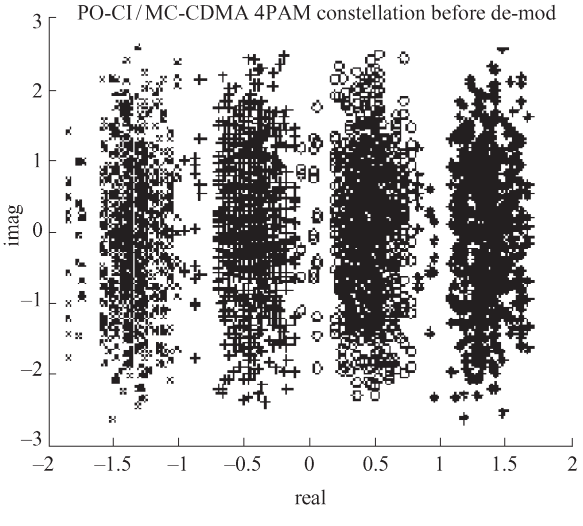

Fig. 4 Constellation of PO-CI/MC-CDMA combined with 4PAM de-spreading

transmitted signal can be clearly distinguished on the constellation of PO-CI/MC-CDMA combined with 4PAM.

4 Performance analysis and simulation results

To demonstrate the performance of PO-CI/MC-CDMA with different modulation types and verify our analysis, computer simulations have been conducted for PO-CI/MC-CDMA. The simulated channel models include AWGN and GSM standard COST 207 typical urban (TU) channel. Vehicle velocity of 120 km/h is used to represent mobile environments. The coding applied to the coded systems is a 1/2 rate turbo code.

It can be seen in Fig. 5 that the inter-code interference caused by pseudo-orthogonality can be totally eliminated when BPSK (2PAM) and other kinds of PAM modulations are applied in PO-CI/MC-CDMA systems. However, bit error ratio (BER) exceeds 10e-1 when QPSK or QAM modulation is applied. Besides, when BER equals to 10e-5, the differences in performance among BPSK, 4PAM and 8PAM amount to 5.5 dB. From the perspective of system capability, the throughputs of the systems combined with 4PAM and 8PAM are twice and triple of that with BPSK respectively, so that the scale in which PO-CI codes can be applied is largely expanded.

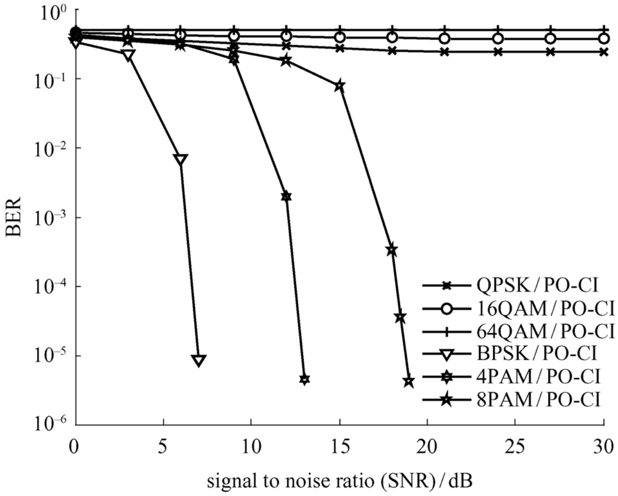

Fig. 5 PO-CI/MC-CDMA BER performance with different modulations types, TU channel, $K = 512$

5 Conclusions

As a kind of spreading method, PO-CI/MC-CDMA is innovative due to its capability of supporting more users than the code length. However, the existing researches are all based upon BPSK modulation type, which is not universally applicable. To further expand its application scale, performances of different modulations in PO-CI/MC-CDMA systems are analyzed. From theoretical analysis and simulations, it can be proved that when PO-CI codes are employed to spread, systems combined with bipolar modulation types such as QPSK and QAM cannot properly operate. Nevertheless, when PAM or other unipolar modulations are utilized, not only can the system de-spread correctly, but its capacity can also be enhanced.

Acknowledgements This work was supported by the National Natural Science Foundation of China (Grant No. 60496312).

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