BIT ERROR RATE (BER) PERFORMANCE ANALYSIS OF CARRIER INTERFEROMETRY CODES IN A COGNITIVE RADIO(CR) ENVIRONMENT

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***Abstract*—Multi Carrier Code Division Multiple Access (MC-CDMA) and Orthogonal Frequency Division Multiplexing (OFDM) are the two most efficient multiple access techniques in a multiuser environment. However, Multiuser Interference (MUI) and Co-Space Interference (CSI) are the two major challenges when multiple antennas are deployed at the transmitter and receiver ends. Moreover, in a Cognitive Radio (CR) system, the secondary users that use MC-CDMA technique must deactivate the sub carriers used by the primary users resulting in the loss of orthogonality of the conventional spreading codes such as Hadamard Walsh codes. To solve the resultant non-orthogonality problem, the Complex Carrier Interferometry (CI) codes are utilized that exist for any length. The method of Total Interference Cancellation (TIC) in combination with Singular Value Decomposition (SVD) helps to combat the problem of MUI and CSI. However, the performance of these CI codes deteriorates due to small singular values of the channel matrix. To enhance the performance of CI-TIC, Minimum Output Energy (MOE) error criterion is employed to reduce the noise.**

***IndexTerms*—Cognitive Radio, MC-CDMA, MIMO, SVD**

I. INTRODUCTION

Cognitive radio is a revolutionary technology that aims for remarkable improvements in the efficiency of spectrum. It makes it possible for group of Secondary Users (SU) to access the frequency bands which are not used by the Primary Users (PU). Green communications, smart grid networks and vehicular communication networks are some of the recently identified application areas for cognitive radios and networks. The intelligence embedded in cognitive radios can be used for efficient utilization of spectrum in wireless networks without compromising on the QoS (Quality of Service).

As the unused spectrums may be non-contiguously available for the secondary users, multicarrier techniques such as Orthogonal Frequency Division Multiplexing(OFDM)[1] and Multicarrier Code Division Multiple Access (MC-CDMA)[1] are good candidates for efficient spectrum usage. MC-CDMA system is able to mitigate the Inter Symbol Interference (ISI)[1] and the multiuser interference (MUI) [1]in the frequency selective channels because of combining OFDM technique and orthogonal spreading codes.

Multiple-input Multiple-output (MIMO)[1][2][10] MC-CDMA systems have attracted attention in broadband wireless communications for their higher capacity.

However, the arising co-space interference (CSI) due to MIMO transmission ruins the orthogonality of the spreading codes that causes MUI.

To address these challenging issues, a linear Total Interference Cancellation (TIC) [1] receiver, based on the singular value decomposition (SVD) [1] [2] of the channel matrix has been employed. The TIC completely eliminates the CSI and MUI by using orthogonal Hadamard Walsh spreading codes. However, these codes can be used only when the number of sub carriers is a multiple of four which is not always the case in the CR environment. This led to the replacement of conventional Walsh Codes with CI codes. But as its performance suffered from the small singular values of the channel, another linear SVD based receiver named CI-MOE is used to solve this problem by minimizing the output energy criterion.

To use MC-CDMA [1][2]in cognitive radio transmission, the SU base station can only deploy the non-contiguous spectrum holes by turning off the sub carriers that are within the spectrum used by the PU. Such system is called Non-Contiguous (NC) MC-CDMA[1]. In this case, the number of available sub carriers could be any integer values. The conventional orthogonal Hadamard Walsh (HW) codes only exist when their length is multiple of four. So these codes cannot provide the desired orthogonality in CR environment.

In NC-MIMO MC-CDMA [1] [2] [10] systems, the deactivation of some of the sub carriers causes the spreading codes to be non-orthogonal and hence the challenging issue of the joint presence of MUI and CSI is severed. Carrier Interferometry (CI) codes are complex orthogonal spreading codes that can be generated with any integer valued lengths.

The paper focuses on evaluating the performance of TIC receiver deployed using CI codes and comparing its efficiency with the same deployed using Hadamard Walsh codes.

II. HADAMARD-WALSH/MC-CDMA SIGNALLING AND TRANSMITTER MODEL

The notations used in this paper are as follows: Upper- and lowercase-boldface/slanted letters represent matrices and vectors respectively. Superscripts $(.)^T$, $(.)^H$, $(.)^{-1}$ stands for transpose,hermitian transpose and matrix inversion,respectively.

In the entire paper, a single cell downlink, MC-CDMA system with N_c subcarriers and K users which have the same spreading factor G have been considered. Values and functions related to users' k are marked by the index $^{(k)}$ where k can take on the values 0, 1 ...K-1.

The antenna specifications are as follows: N transmit antennas at the base station and M receiver antennas at the mobile terminal which follow the criterion M≥N.

A. Signal Structure

The basic MC-CDMA signal is generated by a serial concatenation of classical DS-CDMA and OFDM. Each chip of the direct sequence spread data symbol is mapped onto a different sub-carrier. Thus, with MC-CDMA the chips of a spread data symbol are transmitted in parallel on different sub-carriers, in contrast to a serial transmission with DS-CDMA.

The data vector is multiplied with the spreading sequence and passed through serial to parallel converter and concatenated with the OFDM sub block

The number of simultaneously active users in an MC-CDMA mobile radio system is K.

This shows multi-carrier spectrum spreading of one complex-valued data symbol $d^{(k)}$ assigned to the user k. The rate of the serial data symbols is $1/T_d$. For brevity, but without loss of generality, the MC-CDMA signal generation is described for a single data symbol per user as far as possible, such that the data symbol index can be omitted. In the transmitter, the complex-valued data symbol$d^{(k)}$is multiplied with the user specific spreading code i.e. Hadamard Walsh code of Length L.

$$c^{(k)} = \left(c_0^{(k)}, c_1^{(k)}, \ldots\ldots, c_{L-1}^{(k)}\right)(1)$$

The chip rate of the serial spreading code $C^{(k)}$ before serial to parallel conversion is

$$\frac{1}{T_c} = \frac{L}{T_d}\,(2)$$

After spreading, the complex valued sequence is given by

$S^{(k)}=d^{(k)} * c^{(k)}$

$=\left(S_0^{(k)}, S_1^{(k)}, S_2^{(k)}, \dots, S_{L-1}^{(k)}\right)$

(3)

The following diagram Represents the generation of Multi Carrier Spread Spectrum Signal:

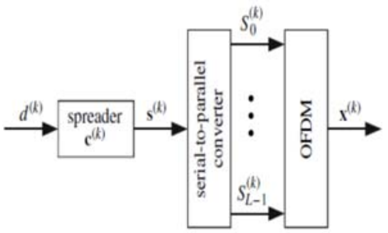

Fig. 1.MC-CDMA Signal Generation

B. Hadamard-Walsh MC-CDMA downlink transmitter

In the synchronous downlink, it is computationally efficient to add the spread signals of the K users before the OFDM operation as depicted in Figure 2. The superposition of the K sequences s (k) results in the sequence.

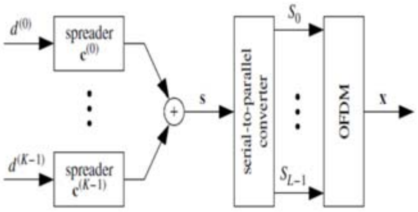

Fig. 2.Hadamard-Walsh MC-CDMA Transmitter

Multiple data vectors are multiplied with the spreading code and passed through serial to parallel converter and in turn OFDM is performed

$s=\sum_{k=0}^{K} s^{\{k\}}=\left(S_0, S_{1,}S_2, \dots\dots S_{L-1}\right)^T$ (4)

$d=\left(d^{(0)}, d^{(1)}, d^{(2)}, \dots\dots d^{(K-1)}\right)^T$(5)

$C=\left(C^{(0)}, C^{(1)}, C^{(2)}, \dots\dots, C^{(K-1)}\right)$ (6)

$S = C * d$
(7)

C: Spreading Code Matrix

d: Vector with transmitted data symbols of ‘K’ Active users

s: Spread data vector

C. Hadamard-Walsh MC-CDMA downlink receiver

The received vector of the received sequence is given by

$r=H*s+n$

$=(R_0, R_1, R_2, \dots, R_{L-1})^T$

(8)

H is L×L channel matrix and n is the noise vector.

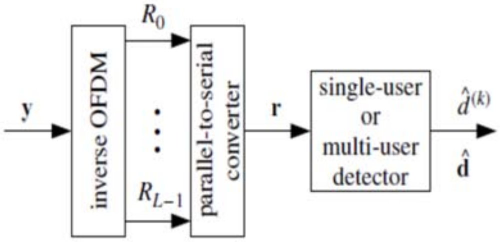

Fig. 3.Hadamard-Walsh MC-CDMA downlink Receiver

Inverse OFDM is performed on the received signal vector and passed through parallel to serial converter. Various single user or multi user detection techniques have been employed.

After de-spreading, the original data is obtained

$d=\left(d^{(0)}, d^{(1)}, d^{(2)}, \dots\dots d^{(K-1)}\right)^T$

(9)

Where d is the vector with transmitted data symbols of K users.

D. CI MC-CDMA transmitter

Each user simultaneously transmits N carriers of MC-CDMA with carefully chosen phase offsets.

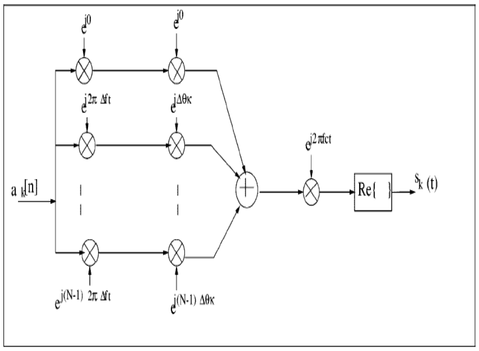

Fig. 4 CI MC-CDMA transmitter

The figure illustrates the CI MC-CDMA transmitter supporting N users where a_k is the input data symbol and θ_k is the phase offset for the k^{th} user.

For K users, the spreading code vector forthe k^{th}user is given by

$$\left(1, e^{j\Delta\theta_k}, e^{j2\Delta\theta_k}, \ldots., e^{j(N-1)\Delta\theta_k}\right)$$

The transmitting signal corresponding to the n^{th} data bit of the k^{th} user is given by

$$s_{(k)}(t)=\sum_{i=0}^{N-1} a_{(k)}[n]\cos(2\pi f_i t + i\Delta\theta_k).\, p(t - nT_b) \quad (10)$$

Where $f_i=f_c + i\Delta f$ (11)

p(t) is the Nyquist pulse corresponding to the interval 0 to T_b and i =0, 1,2,..N-1.

E. CI MC-CDMA receiver

The CI MC-CDMA receiver for 'K' users is shown in the Fig. 4.

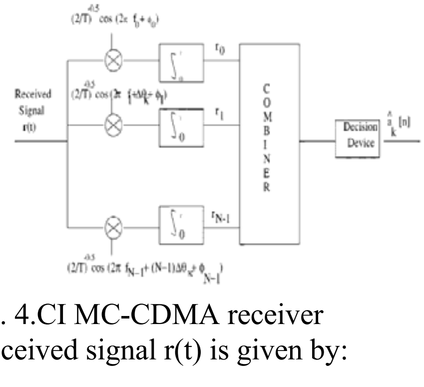

Fig. 4.CI MC-CDMA receiver

The received signal r(t) is given by:

$$r(t) = \sum_{k=1}^{K} \sum_{i=0}^{N} a_i a_k[n]\cos(2\Pi f_i t+i\Delta\theta_k+\varphi_i) \quad (12)$$
$$.p(t - n\, T_b)+\eta(t)$$

Where $\alpha_i$the gain and φ_i is the phase offset due to the channel and K refers to the no of users and n (t) represents Additive White Gaussian Noise (AWGN).

The received signal is projected onto the orthonormal carriers of the transmitted signal,

$$x = (r_0, r_1, \ldots. r_{N-1}) \quad (13)$$

Where

$$x_i = a_i a_k[n] + \sum_{j=1, j\neq k}^{K} a_i a_j[n] . \cos\left(i(\Delta\theta_j - \Delta\theta_k)\right) + \eta_j \quad (14)$$

III. SVD BASED TOTAL INTERFERNCE CANCELLATION

The desired user's transmitted signal is given by

$$d_m = \left[d_{m,1}, d_{m,2}, \ldots \ldots d_{m,J}\right]^T (15)$$

which is spread in both time and frequency domain.

The orthogonal spreading code matrix is given by

$$C_m = \left[c_{m,1}, c_{m,2}, \ldots. c_{m,J}\right] \quad (16)$$

The size of spreading code Matrix is NL×J that consists of J different spreading code vectors. The signal of the m^{th} user that is transmitted over L sub carriers is given by

$$s_m = C_m * d_m (17)$$

Where size of s_m is NL×1

The received signal at the m^{th} user is given by

$$Y_m = H_m \sum_{k=1}^{K} C_K d_k + \zeta_m (18)$$

The space frequency channel matrix is given by

$$H_m = \begin{bmatrix} H_m^{(1)} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & H_m^{(L)} \end{bmatrix} \quad (19)$$

Size of H matrix is ML×NL

By using SVD the channel matrix can be decomposed as

$H_m = U_m \Lambda_m V_m^H$(20)

Where U_m and V_m are Block unitary matrices of size Ml×NL and NL×NL. Λm is the diagonal NL ×NL matrix.

After utilizing beam forming methods,

$\widetilde{y_m} = \Lambda_m^{-1} U_m^H y_m$

$= V_m^H \sum_{k=1}^{K} C_k\, d_k + \Lambda_m^{-1} U_m^H \zeta_m$(21)

Using the dispreading matrix given by

$C_m^H = G_m^H V_m^H$ (22)

Utilizing the equations (21) and (22);

$\widetilde{d_m} = G_m^H \widetilde{y_m}$

$= G_m^H V_m^H \sum_{k=1}^{K} C_k\, d_K + G_m^H \Lambda_m^{-1} U_m^H \zeta_m$

$= C_m^H \sum_{k=1}^{K} C_k\, d_K + G_m^H \Lambda_m^{-1} U_m^H \zeta_m$
(23)

Since CI codes satisfy the condition of orthogonality,

$C_m^H C_k = I_J \delta(m-k)$
(24)

The output after de-spreading becomes,

$\widetilde{d_m} = C_m^H C_m d_m + C_m^H \sum_{k=1}^{K} C_k\, d_k + \eta_m$
(25)

It can be observed that SVD is an effecient technique to mitigate CSI and MUI.The small singular values of the channel matrix degrades the performance of the receiver.

IV. MINIMUM OUTPUT ENERGY

Minimum Output Energy is a method of minimising the energy of the output signal without distorting the array gainof the desired received signal. Since the gain is fixed, the total output energy is reduced by supressing the interference due to small singular values of the channel.

Consider the signal and noise covariance matrices to be:

$R = E[r, r^H]$ and $R_n = E[\eta, \eta^H]$ respectively.

The received signal given by,

$r(t) = \sum_{k=1}^{K} \sum_{i=0}^{N} a_i a_k[n] \cos(2\Pi f_i t + i\Delta\theta_k + \varphi_i)$ $.p(t - n\, T_b) + \eta(t)$
(26)

$r(t) = w_m^H h_0 + \eta(t)$ (27)

where $h_0 = \sum_{k=1}^{K} \sum_{i=0}^{N} a_i a_k[n] \cos(2\Pi f_i t + i\Delta\theta_k + \varphi_i)$ $.p(t - n\, T_b)$
(28)

Using the Lagrange multipliers;

$L(w_m h_0; \lambda) = E\{|w_m^H r|^2\} - \lambda\,(w_m^H h_0 - c)$
(29)

$= E\{w_m^H r r_m^H w\} + \lambda[w_m^H h_o - c]$
(30)

$w_m^H R w_m + \lambda[w_m^H h_o - c]$

The energy component J can be minimised by taking the derivative w.r.t to $h_0$and equating it to zero. The arbitrary constant c=1.

$\frac{\partial L(w_m h_0; \lambda)}{\partial h_0} = R w_m + \lambda h_o$
(31)

$w_m = -\lambda R^{-1} h_0$
(32)

MOE algorithm is useful when there is no necessity to take a particular reference signal.

V. SIMULATIONS AND RESULTS

In this section, the bit error rate (BER) versus the Signal to noise ratio for the downlink MIMO MC-CDMA receivers with Hadamard Walsh codes and CI codes have been studied.

A 2×2 MIMO system where M=2, N=2, with number of subcarriers L=4 has been simulated. Hadamard Walsh codes have been employed as the spreading codes. Each user transmits a 10 bit data; hence the size of the data vector is 1×10.

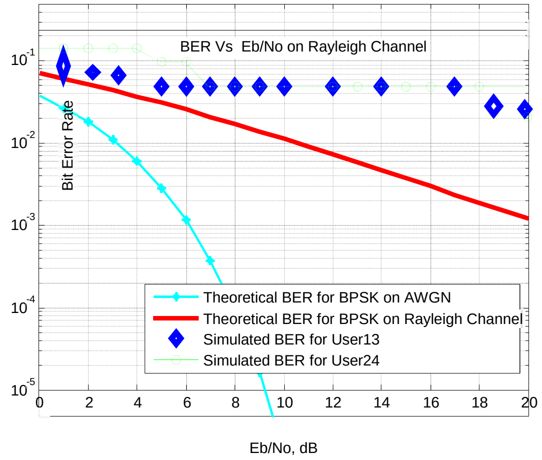

Fig. 1.BER versus SNR $(E_b/N_o)$of an MC-CDMA receiver employing Hadamard-Walsh codes for flat fading Rayleigh channel.

CSI and MUI are the major challenges in a multi user environment with regard to MIMO systems. SVD is a tool to mitigate CSI in a multiuser environment. In the following figures CI based total interference cancellation has been employed and the performance of Hadamard Walsh codes and CI codes has been studied.

A 2×2 MIMO system, where M=2, N=2 and the number of sub carriers =4 has been simulated. Each of the user transmits data bits of length=4.Hence the size of the data vector is 1×4.

Here, Hadamard-Walsh codes have been deployed in the SVD based TIC receiver.

The program is run many times and after successive trials the data vector and the received vector are compared and the number of bits in error is noted. It has been observed that at the most 1 bit error has been observed for 20 different values of noise added for the second data vector transmitted. The first data vector was received correctly with almost no errors. The Upper and the lower bounds of probability of bit error have been calculated using Monte Carlo statistical methods as described in theory.

While running the programme it was observed that Walsh codes are efficient when the number of sub carriers is a multiple of four. When the number of sub carriers was changed to a number which was not a multiple of four, Walsh codes could not be used since Hadamard matrix could not be constructed.

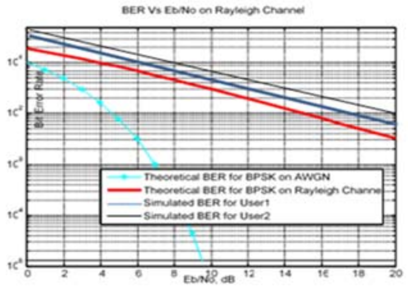

Fig. 2.BER versus SNR (E_b/N_o)on a flat fading Rayleigh channel where M=2, N=2, L=4 for a TIC receiver based on Hadamard-Walsh codes after the elimination of CSI and MUI.

As stated earlier, in a cognitive radio environment when the secondary users tried to access the spectrum allotted to primary users, the number of subcarriers which they can utilize may or may not be a multiple of four. In case the number of subcarriers is not a multiple of four, the conventional spreading codes such as Hadamard Walsh codes lose their orthogonality. Hence, CI codes were introduced which helped to preserve orthogonality for any length.

Fig.3 shows the BER performance of the CI-TIC when deployed in a 2×2 MIMO receiver with number of subcarriers L=12, out of which 6 subcarriers are activated.Here,L=6 is not a multiple of four, so CI codes turned out to be an optimal choice.

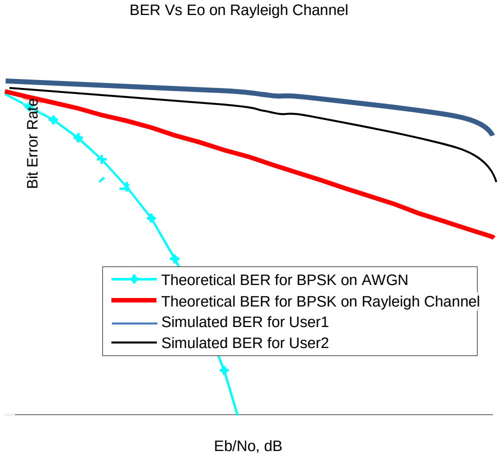

Fig. 3 BER versus SNR on a flat fading Rayleigh channel

M=2, N=2, L=6(active) for a CI-TIC

Randomly varying flat fading Rayleigh channel has been modeled by using circularly symmetric Gaussian random variable given by RANDN function in MATLAB. The selection matrix is of size 24X24. The upper and the Lower Bounds have been calculated using Monte Carlo Statistical methods.

It has been observed that when the secondary users try to use the spectrum by deactivating the sub carriers used by the primary users, the CI codes are able to maintain their orthogonality. Moreover there is no restriction on the length of the CI code, thus making it robust to the diverse requirements of the wireless environment.

After successive trial wherein the data vector and the received vector have been analyzed, it is observed that the the performance of CI based MC-CDMA is not optimal because space frequency noise at the channel input gets multiplied with the inverse of the related singular values of the channel matrix, which degrade the performance.Moreover the bit error rate changes when the phase jitter of the CI codes are changed.To improve the performance of the CI-TIC receiver, MOE criterion has been employed.

Fig.4 shows the BER versus SNR of a CI-TIC employing MOE in order to minimize the small singular vales of the channel matrix.

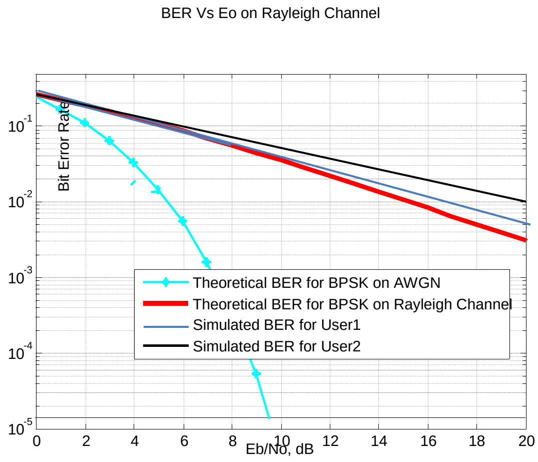

Fig. 4.BER versus SNR plot for CI-TIC receiver in a flat fading Rayleigh channel after employing MOE.

After applying MOE criterion to the CI-TIC receiver described earlier, it has been observed that the number of bits in error has been significantly reduced. The CI MOE eliminates/reduces the deteriorating effect of the small singular values of the channel matrix.

It has been observed that both CSI and MUI has been resolved and at the same time orthogonality has been preserved.

VI. CONCLUSION

In a cognitive radio environment, MC-CDMA employing HadamardWalsh codes lose their orthogonality when the number of available subcarriers used by the secondary user is not a multiple of 4. To overcome this non-orthogonality problem, Complex Carrier Interferometry codes which exists for all lengths was used as the spreading code instead of Hadamard Walsh codes.

Upon use of Carrier Interferometry codes, though the non-orthogonality problem was solved, it showed a higher number of bits in error in the received data. To mitigate Co-space interference and Multiuser Interference, the technique of Total Interference Cancellation was used. Singular Value Decomposition was used to eliminate CSI to large extent.

The problem faced at this stage was the amplification of the noise power. So, the MOE technique was employed, considering the interferences and noise as well as the deactivation of the sub-carriers. CI-MOE method shows a better performance in comparison with the CI-TIC.

On comparison of MC-CDMA CI-TIC-MOE with MC-CDMA Hadamard Walsh coded, it has been observed that the former shows a much better bit error rate performance and can efficiently incorporate any number of users who try to access the spectrum at any instant of time. Therefore, this system is a very good choice for any CR based reconfigurable multi- used broadband systems.

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