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MAI Cancellation in MCCDMA Systems Using OCC Codes and Adaptive Constellations

[1]G. Senthilkumar and [2]R. Amutha
[1]Department of Electronics and Communication Engineering, Sri Chandrasekharemdra Saraswathi Viswa Mahavidyalya University, Enathur, Kanchipuram, 631561, Tamil Nadu, India
[2]Department of Electronics and Communication Engineering, SSN College of Engineering, Chennai, India

Corresponding Author: G. Senthilkumar, Department of Electronics and Communication Engineering, Sri Chandrasekharemdra Saraswathi Viswa Mahavidyalya University, Enathur, Kanchipuram, 631561, Tamil Nadu, India

ABSTRACT

The Multi-Carrier Code Division Multiple Access (MC-CDMA) is a strong candidate for the future wireless systems to provide high speed packet data and multimedia streaming services. The MCCDMA faces the problem from Multiple Access Interference (MAI) due to failure of orthogonality among the users under the frequency-selective fading channels and multipath effects. In this study, the MCCDMA system is developed by joining with Space-Time Block Coding (STBC) scheme and Multi Input Multi Output (MIMO) scheme for capacity enhancement. Along with STBC and MIMO schemes, Orthogonal Complete Complementary (OCC) spreading codes with suitable cross-correlation properties determine the interference-resist capability as well as spectral efficiency. Further, the mitigation of MAI in MCCDMA systems is approached in different way to minimize the error rates and to improve the spectral efficiency. The constellation movement scheme is proposed for Quadrature Amplitude Modulation (QAM) signal set where the constellation of one of the users is moved relative to the other by an angle chosen adaptively according to the channel conditions which causes MAI in order to satisfy minimum distance threshold at the detectors. The simulation result shows that the developed MCCDMA system achieves significant performance improvement in terms of Bit Error Rate (BER) and spectral efficiency compared to MCCDMA systems with Wash and Gold spreading codes. It also shows that the proposed constellation movement scheme combats MAI further and achieves a significant improvement in user capacity.

Key words: Multicarrier code division multiple access, multiple access interference, orthogonal complete complementary codes, channel states, adaptive constellations, capacity enhancement

INTRODUCTION

With increasing requirements on current wireless systems put forth by high-speed packet data and multimedia applications, capacity enhancement techniques has captivated researchers in recent years. MCCDMA systems have emerged as a powerful candidate to wireless communication systems. Among its many advantages, it is worth mentioning the high spectral efficiency deriving from the use of Orthogonal Frequency Division Multiplexing (OFDM) and the capability of collecting the received signal energy scattered in the frequency domain which results into a remarkable frequency diversity gain to mitigate fading effect (Hara and Prasad, 1999). In a

MCCDMA system, the user's data are spread in the frequency domain using orthogonal spreading codes. After passing through a frequency selective channel, however, the received codes are no longer orthogonal due to non ideal correlation properties of spreading codes and MAI will arise (Fazel and Kaiser, 2008).

Interference mitigation is traditionally accomplished at the receiver side by resorting to well known multiuser detection schemes (Verdu, 1998). Due to heavy processing load as number of users increases, these schemes may be unfamiliar. Interference suppression is achieved by selecting user codes that convert the multipath environment into a frequency-flat fading channel (Scaglione *et al.*, 2000). The price to pay is a loss of the diversity gain which can be partially recovered by means of a power control procedure or assigning multiple codes to each user. This motivates well the methods to increase the diversity gain as well as choice of MAI-free spreading codes for multiple access through frequency selective fading channels.

As an effective method to increase the diversity gain and combat the effects of fading, transmit diversity has been studied extensively in the past. The STBC provides full diversity gain as well as full rate and does not sacrifice bandwidth efficiency (Alamouti, 1998). Space-Time (ST) coding based MIMO systems have emerged as an extremely important enabling technology for 4G wireless to offer substantially improved detection efficiency and system throughput by exploiting its unique spatial diversity gain and spatial multiplexing capability without consuming extra spectrum (El-Hajjar and Hanzo, 2010). Many works have been reported in the literature to discuss the issues on design and applications of different types of spreading codes, whose correlation properties can be exploited to mitigate interferences such as Multipath Interference (MI) and MAI. The code scheme based on the complementary code was proposed to design an MAI-free CDMA system in a flat fading channel (Chen *et al.*, 2006). This scheme can achieve higher spectrum efficiency using offset stacked spreading modulation than conventional CDMA system (Chen *et al.*, 2001). In order to exploit the maximum possible channel diversity and totally remove the MAI effect, MCCDMA system using OCC codes is developed for capacity enhancement based on the discussion in this study by combining those technologies (Alamouti, 1998; El-Hajjar and Hanzo, 2010; Chen *et al.*, 2001, 2006). The proposed system is more resistant to frequency-selective fading. The performance in terms of BER and spectral efficiency will be considered in this study, for a frequency-selective fading channel.

In a multipath environment, this scheme fails to remove MAI completely at particular channel conditions due to the fact that received signals from multi-paths add destructively causing multiuser interference which results in high error rates (Koike-Akino *et al.*, 2009). With increasing MAI, the transmission quality for all users worsens and the number of subscribers able to be facilitated (user capacity) is limited by a specified BER threshold. To overcome these propagation effects, channel estimation must be applied and compensate for it to reduce BER as the channel parameters varies randomly (Magana *et al.*, 2007). Adaptive modulation schemes have been proposed earlier which vary various transmission parameters according to existing channel conditions to minimize the error rates (Chung and Goldsmith, 2001). The QAM constellations are designed and the constellation size adapted according to the channel conditions for improved error performance (Goldsmith and Chua, 1997). Adaptive loading algorithms for OFDM system with imperfect Channel State Information (CSI) are proposed (Ye *et al.*, 2006). All these schemes applied only for non multi access setup and it requires perfect CSI at the transmitter. The perfect CSI at the transmitter is not easily feasible, as it would require additional processing for feedback. To overcome this detrimental effect of MAI, the constellation movement technique is proposed for 4-QAM signal set without varying the transmit power where the constellation of one of the users is moved relative to the other by an angle chosen adaptively according to the channel conditions in order to satisfy minimum distance threshold at the detector. For this purpose, only a quantized detail of the ratio of the individual channel gains (channel state) is required at the users such that the associated overhead is nominal compared to perfect CSI at the users.

SYSTEM DESCRIPTION

Figure1 illustrates a simplified transceiver structure of MCCDMA system model. The signal spectrum is modulated by an OCC code set which is unique for each user. The flock of M element codes, $\{c_{k,1}, c_{k,2}, .., c_{k,M}\}$ are allocated to K users. Each element code $c_{k,m}$ consists of N chips where k∈(1,K) and m∈(1,M). The information symbols which are typically coming from the outputs of data source are first space-time block-encoded into P parallel independent symbol streams. Based on the Alamouti STBC algorithm (Alamouti, 1998), an encoded signal block for the mth element code of the kth user in this MCCDMA system can be written as:

$$S_{1,k,m} = (b_{1,o}\, C_{o\, k,m} + b_{1,e}\, C_{e\, k,m}) \tag{1}$$

$$S_{2,k,m} = (b_{1,e}\, C_{o\, k,m} + b_{1,o}\, C_{e\, k,m}) \tag{2}$$

The P parallel symbol streams are fed into OCC encoding module that consists of M OCC encoding branches, each of which has P OCC slices (Chen *et al.*, 2006). There are in total upto M replicas of P parallel symbol streams encoded by different OCC code sets to implement diversity order of P and parallel transmission order of M. Therefore, the family size of the OCC must be at least MP.

This MCCDMA combines its OCC spread-coded bits together using offset stacked modulator (Chen *et al.*, 2001). This modulator improves the spectral efficiency which is defined in unit of bit(s) per chip to measure the bandwidth efficiency. The spreading modulator used by every user in which the input data stream is from the kth user $b_k = (b_{k1}, b_{k2}, .. b_{kj} ..,)$. The input bit sequence of each user is spread with the corresponding element code $c_{km} = (c_{1km}, c_{2km} \dots c_{Nkm})$. Also, each information bit is shifted by one chip relative to one another and then added. The OCC encoding output from user k is expressed as:

$$d_{K,m}(t) = \sum\nolimits_{i=0}^{\infty} \sum\nolimits_{n=0}^{N-1} b_{K,i} C_{m,n} \quad C_{m,n} \Pi \frac{\left(t - \left(i + n + \frac{1}{2}\right)\right)}{Tc} \times \Pi \frac{\left(t - \left(\frac{T}{2}\right) - iTc\right)}{T} \tag{3}$$

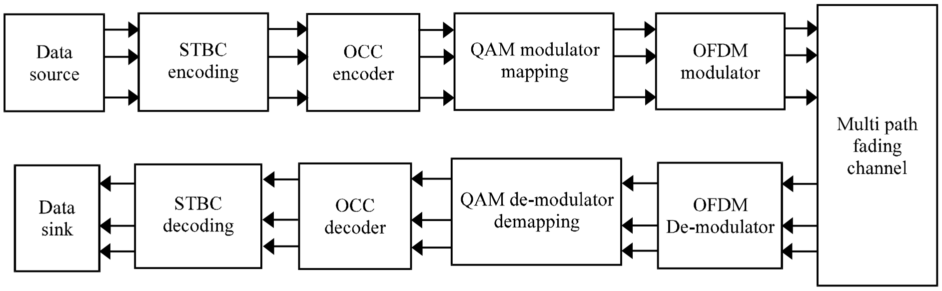

Fig. 1: Simplified transceiver structure of MCCDMA system model

Where:

$$\Pi\left(\frac{t}{T\omega}\right)=\begin{cases}1, & t\in\left(-\frac{T\omega}{2},\frac{T\omega}{2}\right)\\ 0, & \text{otherwise}\end{cases} \tag{4}$$

where, $d_{K,m}(t)$ represents the mth OCC encoding output from user K, $b_{K,i}$ denotes the ith information bit from user K, $C_{m,n}$ denotes the nth chip of the mth element code and T_c and T denote chip and bit duration, respectively. Then, each element code, c_{km} is carrier modulated with sub-carrier, fm. Thus, in effect, the user data information has been spread in both the time and frequency domains. The time domain spreading is carried out by each individual element code while the frequency spreading is fulfilled across different sub-carriers in different carrier frequencies. The two-dimensional spreading offers much more degrees-of-freedom to achieve orthogonality of the spreading codes in both the time and frequency domains.

To maintain good performance in the presence of fading, for the element code length of 'N' of the OCC code the offset stacked modulator is followed by a QAM map to transmit the L = (N-1) different levels in symbol duration for its robustness in detection efficiency. In the case of the downlink, the mth OCC encoding output is the sum of all OCC spread streams from all the users associated with the mth element code of each code family; for example, A_0, B_0, C_0 and D_0 belong to family 0. It is expressed as:

$$S_m(t)=\sum\nolimits_{k=0}^{M-1}, d_{K,m}(t) \tag{5}$$

where, M denotes the flock size, K = M = vN and $s_m(t)$ denotes the mth OCC code stream. Each transmitter will use M different sub-carriers to transmit M element codes and the whole MC-CDMA system will share the same M sub-carriers. The transmitter can be implemented using OFDM architecture for hardware implementation simplification. The sub-carriers carry the same data information but encoded by different element codes belonging to the same code flock. It is assumed to use only two antennas ($n_t = P = 2$) to achieve transmitter diversity. It is also assumed that signals from different antennas in a transmitter experience independent Rayleigh fading and Additive White Gaussian Noise (AWGN).

At a receiver, the received symbol streams should go through maximum ratio combining from M replicas to extract P parallel symbol streams (Meng *et al*., 2013). The carrier demodulation should be carried out first and then the correlation takes place between local sub-codes and the incoming signals in the M sub-channels and is given by:

$$\mathrm{Cor}_K(t)=\sum\nolimits_{m=0}^{M} r_K(t)\times C_{K,m}, \tag{6}$$

where, $r_K(t)\times C_{K,m}$ is the correlation between the received signal of user K and element code m of the flock assigned to the user K. M correlation outputs are then added together to obtain the decision variable. The receiver performs coherent decoding with perfect or estimated CSI. Then:

$$b_{K,i}(t)=\mathrm{sgn}(\mathrm{cor}_K(t)) \tag{7}$$

where, $b_{K,i}(t)$ denotes the ith demodulated information bit of user K and sgn(.) denotes signum function.

ORTHOGONAL COMPLETE COMPLEMENTARY (OCC) CODES

The OCC codes are kind of ideal orthogonal code and defined by three parameters, set size (K), flock size (M) and element code length (N) (Chen *et al.*, 2001). The OCC code consists of several sets of auto complementary codes, any two of which are cross complementary codes (Li and Huang, 2009). This can be constructed by using a vN-dimensional orthogonal matrix. The orthogonality of this code is based on its correlation functions which determine system robustness against the adverse effects of the channel and the division among users (Senthilkumar and Nagarajan, 2013). The Auto Correlation Function (ACF) of the OCC codes is zero for any shifts except zero shift which help to remove the delayed version of received signals due to multipath propagation and its Cross Correlation Function (CCF) is zero for any possible number of shifts which allow the receiver to remove undesired other user's signals. The correlation function of the OCC code is based on a group of element codes jointly. This implies that each user should use group of M element codes as its spreading code instead of a single code. The processing gain of OCC code is N.M = NvN since each symbol bit will be spread by the whole set of CC code sequences instead of a single sequence.

An example of OCC code: An example of OCC code set S (N = 4, M = 2, K = 2) is generated from a three 2×2 orthogonal matrices X, Y and Z (where semi-column ";" is used to separate different sub-codes) and given as follows X = [++; +-]; Y = [++; +-]; Z = [++; +-] ; then obtain the matrix E as [E1 = (++ +-); E2 = (++ -+)]based on X and Y. Then, E and Z are used to generate the orthogonal complete complementary code set, C [C11 = (++ +-); C12 = (+- ++); C21 = (++ - +); C22 = (+- --)] with M = 2 and length of $N = M^2 = 4$.

PROPOSED CONSTELLATION MOVEMENT SCHEME

To further improve the performance of the OCC code-based MCCDMA system, the constellation movement technique is proposed for mitigating the adverse effects of MAI which is caused by particular channel conditions. It is assumed that destination knows details of channel gains h_k for the users-k separately and the channel amplitude ratio:

$$\gamma = \left|\frac{h_B}{h_A}\right|$$

and phase difference:

$$\theta = \frac{\sqrt{h_B}}{\sqrt{h_A}}$$

are calculated. The pair (γ, θ) is used to represent $\gamma e^{j\theta}$ which is called channel state in the complex plane (Γ, Φ). The received symbols are represented collectively as additive constellation:

$$S_{ADD}(h_A, h_B) = \sqrt{P_A}\, h_A S_{grp}(\gamma, \theta)$$

where, $S_{grp}(\gamma, \theta)$ is group constellation, $(S_A\text{-}\gamma e^{j\theta}\, S_B)$ (Koike-Akino *et al.*, 2009).

The first design criterion to improve the error performance at the destination is the minimum squared Euclidean distance between the transmitted data $(s_A, s_B)_{ADD}$ and its candidate $(s'_A, s'_B)_{ADD}$. The normalized squared distance can be written as:

$$d^2_{(SA,\ SB)\leftarrow(S'A,\ S'B)} = |(S_A\text{-}S'_A)+)\gamma e^{j\theta}(S_B\text{-}S'_B)|^2 \tag{8}$$

The values of γ and θ are obtained at which the squared Euclidean distance $d^2_{(sA,\ sB)\leftarrow(s'A,\ s'B}$ goes to zero whenever the two signals are overlapped due to MAI at particular channel conditions such that:

$$\gamma e^{j\theta} = -\frac{S_A - S'_A}{S_B - S'_B} \tag{9}$$

This is called as singular channel state at which the minimum distance is very low, resulting in poor error performance at the destination.

The second design criterion to avoid the channel states (γ, θ) lying close to any singular channel states is minimum distance threshold of δ. The set of singular channel states (γ_i, θ_i) are obtained in the space for $\gamma \geq 1$ and $\theta\epsilon[0, \pi/M]$ where $1 \leq i \leq N_S$. For M-QAM input signal set S, the number of singular channel state:

$$N_S = \frac{M^2}{8} - \frac{M}{4} + 1$$

For each (γ_i, θ_i), the distance set of minimum cluster distance functions $d_{Cimin}(\gamma,\ \theta)$ are obtained among the sets of cluster distance functions, $d_{Cij}(\gamma,\ \theta)$, $1 \leq i \leq N_g$; $1 \leq j \leq J$ which gives zero value of the distance between the two additive constellation points. Also, the minimum distance $d_{min}(S)$, in $S_{grp}(\gamma,\ \theta)$ are obtained. The partitions P_S (c_i) corresponding to $d_{Cimin}(\gamma,\ \theta)$ for the values of (γ, θ)ϵspace $[0, \pi/M]$ are found where pair wise boundary between the partitions is formed by the curves $d^2_{Ci} = d^2_{Cj}$, $1 \leq i \neq j \leq N_g$ and $d^2_{Ci} = d^2_{min}(S)$. The partition exterior to all these partitions, is $P_S(c_{dmin})$ lying within the space $[0, \pi/M]$. In order to satisfy the minimum distance threshold of δ, it is thus required to avoid the channel states (γ, θ) lies inside the partitions, centered at the singular channel state (γi, θi) and radius, $\delta/|s_{2,i}\text{-}s'_{2,i}|$ for which d_{Ci} (γ, θ)<δ, $1 \leq i \leq N_s$ where:

$$\left|\gamma e^{j\theta} - \gamma_i e^{j\theta_i}\right| < \frac{\delta}{\left|S_{B,i} - S'_{B,i}\right|} \tag{10}$$

are called the disturbance circles because the minimum distance requirement of $S_{grp}(\gamma,\ \theta)$ is disturbed.

The position of the channel state, whether in any of the N_S, disturbance circles or outside is indicated to the users by a feedback of $|\log2(N_S+1)| = 3$ bits for 4QAM such that the incurred overhead is minimum compared to required feedback of perfect CSI at transmitter. Thus, the proposed idea is to move the constellation of user-j by an angle β relative to the adjacent user without increasing the transmit power if the channel state (γ, θ) lies inside any of the disturbance circles in order to meet the minimum distance threshold and no constellation movement is required for channel states outside the disturbance circles.

In order to obtain the optimal angle of movement $\beta_{i,opt}$ for the disturbance circle centered at (γ_i, θ_i), it is required to compute the value of optimal phase $\theta = \theta_{i,opt}$, $\theta\epsilon[0, \pi/M]$ which maximizes the minimum distance and transforms channel state from θ to $\theta+\beta$ lies outside the disturbance circles. The phase and minimum distance are computed at the points of intersection ($1 \leq b \leq B$) of the arc $\gamma = \gamma_i$ and the boundaries between the partitions surrounding other singular channel states while moving the phase away from θ_i but for fixed radius γ_i. Among all the above points, the maximum of minimum distance is selected for the channel state corresponding to the point of intersection (γ_i, $\theta_{intersect}$). The optimal phase, $\theta_{i,opt} = \theta_{intersect}$. Then, the optimal angle of movement $\beta_{i,opt}$ for the constellation of user-B relative to user-A is:

- If $\theta_i = \pi/M$, then, $\beta_{i,opt} = \pi/M-\theta_{i,opt}$ in a clockwise direction
- If $\theta_i = 0$, then, $\beta_{i,opt} = \theta_{i,opt}$ in an anticlockwise direction

Thus after movement, the disturbance circle is called as the changed circle since its center at (γ_i, θ_i) is changed to (γ_i, $\theta_{i,opt}$).

To avoid the overlap, it is necessary that the distance between the center of each of the changed circle (γ_i, $\theta_{i,opt}$), $1 = i = N_S$ and the singular channel states (γ_j, θ_j), $1 = j = N_S$ should be at least equal to the sum of the radius of the changed circle and the radius of the disturbance circles centered at (γ_j, θ_j). i.e.:

$$r(\gamma_i, \theta_j) + r(\gamma_j, \theta_j) \leq d_{(\gamma_i,\ \theta_{i,opt}) \leftrightarrow (\gamma_j, \theta_j)}, \forall 1 \leq j \leq N_S \tag{11}$$

and Eq. 11 provides an upper bound on the value δ.

SIMULATION AND RESULTS

Based on the discussion given in the earlier sections, the BER performance and spectral efficiency of MCCDMA systems are evaluated using MATLAB 7.10 software package with respect to Signal to Noise Ratio (SNR) for downlink frequency selective Rayleigh fading channel with AWGN floor using different spreading codes, such as Walsh code, Gold code and OCC code with and without constellation movement scheme. The Gold codes and Walsh codes are taken as examples for traditional quasi-orthogonal codes and typical orthogonal codes respectively. The data packet of 256 symbols, the symbol length of 64, the modulation of 4-QAM, the number of subcarriers of 128 and the following key parameters of those spreading codes used in the simulations are:

- **OCC:** Flock size (M) = 4, element code length (G) = 16, sequence length (N) = 64
- **Walsh code:** Sequence length G = N = 64
- **Gold code:** Sequence length G = N = 63

Figure 2 shows the BER curves simulated for the 16 users against SNR for MCCDMA systems using different spreading codes under a two-ray multipath channel with its delay profile being [1/2, 0,1/2] and one chip inter path delay. The BER curves for the unitary spreading codes (Walsh codes and Gold codes) deteriorate obviously due to increased MAI while OCC performs nearly the same as that in the single user scenario. Hence, the orthogonality of the spectral modulated signal is retained and the minimum MAI is achieved as well.

BER performance of MCCDMA system using OCC code with chip based spreading modulation is compared with and without constellation movement scheme for increased number of users (16)

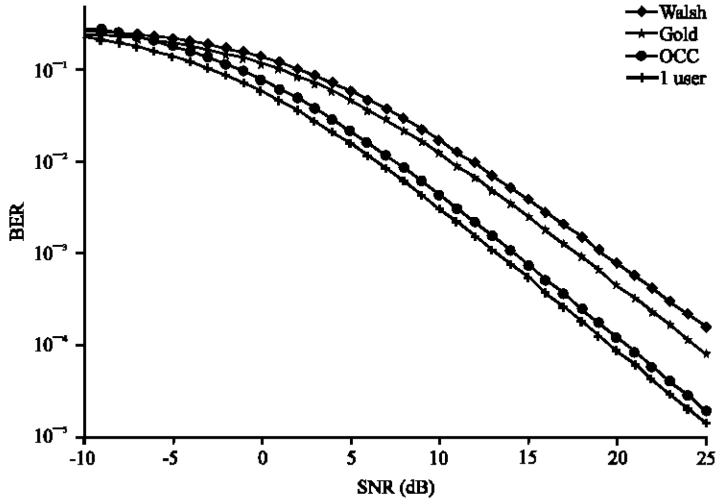

Fig. 2: BER comparison for the increased No. of users among MCCDMA systems with different spreading codes

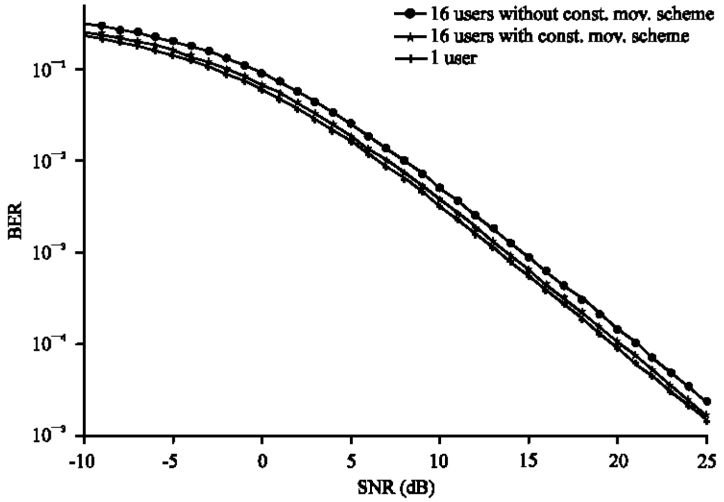

Fig. 3: BER comparison for MAI robustness among MCCDMA systems using OCC code with and without constellation movement scheme

in Fig. 3. The performance gain of SNR of 1 dB is achieved in the proposed constellation movement scheme by mitigating the detrimental effects of MAI compared to system using OCC codes without this scheme. The result shows that the system with proposed constellation movement scheme achieves minimum MAI and robust performance.

Figure 4 compares SEs of MCCDMA system against SNR for Walsh code and OCC code with and without constellation movement scheme, where the required BER is assumed to be 10^{-3}. The SEs for Walsh code cannot be improved further beyond some high SNR due to the excessive interferences. Obviously, the spectral efficiency of the MCCDMA system is improved due to OCC

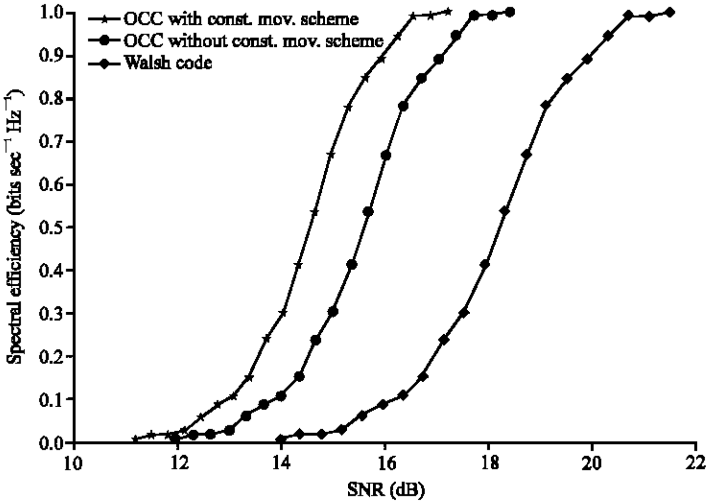

Fig. 4: Spectral efficiency comparison against SNR among MCCDMA systems using Walsh code and OCC code with and without constellation movement scheme

codes and spreading modulation and thus the SE is higher than Walsh code. The result shows further improvement of spectral efficiency due to interference-resist capability of the proposed adaptive constellation movement technique which mitigates the detrimental effects of MAI.

CONCLUSION

In this study, the MCCDMA system was developed by joining the STBC and MIMO schemes in order to utilize the maximum diversity and multiplexing gain. Also, the chip based spreading modulation and OCC spreading codes were studied to employ in MCCDMA system for MAI cancellation and spectral efficiency. Further, the constellation movement scheme was proposed for M-QAM signal set to remove the MAI completely in another way. The simulation result concluded that the performance of MCCDMA system using OCC codes in terms of BER and spectral efficiency outperforms system with Walsh and Gold codes. The proposed adaptive constellation movement scheme enhanced the performance of MCCDMA system without extra power or bandwidth under the particular channel conditions. The simulation results also showed that the developed system is more resistant to MAI as the number of users increases and thus, the user capacity is thus increased.

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