MAI and MI Performance of the Orthogonal Complementary Code Based DS-BPAM UWB System

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Abstract—**In this paper, we investigate the performance of the orthogonal complementary code (OCC) based direct sequence ultra wideband (DS-UWB) system. OCC has perfect partial autocorrelation and cross-correlation characteristics. With the application of OCC in DS-UWB system, we can offer multiple access interference (MAI) free operation in both synchronous and asynchronous transmissions over MAI-AWGN channel. Theoretical analysis illustrates that multipath interference (MI) as well as MAI can be also mitigated over lognormal multipath fading channels in OCC based DS-UWB system. Our simulation also shows the superiority of the OCC based DS-UWB to unitary code based system.**

Keywords- ultra-wide band (UWB); orthogonal complementary code (OCC); multiple access interference (MAI); multipath interference (MI)

I. Introduction

Ultra-wideband (UWB) technology was proposed in 1960s and has drawn much more attentions in recent years. Federal Communication Commission (FCC) has regulated that the band allocated for UWB is 7.5GHz, from 3.1GHz to 10.6GHz. UWB technology has many merits such as high data rate, low cost, low power spectrum density and good resistance to severe multipath interference, etc. Thus, it has been an attractive technology for short-range high speed wireless communications. There are two main kinds of multi-access technology for UWB system, the time-hopping (TH) spread spectrum (SS) system and the direct-sequence (DS) SS system. For its inherent characteristics, DS-UWB system where the information symbols are transmitted by dense pulse train becomes an important candidate for wireless personal area networks (WPANs) to resist multiple access interference (MAI) in UWB system.

In DS-UWB system, MAI is an important factor that affects the system performance with the increase of the user number. Some basic studies on multiple access performance analysis of DS-UWB system have been done in [1]-[3]. [4] investigated the influence of the different spreading sequences on asynchronous DS-UWB system. However, the spreading codes studied in [4] are all unitary codes, such as i.i.d, Gold and Kasami sequences. [5] proposed ternary complementary sets based UWB system which could alleviate MI and MAI. It is interesting and necessary to optimize the performance of DS-UWB system with good spreading codes.

As we know, the system performance can be improved significantly if the correlation characteristics of the spreading codes are perfect, that is, the side lobes of auto-correlation functions and the cross correlation functions are all zeros. It is proved that unitary codes with perfect correlation properties do not exist. With this view, complete complementary (CC) code whose partial autocorrelation function (PAF) is zero for all shifts except for zero shift and whose partial cross-correlation function (PCF) for any pair is zero for all shifts is proposed in [6]-[9]. CC code is a kind of orthogonal complementary code. Other orthogonal complementary codes (super complementary code and perfect orthogonal complementary code) have the properties of CC code [10]. OCC has been widely used in CDMA system because of its perfect correlation properties. In this paper, we propose a OCC based DS-UWB system and analyze the BER performance over lognormal multipath fading channel. Simulation results demonstrate that the OCC based DS-UWB system is significantly superior to unitary code based system both in AWGN and multipath channel.

This paper is organized as follows. In section II, CC code and its correlation properties are presented. Section III presents the system model and channel model. Based on the system signal processing, we analyze the performance of OCC based UWB system over multipath channel in section IV. Simulation results about the system performance of MAI are illustrated in section V. At last, we concluded this paper in section VI.

II. Complete Complementary Code and Correlation Characteristics

A. Complete Complemenrtary Code

We use the notation $\{K, M, N\}$ to characterize an orthogonal complementary spreading code set. K is set size, M is flock size, and N is the element code length. And K is equal to M. Assume that we have two flocks in a set, i.e.,

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$\boldsymbol{x}=\{\boldsymbol{x_1},\boldsymbol{x_2},...,\boldsymbol{x_M}\}$ and $\boldsymbol{y}=\{\boldsymbol{y_1},\boldsymbol{y_2},...,\boldsymbol{y_M}\}$, where $\boldsymbol{x_i}=\{x_{i1},x_{i2},..., x_{iN}\}$, $\boldsymbol{y_i}=\{y_{i1},y_{i2},...,y_{iN}\}$ for $1\le i\le M$, and x_{ij}, y_{ij} ($1\le i\le M$, $1\le j\le N$) take values from $\{\pm 1\}$.

The partial autocorrelation function for sequence $\boldsymbol{x_i}$ can be defined as,

$$\rho(\boldsymbol{x}_i;l)=\begin{cases}\sum_{j=1}^{N-l} x_{ij}x_{i,j+l} & l=0,1,\cdots N-1\\ \sum_{j=1-l}^{N} x_{ij}x_{i,j+l} & l=-1,\cdots,-N+1\end{cases}, \quad (1)$$

where l is the relative chip shift of autocorrelation function.

Similarly, the partial cross-correlation function between $\boldsymbol{x_i}$ and $\boldsymbol{y_i}$ can be defined as follows,

$$\rho(\boldsymbol{x}_i,\boldsymbol{y}_i;l)=\begin{cases}\sum_{j=1-l}^{N} x_{ij}y_{i,j+l} & l=-1,\cdots,-N+1\\ \sum_{j=1}^{N-l} x_{ij}y_{i,j+l} & l=0,1,\cdots N-1\end{cases}, \quad (2)$$

where l is the relative chip shift of cross-correlation function.

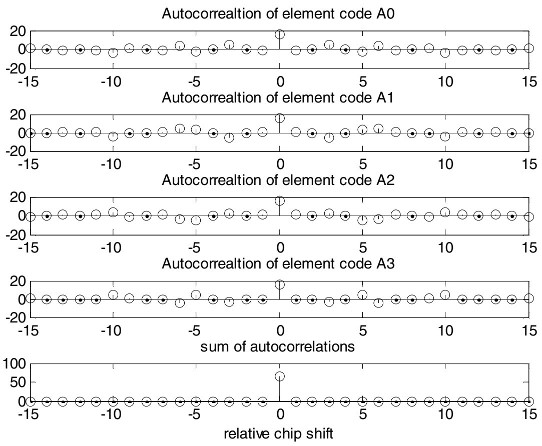

Figure 1 Each autocorrelation and the sum of autocorrelations for OCC

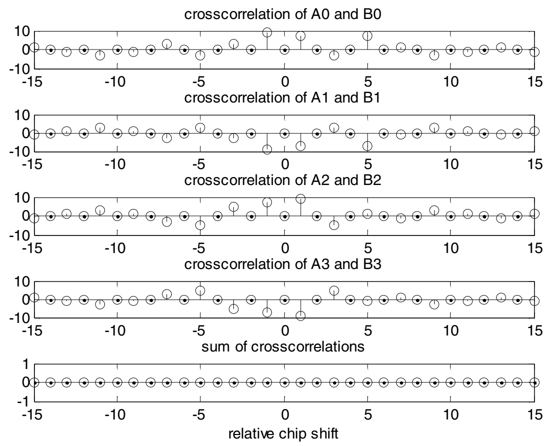

Figure 2 Each cross-correlation and the sum of cross-correlations for OCC

K sets of M sequences $\{\boldsymbol{C^1}, \boldsymbol{C^2}, \ldots, \boldsymbol{C^K}\}$ with $\boldsymbol{C^i}=\left\{\boldsymbol{c_1^i},\boldsymbol{c_2^i},...,\boldsymbol{c_m^i},...,\boldsymbol{c_M^i}\right\}$ ($1\leqslant i\leqslant k$) being the *ith* flock and $\boldsymbol{c_m^i}=\left\{c_{m,1}^i,c_{m,2}^i,\cdots,c_{m,N}^i\right\}$ ($1\leqslant m\leqslant M$) denoting the *mth* element code in the *ith* flock are called a "complete complementary (CC) code of order K" if the sum of M partial autocorrelation functions is zero for any shift except the zero shift and the sum of M partial cross-correlation functions between the corresponding element codes of distinct sets chosen from the K sets is zero for any shift (including the zero shift) [9],

$$\begin{cases}\sum_{m=1}^{M}\rho(\boldsymbol{c_m^i};l)=0, & for \quad l\neq 0, \quad i=1,2,\cdots,M\\ \sum_{m=1}^{M}\rho(\boldsymbol{c_m^i},\boldsymbol{c_m^j};l)=0, & for \quad any\,l, \quad i\neq j, \quad i,j=1,2,\cdots,M\end{cases}. \quad (3)$$

Complete complementary code is a kind of orthogonal complementary code. Other orthogonal complementary codes all satisfy (3).

B. Correlation Characteristics

In this subsection, two flocks of an OCC set are taken as an example to illustrate the perfect partial correlation properties [11]. Figure 1 shows the autocorrelation of each element code of a flock and the sum of their autocorrelations. It can be seen that the correlation of each element code is not so good, but the sum is a delta function $\delta(t)$. Similarly, owing to the complementation of element codes, the sum of the cross correlations is null as depicted in Figure 2.

III. SYSTEM MODEL AND CHANNEL MODEL

We consider a DS-UWB system supporting K users. $\{C^1, C^2, \ldots, C^K\}$ is a orthogonal complementary code set which works on a flock per user basis, $C^k=\{c_0^k,c_1^k,\cdots,c_i^k,\cdots,c_{M-1}^k\}$ $(1\le k\le K)$ is the *kth* flock in the set , and $c_i^k=\{c_{i0}^k,c_{i1}^k,\cdots,c_{ij}^k,\cdots,c_{iN-1}^k\}$ $(0\le i\le M-1)$ is the *ith* element code in the *kth* flock. Each user is assigned one flock as DS code. As has been stated that, one flock contains M element codes, however, M element codes of a user can not be transmitted together. A kind of transmission way must be adopted to distinguish M element codes. In this paper, we employ time to differentiate M element codes of a flock, i.e., we send spreading sequences serially in time. Thus, the *kth* flock of the complementary code set is modified to $C_{ZCZ}^k=\{c_0^k,\underbrace{0,\cdots 0}_{\gamma+1},c_1^k,\underbrace{0,\cdots,0}_{\gamma+1},\cdots,c_{M-1}^k,\underbrace{0,\cdots,0}_{\gamma+1}\}$ as the spreading sequence of the *kth* user. We add zeros to distinguish M element codes.

The number of zeros ($\gamma+1$) between c_i^k and c_{i+1}^k is relevant to maximum delay. We assume that the maximum delay is $\tau=\gamma T_c+\alpha$, $\gamma=\lfloor\tau/T_c\rfloor$. α is a random variable uniformly distributed over $[0,T_c]$. T_c is the chip duration. To guarantee complementation of element codes in an orthogonal complementary code set, the number of zeros between element codes must be (γ+1). If the maximum delay is more than a flock duration (NT_c), the number of zeros is N.

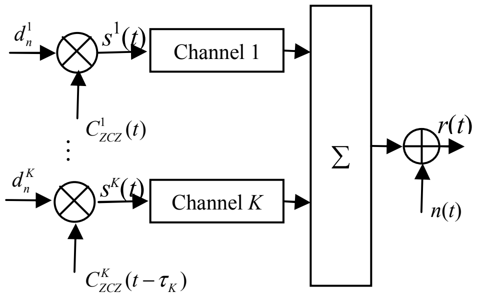

Figure 3 OCC based DS-BPAM UWB system

A. System Model

The asynchronous DS-BPAM UWB system is shown in Figure 3. The mathematical expressions of DS BPAM UWB signals are given by,

$$s^k(t)=\sqrt{\frac{E_{bT}}{MN}}\sum_{n=-\infty}^{\infty}\sum_{i=0}^{M-1}\sum_{j=0}^{N-1}d_n^k c_{ij}^k w\left(t-nT_b-iT-jT_c\right), \quad (4)$$

where M and N are flock size and element code length of orthogonal complementary code set respectively. $\sqrt{E_{bT}/MN}$ is normalization factor and $w(t)$ is pulse waveform. The pulse duration T_w is far less than chip duration T_c. $d_{n0}^k\in\{0,1\}$ is the *nth* information bit transmitted by the *kth* user and $d_n^k=2d_{n0}^k-1$ is the modulated signal with bipolar pulse amplitude modulation (BPAM). c_{ij}^k denotes the *jth* chip of *ith* element code of *kth* user, which also takes values from {±1}. $T=(N+\gamma+1)\cdot T_c$ denotes the duration of a flock. $T_b=MT$ is the duration of a symbol.

B. UWB Channel Model

The channel impulse response of the *kth* user is modeled as,

$$h^k(t)=\sum_{l=0}^{L-1}\alpha_{k,l}\delta\left(t-\tau_{k,l}\right), \quad (5)$$

where L is the number of resolvable multipath components, $\alpha_{k,l}=\theta_{k,l}\beta_{k,l}$ represents the *lth* path gain. The parameter $\theta_{k,l}\in\{\pm1\}$ with equal probability is used to account for the random phase because of reflection and $\beta_{k,l}$ is the lognormal fading amplitude. $\tau_{k,l}$ is the *lth* delay, it can be described by the delay of the cluster and the delay of the ray relative to the cluster.

IV. System Performance Analysis

The received signal is given by,

$$r(t)=\sum_{k=1}^{K}\sum_{l=0}^{L-1}\alpha_{k,l}s^k(t-\tau_k-\tau_{k,l})+n(t), \quad (6)$$

where τ_k is the asynchronous delay of the *kth* user uniformly distributed over [0, NT_c], $n(t)$ is AWGN with double sided power spectral density $N_0/2$.

The first user is assumed to be the desired user with perfect synchronization and the data bit d_0^1 is transmitted. To improve the link performance, selective Rake (SRake) receiver is considered in this paper. The template signal used in the $l'th$ branch of the SRake receiver is given by,

$$v_{l'}(t)=\alpha_{1,l'}\sum_{i=0}^{M-1}\sum_{j=0}^{N-1}c_{ij}^1 w\left(t-iT-jT_c-\tau_{1,l'}\right). \quad (7)$$

The statistic decision of the output of the $l'th$ correlator is given by,

$$Z_{l'}=S+I+M+N, \quad (8)$$

where S denotes the item of the desired signal, I is the self-interference (SI) item caused by multipath propagation, M and N are MAI and the noise term, respectively.

S is the contribution of the $l'th$ receiver from the desired user, which is expressed as,

$$S=\int_0^{T_b}\alpha_{1,l'}s^1(t-\tau_{1,l'})\cdot v_{l'}(t)dt=\alpha_{1,l'}^2 d_0^1\sqrt{E_{bT}MN}. \quad (9)$$

The noise term N is given by,

$$N=\int_0^{T_b}n(t)v_{l'}(t)dt. \quad (10)$$

A. Self Interference Evaluation

SI caused by the total multipath propagation is given by,

$$I=\int_0^{T_b}\sum_{l=0,l\neq l'}^{L-1}\alpha_{1,l}s^1(t-\tau_{1,l})\sum_{i=0}^{M-1}\sum_{j=0}^{N-1}\alpha_{1,l'}c_{ij}^1 w(t-iT-jT_c-\tau_{1,l'})dt$$
$$=\sum_{l=0,l\neq l'}^{L-1}I_l. \quad (11)$$

SI for the *lth* path is modeled as,

$$I_l=\int_0^{T_b}\alpha_{1,l}s^1(t-\tau_{1,l})\sum_{i=0}^{M-1}\sum_{j=0}^{N-1}\alpha_{1,l'}c_{ij}^1 w(t-iT-jT_c-\tau_{1,l'})dt. \quad (12)$$

If $\left|\tau_{1,l}-\tau_{1,l'}\right|<NT_c$ and $\tau_{1,l}-\tau_{1,l'}<0$, I_l can be rewritten as,

$$I_l=\sqrt{\frac{E_{bT}}{NM}}\alpha_{1,l'}\alpha_{1,l}d_0^1\left[\begin{array}{l}\sum_{i=0}^{M-1}\rho(c_i^1,c_i^1;\gamma_{ll'})\cdot F_w(\alpha_{ll'})\\+\sum_{i=0}^{M-1}\rho(c_i^1,c_i^1;\gamma_{ll'}+1)\cdot\hat{F}_w(\alpha_{ll'})\end{array}\right]. \quad (13)$$

If $\left|\tau_{1,l}-\tau_{1,l'}\right|<NT_c$ and $\tau_{1,l}-\tau_{1,l'}>0$, I_l can be expressed as,

$$I_l=\sqrt{\frac{E_{bT}}{NM}}\alpha_{1,l'}\alpha_{1,l}d_0^1\left[\begin{array}{l}\sum_{i=0}^{M-1}\rho(c_i^1,c_i^1;-\gamma_{ll'})\cdot R_w(\alpha_{ll'})\\+\sum_{i=0}^{M-1}\rho(c_i^1,c_i^1;-(\gamma_{ll'}+1))\cdot\hat{R}_w(\alpha_{ll'})\end{array}\right]. \quad (14)$$

Here, we will introduce the following ancillary. The relative multipath delay $\left|\tau_{1,l}-\tau_{1,l'}\right|$ can be written as,

$$\left|\tau_{1,l}-\tau_{1,l'}\right|=\gamma_{ll'}T_c+\alpha_{ll'}, \quad (15)$$

where $\gamma_{ll'}=\left\lfloor\left|\tau_{1,l}-\tau_{1,l'}\right|/T_c\right\rfloor$ and $\alpha_{ll'}$ is a random variable uniformly distributed over [0, T_c].

The template signal used in the $l^{'}th$ branch of SRake receiver may lags or be priors to the other paths. Thus, the autocorrelation functions of $w(t)$ are defined as,

$$F_w(s) = \begin{cases} \int_0^{T_c - s} w(t)w(t+s)dt & 0 \le s \le T_c \\ 0 & elsewhere \end{cases}, \quad (16)$$

$$\hat{F}_w(s) = \begin{cases} \int_{T_c - s}^{T_c} w(t)w(t - T_c + s)dt & 0 \le s \le T_c \\ 0 & elsewhere \end{cases}, \quad (17)$$

$$R_w(s) = \begin{cases} \int_0^{s} w(t)w(t + T_c - s)dt & 0 \le s \le T_c \\ 0 & elsewhere \end{cases}, \quad (18)$$

$$\hat{R}_w(s) = \begin{cases} \int_s^{T_c} w(t)w(t - s)dt & 0 \le s \le T_c \\ 0 & elsewhere \end{cases}. \quad (19)$$

According to the properties of OCC we can obtain I_l=0, that means, the partial SI can be eliminated.

B. Multiple Access Interference Evaluation

The sum of the signals from the other K-1 interfering users is denoted as M, which is given by,

$$M = \int_0^{T_b} \sum_{k=2}^{K} \sum_{l=0}^{L-1} \alpha_{k,l} s^k (t - \tau_k - \tau_{k,l}) v_{l^{'}}(t)dt = \sum_{k=2}^{K} \sum_{l=0}^{L-1} M_{k,l} \ . \quad (20)$$

The interference of the lth path from the kth user is described as,

$$M_{k,l} = \int_0^{T_b} \alpha_{k,l} s^k (t - \tau_k - \tau_{k,l}) \sum_{i=0}^{M-1} \sum_{j=0}^{N-1} \alpha_{1,l^{'}} c_{ij}^1 w(t - iT - jT_c - \tau_{1,l^{'}})dt \ . \quad (21)$$

Similarly, if $\left|\tau_k + \tau_{k,l} - \tau_{1,l^{'}}\right| < NT_c$ and $\tau_k + \tau_{k,l} - \tau_{1,l^{'}} < 0$, $M_{k,l}$ can be written as,

$$M_{k,l} = \sqrt{\frac{E_{bT}}{NM}} \alpha_{1,l^{'}} \alpha_{k,l} d_0^k \begin{bmatrix} \sum_{i=0}^{M-1} \rho(c_i^k, c_i^1; \gamma_{kll^{'}}) \cdot F_w(\alpha_{kll^{'}}) \\ + \sum_{i=0}^{M-1} \rho(c_i^k, c_i^1; \gamma_{kll^{'}} + 1) \cdot \hat{F}_w(\alpha_{kll^{'}}) \end{bmatrix} . \quad (22)$$

If $\left|\tau_k + \tau_{k,l} - \tau_{1,l^{'}}\right| < NT_c$ and $\tau_k + \tau_{k,l} - \tau_{1,l^{'}} > 0$, $M_{k,l}$ is rewritten as,

$$M_{k,l} = \sqrt{\frac{E_{bT}}{NM}} \alpha_{1,l^{'}} \alpha_{k,l} d_0^k \begin{bmatrix} \sum_{i=0}^{M-1} \rho\left(c_i^k, c_i^1; -\gamma_{kll^{'}}\right) R_w\left(\alpha_{kll^{'}}\right) \\ + \sum_{i=0}^{M-1} \rho\left(c_i^k, c_i^1; -\left(\gamma_{kll^{'}} + 1\right)\right) \cdot \hat{R}_w\left(\alpha_{kll^{'}}\right) \end{bmatrix} . \quad (23)$$

where τ_k is the asynchronous transmission delay and $\left|\tau_k + \tau_{k,l} - \tau_{1,l^{'}}\right| = \gamma_{kll^{'}} T_c + \alpha_{kll^{'}}$. $\gamma_{kll^{'}}$ and $\alpha_{kll^{'}}$ are similar to $\gamma_{ll^{'}}$ and $\alpha_{ll^{'}}$, respectively.

According to the characteristics of OCC, we have $M_{k,l}$=0, that is, the partial MAI can be eliminated in this OCC based DS-UWB system.

From aforementioned theoretical analysis, we can see that both the multipath interference and the multiple access interference can be alleviated in DS-UWB system due to the perfect correlation properties of the orthogonal complementary code.

V. SIMULATION RESULTS

In this section, we present the simulation results of the OCC based DS-BPAM UWB system under AWGN and IEEE 802.15.3a CM1 channel. The transmitted pulse can be modeled as second order Gaussian monocycle with $w(t) = \left[1 - 4\pi\left(\frac{t}{\tau_m}\right)^2\right] \exp\left[-2\pi\left(\frac{t}{\tau_m}\right)^2\right]$, where τ_m=0.2ns, T_w=0.5ns. At the receiver end, the SRake receiver with 6 fingers is employed.

Figure 4 shows the performance for the bit error rate (BER) in AWGN channel. The length of each element code of OCC set is 8. The length of m sequence and Walsh code are 63 and 64, respectively. In case of four users scenario, it is observed that OCC based DS-UWB system is superior to the unitary code based systems. And one of the most interesting phenomena for the studied system is that it can achieve almost the theoretic BER performance, which shows that the OCC based UWB system can offer MAI-free performance over AWGN channel.

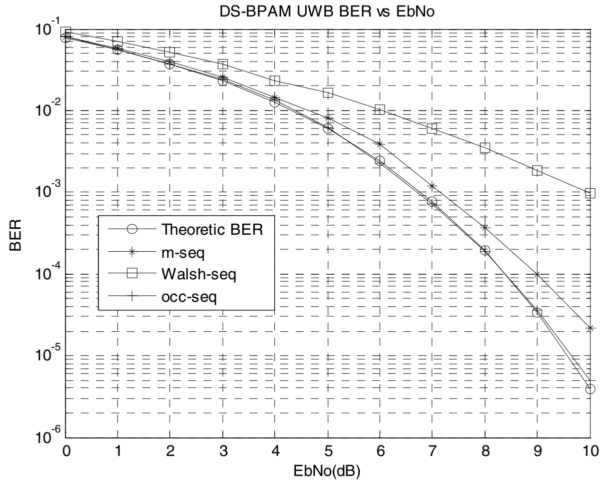

Figure 4 BER performance of the OCC based DS-BPAM UWB system over AWGN channel (4 users)

The BER performance under IEEE 802.15.3a CM1 channel is shown in Figure 5. In single user case, it is seen that the OCC based system performs better than the m sequence and the Walsh code, especially at high SNRs. The OCC based system can obtain about 3.0dB gains when BER is 10^{-3} compared to Walsh code based system. We can also see from Figure 6 that the UWB system with m sequence and Walsh code suffer more severe interference than OCC based system due to the fact that the orthogonality among either the m sequence or Walsh code is destroyed by asynchronous transmission. The simulation results show that the multiple access interference and multipath interference mitigation depends much on the selection of the spreading sequence.

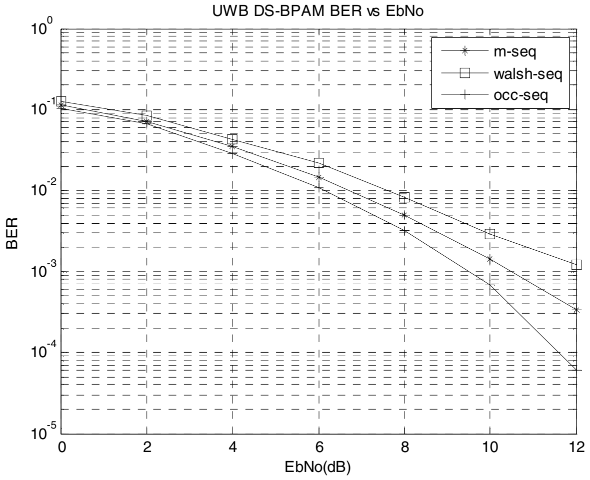

Figure 5 BER performance of the OCC based DS-BPAM UWB system over CM1 channel (single user)

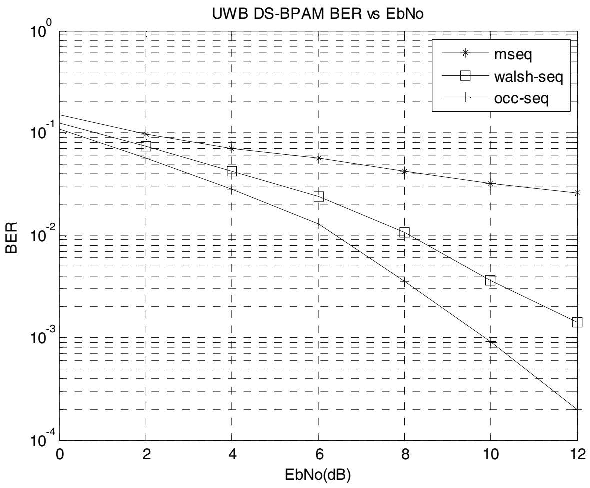

Figure 6 BER performance of the OCC based DS-BPAM UWB system over CM1 channel (4 users)

VI. CONCLUSIONS

In this paper, OCC based UWB system is presented, and its performance is analyzed in AWGN and multipath channel. Simulation results show that the proposed system can offer MAI-free performance in asynchronous AWGN channel. And the MAI as well as MI can be alleviated over multipath channel because of the perfect correlation properties of OCC. OCC based DS-UWB system achieves better performance than the unitary code based system, especially in the asynchronous transmission.

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