Comparison of Fiber-Optic CDMA Systems Using Different Modulation Schemes

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Abstract

In order to provide different data rate transmission and quality of service (QoS) for multimedia communications and networks, three common modulation techniques used for optical code-division multiple-access (O-CDMA) are multiple code (MC), multicode keying (MK) and pulse position modulation (PPM). In this paper, the performance and normalized spectral efficiency (NSE) of the O-CDMA systems using above three different modulation techniques are analyzed and compared. Moreover, the computer simulation of each O-CDMA system is performed and compared with the theoretical results to identify the validity of the performance analysis. Our numerical results show that MK scheme always has a better NSE than other two schemes (i.e., MC and PPM schemes), but PPM scheme can provide the best system performance among these three schemes at the expense of the increased bandwidth.

Keywords: optical code-division multiple-access, multicode keying, multiple code, pulse position modulation.

1. Introduction

Optical code-division multiple-access (O-CDMA) has been widely applied in optical communication systems and networks⁽¹⁻³⁾, because the multiple access technique can provide many desirable features, such as dynamic bandwidth assignment, efficiency in bursty traffic, asynchronous and uncoordinated access, flexible user allocation and gradual performance degradation, compared with wavelength-division multiple-access (WDMA) and time-division multiple-access (TDMA) techniques⁽¹⁻⁴⁾. O-CDMA can mainly allow many simultaneous users to share the same transmission channel by assigning a unique spreading code to each user⁽⁵⁾. Recently, with the growing demand for high

speed networks and multimedia communication services, it is expected that the future O-CDMA systems should support a larger variety of multimedia services with different data rate and quality-of-service (QoS) to accommodate the transmission requirements of the system subscribers^(1,6-8). In addition to the multiple length and variable-weight techniques, three common modulation techniques which can support the different data rate and QoS transmission requirements for O-CDMA systems are multiple code (MC)⁽⁶⁾, multicode keying (MK)^(7,8) and pulse position modulation (PPM)^(9,10), respectively. In this paper, not only the performance but also normalized spectral efficiency (NSE) of three schemes are also analyzed and compared to determine which scheme should be used under certain conditions^(8,11).

The remainder of the paper is organized as follows. In Section 2, the system model of MC, MK and PPM schemes are studied. Numerical examples which evaluate and investigate the system parameters how to affect the system performance, are given in Section 3. Our results show that MK scheme always has a better NSE than MC and PPM schemes, but PPM scheme can provide the best performance among these three schemes at the expense of the increased bandwidth. Conclusions are finally drawn in Section 4.

2. System Model

First, a brief review of two-dimensional (2-D) multilevel prime code (MPC)⁽¹²⁾, which is used as numerical examples in the next section, is given in this section. Moreover, the system model of O-CDMA systems using MC, MK and PPM schemes are also introduced as follows.

2.1 Multilevel Prime Code

The use of $(L \times N, w, \lambda_a=0, \lambda_c=n)$ 2-D MPC⁽¹²⁾ with code cardinality p^n (i.e., the number of codewords), the number of available wavelengths L , code length $N=p$ (i.e., number

of time slots), code weight w , autocorrelation sidelobe of at most $\lambda_a=0$, and cross-correlation value of at most $\lambda_c=n$, where p is a prime number and $n \leq w \leq p$, are assumed for the numerical examples in Section 3. Each code matrix of 2-D MPC can be denoted by $C_{i1,i2,\dots,in} = (c_{i1,i2,\dots,in,0}, c_{i1,i2,\dots,in,1}, \dots, c_{i1,i2,\dots,in,j}, \dots, c_{i1,i2,\dots,in,w-1})$, in which the j th element can be represented by⁽¹²⁾

$$c_{i1,i2,\dots,in,j} = (i_1 j) \oplus_p (i_2 j^2) \oplus_p \dots \oplus_p (i_n j^n) \quad (1)$$

which indicates the time-slot position (among p) of the j th carrier wavelength for $j \in [0, w-1]$, where $\{i_1, i_2, \dots, i_n\} \in \text{GF}(p)$, and “ $\oplus_p$ ” denotes a modulo- p addition. Moreover, in order to obtain the larger cardinality in MC, MK, and PPM schemes, the use of the time-shifted copies of 2-D MPC is also assumed to represent the m symbols^(8,11,13).

Using $N=p=5$, $L=w=5$, and $n=1$ as an example, based on (1), the $(5 \times 5, 5, 0, 1)$ 2-D MPC has five code matrices C_{i1} , $i_1 \in [0, 4]$ (i.e., represented by $(0,0,0,0,0)$, $(0,1,2,3,4)$, $(0,2,4,1,3)$, $(0,3,1,4,2)$, $(0,4,3,2,1)$, respectively) of five time-shifted copies for each code matrix in Table 1. For example, five time-shifted copies of code matrix C_3 (i.e., $(0,3,1,4,2)$) are $(0,3,1,4,2)$, $(1,4,2,0,3)$, $(2,0,3,1,4)$, $(3,1,4,2,0)$, $(4,2,0,3,1)$ with time shift $\tau \in [0, 4]$, respectively.

2.2 Multiple Code Scheme^(6,11)

In the MC scheme, each user is allocated m_c code matrices when a user need to transmit at the rate of m_c times the basic bit transmission rate R (i.e., the data bit rate of the on-off keying (OOK) scheme). First, the serial data bits are converted into the parallel data bits. Then, each parallel data bit one is transmitted with one of the allocated m_c code matrices, but nothing is transmitted for a data bit zero^(6,11). That is, the number of code matrices allocated to each user determines the transmission bit rate of the scheme. Thus, the m_c code matrices are transmitted at the same time results in data bit rate of the scheme $R_{MC} = m_c \times R$ ⁽¹¹⁾. For example, the code matrix C_2 (i.e., $(0,2,4,1,3)$) and its three time-shifted copies (e.g., $(1,3,0,2,4)$, $(3,0,2,4,1)$, and $(4,1,3,0,2)$), shown in Table 1, are allocated to the user for $m_c=4$ multiple code transmission, thus the data bit rate of the scheme becomes $R_{MC} = m_c \times R = 4R$.

2.3 Multicode Keying Scheme^(8,11)

In this scheme, each user is assigned $m_k=2^r$ code matrices to represent m_k symbols, corresponding to the transmission of r data bits per symbol^(8,11). That is, every r serial data bits are mapped into one symbol, and each symbol is transmitted with one of the assigned m_k code matrices. Thus, the data bit rate of the scheme becomes $R_{MK} = (\log_2 \lfloor 2^r \rfloor) \times R$

Table 1. Code Matrices of $(5 \times 5, 5, 0, \lambda_c=1)$ 2-D MPC and Its Time-Shifted Copies⁽¹²⁾

Level 1					
τ	$i_1=0$	$i_1=1$	$i_1=2$	$i_1=3$	$i_1=4$
0	(0,0,0,0,0)	(0,1,2,3,4)	(0,2,4,1,3)	(0,3,1,4,2)	(0,4,3,2,1)
1	(1,1,1,1,1)	(1,2,3,4,0)	(1,3,0,2,4)	(1,4,2,0,3)	(1,0,4,3,2)
2	(2,2,2,2,2)	(2,3,4,0,1)	(2,4,1,3,0)	(2,0,3,1,4)	(2,1,0,4,3)
3	(3,3,3,3,3)	(3,4,0,1,2)	(3,0,2,4,1)	(3,1,4,2,0)	(3,2,1,0,4)
4	(4,4,4,4,4)	(4,0,1,2,3)	(4,1,3,0,2)	(4,2,0,3,1)	(4,3,2,1,0)

$= rR$ ^(8,11), where $\lfloor \cdot \rfloor$ is the floor function. For example, the code matrix C_4 (i.e., $(0,4,3,2,1)$) and its three time-shifted copies (e.g., $(1,0,4,3,2)$, $(2,1,0,4,3)$, and $(3,2,1,0,4)$), shown in Table 1, are assigned to the user for $m_k=2^2=4$ multicode keying transmission, thus the data bit rate of the scheme becomes $R_{MK} = (\log_2 \lfloor 4 \rfloor) \times R = 2R$.

2.4 Pulse Position Modulation Scheme^(9,10,14)

Unlike MC or MK scheme, each user is only assigned one district code matrix in the PPM scheme, but the code matrix is located entirely in one of the $m_p=2^s$ PPM frames to represent the corresponding symbol, based on every transmitted s data bits^(9,10,14), where $m_p=2^s$ is the number of PPM frames. Thus, the data bit rate of the scheme becomes $R_{PPM} = (\log_2 \lfloor 2^s \rfloor / 2^s) \times R = sR/2^s$ ^(9,10,14). For example, the code matrix C_1 (i.e., $(0,1,2,3,4)$) is assigned to the user for $m_p=4$ PPM transmission. Then, the code matrix C_1 is placed into one of the $m_p=4$ PPM frames to represent one of $m_p=4$ symbols, based on every $s=2$ data bits, thus the data bit rate of the scheme becomes $R_{PPM} = 2R/2^2 = R/2$.

In summary, the above-mentioned three schemes can support the multi-rate transmission requirements by simply varying the number of the transmitted code matrices at the same time (i.e., m_c) for MC scheme, the number of bits per symbol (i.e., $\log_2 \lfloor m_k \rfloor$) for MK scheme, and the number of PPM frames (i.e., m_p) for PPM scheme, respectively.

3. Numerical Examples

In this section, we mainly focus on the effect of multiple access interference (MAI) to system performance, and any physical noise, such as thermal noise, beat noise and shot noise are neglected^(5,8,11,12). It is because a practical O-CDMA system should always perform with optical power above the noise level⁽¹¹⁾. Moreover, the use of $(w \times p, w, \lambda_a=0, \lambda_c=1)$ 2-D MPC briefly introduced in Section 2.1 is here assumed for the following numerical examples.

3.1 Multiple Code Scheme

The bit error probability of the MC scheme with the use of $(w \times p, w, 0, 1)$ MPC for m_c multiple code transmission is

given by⁽¹¹⁾

$$P_{e,MC}(K) = \frac{1}{2} \sum_{i=0}^w (-1)^{w-i} \binom{w}{i} \left[q_0 + q_1 \frac{i}{w} \right]^{Km_c-1-h} \quad (2)$$

where K denotes the number of simultaneous users in the MC scheme and the effective number of interfering users is reduced to Km_c-1-h and $h=m_c-1$ due to the use of m_c time-shifted copies which have $\lambda_c=0$. Moreover, q_j denotes the probability of getting j hits in a time slot, out of $\lambda_c=1$ possible hits, $j \in [0, 1]$, and are given by^(11,12)

$$q_1 = \frac{w}{2p} \quad (3)$$

$$q_0 = 1 - q_1 = 1 - \frac{w}{2p}, \quad (4)$$

respectively.

3.2 Multicode Keying Scheme

The bit error probability of the MK scheme with the use of $(w \times p, w, 0, 1)$ MPC for m_k multicode keying transmission is given by^(8,11)

$$P_{e,MK}(K) = \frac{m_k}{2(m_k-1)} \left[1 - \sum_{t=0}^{m_k-1} \frac{1}{t+1} P_r(w, t) \right] \quad (5)$$

where K denotes the number of simultaneous users in the MK scheme, and $P_r(w, t)$ represents the probability that t decoders have an output intensity level of at least w and m_k-1-t decoders have an output intensity level less than w and is given by^(8,11)

$$P_r(w, t) = \binom{m_k-1}{t} [P_r(w)]^t \left[\sum_{v=0}^{w-1} P_r(v) \right]^{m_k-1-t} \quad (6)$$

where $P_r(v)$ denotes the probability of having a peak of v appearing at any one of m_k-1 wrong decoder in the desired user and is obtained by^(8,11)

$$P_r(v) = \binom{w}{v} \sum_{i=0}^v (-1)^i \binom{v}{i} \left[q_0 + q_1 \frac{v-i}{w} \right]^{K-1} \quad (7)$$

where the hit probabilities become $q_1=w/p$ and $q_0=1-w/p$ ⁽¹¹⁾, respectively, because of continuous symbol transmission, such that the factor $1/2$ is not need in MK scheme.

3.3 Pulse Position Modulation Scheme

The bit error probability of the PPM scheme using $(w \times p, w, 0, 1)$ MPC for m_p PPM transmission is modified from^(9,10,14) as

$$P_{e,PPM}(K) = \frac{m_p}{2(m_p-1)} \left[(m_p-1) \sum_{i=0}^w (-1)^i \binom{w}{i} \left[1 - \frac{(i+w)w}{m_p wp} \right]^{K-1} - \binom{m_p-1}{2} \left[\frac{(K-1)w}{m_p wp} \right]^{2w} \right] \quad (8)$$

Fig. 1. Bit error probability $P_{e,MC}(K)$ of $(10 \times 43, 10, 0, \lambda_c=1)$ MPC in MC scheme versus the number of simultaneous users K , where $m_c = \{1, 2, 4, 8\}$.

Fig. 2. Bit error probability $P_{e,MK}(K)$ of $(10 \times 43, 10, 0, \lambda_c=1)$ MPC in MK scheme versus the number of simultaneous users K , where $m_k = \{2, 4, 8, 16\}$.

where K denotes the number of simultaneous users in the PPM scheme.

3.4 Normalized Spectral Efficiency^(8,11)

In addition to the bit error probability, the another figure of merit, NSE, which considers the normalized data rate R_b (i.e., set the basic bit transmission rate $R=1$), number of available wavelengths L , number of time slots N , and the number of simultaneous users K as a whole, is used to fairly compare the three schemes and is given by^(8,11)

$$NSE = \frac{KR_b}{LN} \quad (9)$$

The goal is to obtain the NSE as large as possible for better spectral efficiency or utilization.

In Fig. 1, the bit error probabilities $P_{e,MC}(K)$ of the MC

Fig. 3. Bit error probability $P_{e,PPM}(K)$ of $(5 \times 13, 5, 0, \lambda_c=1)$ MPC in PPM scheme versus the number of simultaneous users K , where $m_p=\{4, 8, 16\}$.

scheme with $(10 \times 43, 10, 0, \lambda_c=1)$ MPC, from (2), are plotted as a function of the number of simultaneous users K , where $m_c=\{1, 2, 4, 8\}$. In general, the bit error probability gets worse as K or m_c increases, because there are more interfering code matrices which result in the effect of MAI, but the data bit rate of the MC scheme also increases as m_c increases. That is, the MC scheme provides a trade-off between the system performance and data bit rate. Note that the dot-dashed curve with $m_c=1$ shows the performance of the OOK scheme, which agrees to ^{(11,eq. (12))}. Also plotted in the figure are the computer-simulation results, which match closely with the theoretical results.

Fig. 2 shows the bit error probabilities $P_{e,MK}(K)$, from (5)-(7), of $(10 \times 43, 10, 0, \lambda_c=1)$ MPC in MK scheme versus the number of simultaneous users K , where $m_k=\{2, 4, 8, 16\}$. Similarly, the bit error probability gets worse as K or m_k increases, because there are more interfering code matrices, and there are more data bits to be decided incorrectly if a symbol detection error occurs. However, the MK scheme also can support the multi-rate transmission requirements by simply varying the number of bits per symbol (i.e., $=\log_2 \lfloor m_k \rfloor$).

In Fig. 3, the bit error probabilities $P_{e,PPM}(K)$ of the PPM scheme using $(5 \times 13, 5, 0, \lambda_c=1)$ MPC, from (8), are plotted against the number of simultaneous users K , where $m_p=\{4, 8, 16\}$. The bit error probability gets worse as K increases but improves with m_p . It is because the hit probability will be reduced as the number of PPM frames (i.e., m_p) increases. In other words, the PPM scheme can mainly provide the better performance at the expense of the data bit rate and increased bandwidth. Again, both Figs. 2 and 3 also show the computer-simulation results, which match closely

Fig. 4. Bit error probabilities of MC, MK and PPM schemes versus the number of simultaneous users K , with $(10 \times 67, 10, 0, \lambda_c=1)$ MPC, where $m_c=m_k=m_p=4$.

Table 2. Comparison of NSE for Three Schemes under Bit Error Probability $P_e=10^{-9(8,11)}$.

$P_e=10^{-9}$	K		R_b	L	N	NSE
MC	6	$m_c=4$	4	10	67	0.0358
MK	14	$m_k=4$	2	10	67	0.0418
PPM	43	$m_p=4$	1/2	10	67	0.0321

with the theoretical results.

Shown in Fig. 4 are the bit error probabilities P_e versus the number of simultaneous users K plots of the MC, MK and PPM schemes with $(10 \times 67, 10, 0, \lambda_c=1)$ MPC, where $m_c=m_k=m_p=4$. Considering $P_e \approx 10^{-9(8,11)}$, from the figure, we can also get the number of simultaneous users $K=6$ for the MC scheme, $K=14$ for the MK scheme, and $K=43$ for PPM scheme, respectively. Based on (9) and the data bit rate R_b of three schemes, we then obtain $NSE=6 \times 4 / (10 \times 67)=0.0358$ for the MC scheme, $NSE=14 \times 2 / (10 \times 67)=0.0418$ for the MK scheme, and $NSE=43 \times (1/2) / (10 \times 67)=0.0321$ for the PPM scheme, respectively.

Table 2 compares the NSEs of three schemes, based on Fig. 4. From the table, we can find that the MK scheme can provide the best spectral efficiency among these three schemes. On the other hand, from Fig. 4 and Table 2, we also can know that the PPM scheme can provide the best system performance among these three schemes, but the data bit rate of the PPM scheme is lower than those of the other two schemes. In other words, the PPM scheme provides the better performance at the expense of the data bit rate and increased bandwidth.

4. Conclusions

In this paper, the three common modulation schemes (i.e., MC, MK and PPM schemes) which can support the different data rate and QoS transmission requirements for O-CDMA systems by simply varying the parameters of m_c , m_k and m_p are introduced and studied. Moreover, not only the performance but also the NSE of three schemes are also analyzed and compared to determine which scheme should be used under certain conditions. Our results show that the MK scheme always has a better NSE than other two schemes, but PPM scheme can provide the best system performance at the expense of the data bit rate or the increased bandwidth. Therefore, if system performance is more important than the spectral efficiency or data bit rate, one should use the PPM scheme. If the spectral efficiency is more important, one should use the MK scheme. That is, there is a trade-off between the system performance, data bit rate and spectral efficiency.

Acknowledgment

This work was supported by the Ministry of Science and Technology of Republic of China under Grant MOST 103-2221-E-239-009.

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