Journal of Theoretical and Applied Information Technology
10th August 2013. Vol. 54 No.1

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

CAPACITY ENHANCEMENT OF MC-CDMA SYSTEM THROUGH RECEIVER PHASE ROTATED CONJUGATE ICI CANCELLATION WITH ITERATIVE CFO AND IQ IMBALANCE ESTIMATION AND COMPENSATION

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ABSTRACT

The ever increasing demand for very high data rate multimedia services such as audio, video, image and data requires the technologies which make use of the available electromagnetic resources in the most intellectual manner. Multi-carrier code division multiple access (MC-CDMA) is one of the best techniques to meet the requirements of next generation wireless mobile communication systems. MC-CDMA system combines the benefit of both orthogonal frequency division multiplexing (OFDM) technique and code division multiple access scheme (CDMA). It offers high spectral efficiency, high data rate, low transmit power, lower implementation complexity, large system capacity and narrowband interference rejection capability. Direct conversion receivers in multi-carrier systems are very sensitive to carrier frequency offset (CFO), gain and phase offsets called IQ imbalances. CFO leads to loss of orthogonality among the subcarriers resulting in intercarrier interference (ICI). IQ imbalance will cause severe degradation in the detection accuracy. To reduce the ICI and to improve the demodulation accuracy, a receiver phase rotated conjugate cancellation (RPRCC) using joint iterative CFO& IQ imbalance estimation and compensation algorithm is proposed in this work. Simulation results show that the proposed method provides better carrier to interference ratio (CIR) and bit error rate (BER) performance compared to phase rotated conjugate cancellation (PRCC) without CFO and IQ compensation and conventional conjugate cancellation (CC) techniques.

Keywords: *CFO, ICI, IQ imbalance, MC-CDMA, RPRCC*

1. INTRODUCTION

Multi-carrier modulation (MCM) technique has been applied widely in wireless communication systems due to its robustness to multi-path fading; high data rate transmission capability and easy implementation using Fast Fourier transform (FFT). MC-CDMA combines the advantages of both orthogonal frequency division multiplexing (OFDM) and code division multiple access (CDMA) technique [1]. The principle of OFDM is dividing the high rate data stream into several low rate substreams. These substreams are transmitted using different subcarriers. CDMA system allows many users to transmit their information on the same channel bandwidth using different spreading codes. MC-CDMA combines MCM with frequency domain spreading. MC-CDMA system is susceptible to carrier frequency offset (CFO) and IQ imbalances due to the non-idealities in the receiver front end. CFO is caused by Doppler shifts and imperfections of transmitter and receiver oscillators, which leads to the loss of orthogonality among the subcarriers. This causes an undesired effect called intercarrier interference (ICI) which degrades the system performance [2]. The IQ imbalance arises due to the mismatch of components in the in-phase (I) and quadrature phase (Q) channels. To improve the BER performance and to estimate the IQ imbalances in a precise manner, ICI cancellation using RPRCC algorithm with a joint CFO and IQ imbalance estimation and compensation is proposed in this paper.

With several ICI cancellation schemes, self-cancellation is one of the simple and low complexity method compared to other ICI cancellation techniques. At the transmitter side, one data symbol is mapped onto two adjacent subcarriers with a predefined weighting factor to self-cancel the ICI. The second method to mitigate the effect of ICI is the conjugate cancellation (CC) technique. In CC technique, one path carries the MC-CDMA signal and the other path carries the conjugate of the first path signal. The CIR performance of CC technique is poor in high frequency offset conditions compared to normal MC-CDMA system. To achieve better carrier to interference ratio (CIR) and bit error rate (BER) performances in both low and high frequency offset conditions, PRCC technique is proposed. In PRCC technique, one path carries the MC-CDMA signal with a phase shift of ϕ and the other path carries the conjugate of the first path with a phase shift of $-\phi$. At the receiver the frequency offset is estimated and feedback to the transmitter to introduce the phase rotation of ϕ at the transmitter. This method increases the computational complexity at the transmitter side, due to the phase rotation of ϕ at the transmitter. To overcome the transmitter complexity of MC-CDMA system, a RPRCC technique using iterative ML based CFO estimation, is proposed in this work. Due to the artificial phase rotation at the receiver, RPRCC technique outperforms the conventional CC technique in both low and high frequency offset conditions. To avoid the use of expensive front end devices at the receiver for precise detection, an iterative IQ imbalance estimation and compensation is proposed along with RPRCC. This algorithm estimates and compensates the gain and phase imbalances in every iteration and repeat the same procedure until the algorithm converges. Thus the joint CFO and IQ imbalance compensation with RPRCC algorithm improves the BER and CIR performances of MC-CDMA system.

2. MC-CDMA SYSTEM MODEL

In MC-CDMA system the main idea is to spread the mth user ($1 \le m \le M$, M is the maximum number of users) binary data sequence b^m using the different chip of spreading sequence C_k^m ($0 \le k \le N-1$, where N is the number of subcarriers). An orthogonal code [3] such as Walsh-Hadamard code is used to achieve minimum multiple access interference (MAI) in the fading channel. The binary signal b^m and spreading signal C_k^m takes the value ± 1. The CDMA signal of all the *M* users are summed and subsequently mapped to *N* subcarriers using OFDM technique [4]. The composite spread (CDMA) signal X_k for the k^{th} chip is expressed as

$$X_k = \sum_{m=1}^{M} b^m C_k^m \qquad k=0, 1, 2,\ldots, N-1 \qquad (1)$$

The MC-CDMA signal at the inverse Fast Fourier transform (IFFT) output is given by

$$x_n = 1/N \sum_{k=0}^{N-1} X_k \exp(j2\pi nk/N) \qquad (2)$$

where n=0, 1…, N-1. A cyclic prefix (CP) is inserted at the starting of each IFFT output and the signal is transmitted through the additive white Gaussian noise (AWGN) channel. In the presence of frequency offset and AWGN (w_n), the received signal is expressed as

$$r_n = x_n \exp(j2\pi n\varepsilon/N) + w_n$$

where ε is the normalized frequency offset, given by NΔf/B and Δf is the difference between transmitter and receiver carrier frequencies. B is the system bandwidth and N is the number of subcarriers. At the receiver, the time domain received signal is converted into frequency domain using fast Fourier transform (FFT) algorithm. The FFT output of p^{th} subcarrier is

$$R_p = \sum_{n=0}^{N-1} r_n \exp(-j2\pi p n/N)$$

$$R_p = \sum_{n=0}^{N-1} (x_n \exp(j2\pi n\varepsilon/N) + w_n) \exp(-j2\pi np/N)$$

$$\text{where } 0 \le p \le N-1 \qquad (3)$$

$$R_p = \frac{1}{N} \sum_{k=0}^{N-1} X_k \sum_{n=0}^{N-1} \exp(-j2\pi n(p-k-\varepsilon)/N) + \sum_{n=0}^{N-1} w_n \exp(-j2\pi np/N)$$

$$R_p = X_p I(-\varepsilon) + \sum_{k=0,k\neq p}^{N-1} X_k I(p-k-\varepsilon) + W_p \qquad (4)$$

where W_p is the FFT of w_n and

$$I(\varepsilon) = 1/N \sum_{n=0}^{N-1} \exp(-j2\pi n\varepsilon/N)$$

$$= \left(\sin \pi\varepsilon \Big/ N \sin\left(\frac{\pi\varepsilon}{N}\right) \right) \exp\left(j\pi\varepsilon(1-N/N) \right)$$

First term in Eq. (4), is the desired term and the second term is the sum of interference due to the presence of frequency offset. Third term is the noise of AWGN nature. When there is no carrier frequency offset and the carriers are orthogonal, the term $I(p-k)$ is zero.

Despreading of FFT signal is given by

$$Y_p = R_p C_k^m \qquad (5)$$

where $(C_k^m)^2$ is always +1.

The output of desired user 'm' on the p^{th} subcarrier after despreading is given by

$$y_p^m = b^m I(-\varepsilon) + \sum_{k=0,k\neq p}^{N-1} X_k I(p-k-\varepsilon) + W_p \quad (6)$$

3. RECEIVER PHASE ROTATED CONJUGATE CANCELLATION TECHNIQUE

The conventional CC technique employs two path algorithm [5, 6]. One path carries the MC-CDMA signal and the second path carries the conjugate of the first path signal. The CC technique could not guarantee good performance in high frequency offset conditions. The simplified block diagram of MC-CDMA system with receiver phase rotated conjugate ICI cancellation with joint CFO and IQ imbalance estimation and compensation is shown in Fig.1. In RPRCC technique, the transmitter employs the conventional CC algorithm. The transmitted signals at two transmission paths are expressed as

$$y_n^{(1)} = x_n$$

$$y_n^{(2)} = (x_n)^*$$

Both the signals are time multiplexed (MUX) and transmitted through the AWGN channel. At the receiver, the signal at the first path in the presence of frequency offset is given by

$$r_n^{(1)} = x_n e^{j2\pi n\varepsilon/N} + w_1 \quad (7)$$

where n=0, 1,…, N-1.The signal at the second path is given by

$$r_n^{(2)} = x_n^* e^{j2\pi n\varepsilon/N} + w_2 \quad (8)$$

where w_1 and w_2 are additive white Gaussian noises. At the receiver the two path signals are separated using a demultiplexer (DMUX) and converted into frequency domain by FFT. The received signal of first path is same as in Eq.7 and the second path signal is conjugated and the resulting signal is passed through the FFT block. The FFT output of the first path signal is phase shifted by $-\phi$ and the second path signal is phase shifted by ϕ.

The FFT output for first path is expressed as

$$R_p^{(1)} = \sum_{n=0}^{N-1} r_n e^{-j2\pi np/N} \quad (9)$$

The first path signal with the phase rotation $-\phi$ is expressed as

$$R_p^{(1)} = \sum_{n=0}^{N-1} r_n e^{-j\phi} e^{-j2\pi np/N}$$

$$= \sum_{n=0}^{N-1} (x_n e^{-j\phi} e^{j2\pi n\varepsilon/N} + w_1) e^{-j2\pi np/N} \quad (10)$$

$$= \sum_{n=0}^{N-1} (x_n e^{-j\phi} e^{j2\pi n\varepsilon/N} + w_1) e^{-j2\pi np/N}$$

$$= \frac{1}{N} \sum_{k=0}^{N-1} X_k \sum_{n=0}^{N-1} e^{-j\phi} e^{-j2\pi n(p-k-\varepsilon)/N} + W_1 \quad (11)$$

where $I(p-k\pm\varepsilon) = \frac{1}{N}\sum_{n=0}^{N-1} e^{\mp j2\pi n(p-k\pm\varepsilon)/N}$

The conjugate of second path signal with the phase rotation ϕ is given by

$$R_p^{(2)} = \sum_{k=0}^{N-1} X_k (e^{j\phi} I(p-k+\varepsilon)) + W_2 \quad (12)$$

where W_1 and W_2 are FFT of w_1 and w_2.

The combined output of both the paths becomes

$$S_l = R_p^{(1)} + R_p^{(2)}$$

$$= X_p (e^{j\phi} I(\varepsilon) + e^{-j\phi} I(-\varepsilon)) +$$

$$\sum_{k=0,k\neq p}^{N-1} X_k \{e^{j\phi} I(p-k+\varepsilon) + e^{-j\phi} I(p-k-\varepsilon)\} + W_1 + W_2 \quad (13)$$

4. CIR PERFORMANCE IMPROVEMENT

The CIR of conventional CC technique [7, 8] is expressed as

$$\mathrm{CIR}_{CC} = \frac{|I(-\varepsilon) + I(+\varepsilon)|}{\sum_{k=1}^{N-1} |I(k-\varepsilon) + I(k+\varepsilon)|} \quad (14)$$

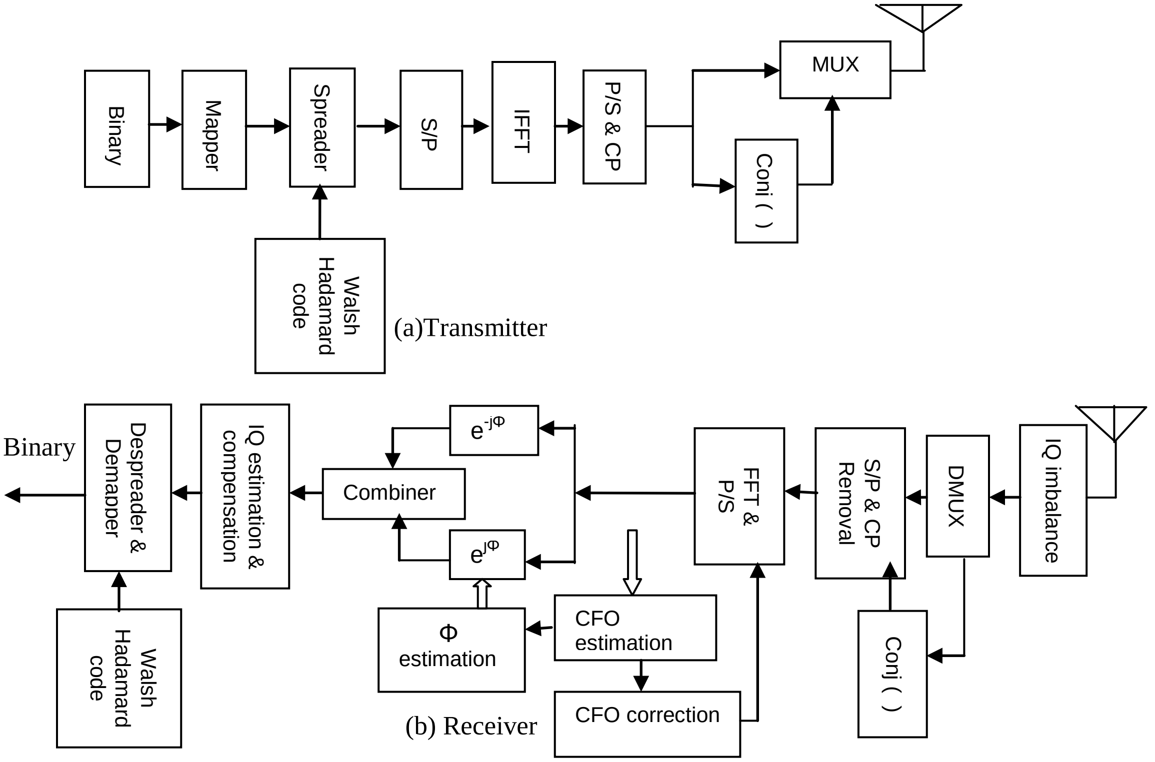
The received signal s_k can be expressed as the sum of desired signal (r_k) and interference signal (I_k).

$$s_k = r_k + I_k$$

$$= X_p \left\{ e^{j\phi} I(\varepsilon) + e^{-j\phi} I(-\varepsilon) \right\} +$$

$$\sum_{k=0,k\neq p}^{N-1} X_k \{e^{j\phi} I(p-k+\varepsilon) + e^{-j\phi} I(p-k-\varepsilon)\} + W_1^{'} + W_2^{'} \quad (15)$$

The first term in Eq.15 represents the desired information and the second term represents the sum of interference from k^{th} subcarrier to p^{th} subcarrier. Third term corresponds to AWGN signal.



(a)Transmitter

(b) Receiver

Figure 1: Block Diagram of Receiver Phase Rotated Conjugate ICI Cancellation with Joint CFO and IQ imbalance Estimation and Compensation

The CIR of RPRCC is expressed as

$$\mathrm{CIR}_{\mathrm{RPRCC}}=\frac{\left|e^{j\phi}I(\varepsilon)+e^{-j\phi}I(-\varepsilon)\right|^2}{\sum_{k=1}^{N-1}\left|e^{j\phi}I(k+\varepsilon)+e^{-j\phi}I(k-\varepsilon)\right|^2} \quad (16)$$

The optimum phase rotation for a given frequency offset ε can be obtained by performing the phase shift corresponding to the maximum CIR value. From Eq.16 the numerator is expressed as

$$(e^{j\phi}I(\varepsilon)+e^{-j\phi}I(-\varepsilon))(e^{-j\phi}I^*(\varepsilon)+e^{j\phi}I^*(-\varepsilon))$$

$$=\left|I(\varepsilon)\right|^2+e^{j2\phi}I(\varepsilon)I^*(-\varepsilon)+e^{-j2\phi}I(-\varepsilon)I^*(\varepsilon)+\left|I(-\varepsilon)\right|^2$$

where $I(-\varepsilon)=I(\varepsilon)e^{-j2\pi\varepsilon(1-N)/N}$ and $\left|I(-\varepsilon)\right|^2=\left|I(\varepsilon)\right|^2$

Thus the term $\left|e^{j\phi}I(\varepsilon)+e^{-j\phi}I(-\varepsilon)\right|^2$ can be expressed as

$$2\left|I(\varepsilon)\right|^2+2\left|I(\varepsilon)\right|\cos(2\phi+j2\pi\varepsilon(1-N)/N) \quad (17)$$

The denominator term in Eq.16 can be expressed as

$$\sum_{k=1}^{N-1}\left|I(k+\varepsilon)\right|^2+\left|I(k-\varepsilon)\right|^2+2\left|I(k+\varepsilon)I(k-\varepsilon)\right|\cos(2\phi+j2\pi\varepsilon(1-N)/N)$$

The optimum phase rotation is obtained by

$$\frac{\partial \mathrm{CIR}_{\mathrm{RxPRCC}}(\varepsilon,\phi)}{\partial\phi}=0 \quad (18)$$

From Equation.18 $\sin(2\phi+j2\pi\varepsilon(1-N)/N)=0$

Then $2\phi+j2\pi\varepsilon(1-N)/N=n\pi$ or 0

$$2\phi+j2\pi\varepsilon(1-N)/N=0$$

Thus the optimum phase shift for maximum CIR can be given as

$$\phi=-\pi\varepsilon\frac{N-1}{N} \quad (19)$$

3. ITERATIVE JOINT CFO AND IQ IMBALANCE ESTIMATION AND COMPENSATION

5.1 Carrier Frequency Offset Estimation

To improve the accuracy of detection process and estimating the gain and phase mismatch in the reduced ICI condition, RPRCC technique with IQ imbalance estimation is proposed. In RPRCC technique, to obtain the optimum phase rotation at the receiver side, the estimated value of CFO must be closer to the actual value caused by Doppler effects or imperfections in the transmitter and receiver oscillators. To achieve the perfect CFO estimation, an iterative ML algorithm is proposed. In ML estimation algorithm, the same data frame is transmitted twice [9], and the two received signals are compared at every frequency. The two path signals are same when the frequency offset is zero. When there is an offset in the carrier frequency, the two received signals are not equal [10, 11]. If noise W_{1P} and W_{2P} is added to the received signals corresponding to the P^{th} element of FFT outputs, R_{1P} and R_{2P} becomes

$$Y_{1P} = R_{1P} + W_{1P}$$
$$Y_{2P} = R_{2P} + W_{2P} \quad (20)$$

where R_{1P} is the FFT output of first path received signal and R_{2P} is the second path FFT signal. To determine the relative frequency offset $\hat{\varepsilon}$, an iterative maximum likelihood estimation algorithm is applied and the steps given are as follows

Step 1: Initialize i=0 and $\hat{\varepsilon}$ =0

Where i is the number of iterations (i_{max}=L) to be carried out.

Step 2: Estimate the CFO using ML algorithm and increment i.

$$\hat{\varepsilon} = \frac{1}{2\pi}\tan^{-1}\left\{\frac{\left(\sum_{P=-N}^{N}\mathrm{Im}\left[Y_{2P}Y_{1P}^{*}\right]\right)}{\left(\sum_{P=-N}^{N}\mathrm{Re}\left[Y_{2P}Y_{1P}^{*}\right]\right)}\right\} \quad (21)$$

Step 3: Adjust the receiver CFO by multiplying it with $-\hat{\varepsilon}$.

Step 4: Apply FFT on the corrected received signal and go back to step 2 to estimate the new CFO. The received signal is adjusted with the new offset. Continue the above steps until i reach L (maximum number of iterations).

The estimated CFO using an iterative method incorporates both the path signals. Therefore the proposed method is less sensitive to offset estimation errors. When the number of iterations is more, the estimated value of CFO is very much closer to the actual value.

5.2 IQ Imbalance Estimation

The received signal is processed to obtain a sequence of digital samples, and these samples may be represented as complex numbers. Each sample in the complex sample stream r(n) may be represented as a sum of real component and imaginary component, r(n)=I(n)+jQ(n), where I(n) represents the in-phase components of the samples, which is in-phase with the original carrier signal, Q(n) represents the quadrature components of the samples, which is always 90° out of phase and with the same amplitude [12,13]. Where n is the sample time index. Any mismatch between I and Q components after down conversion will affect the system performance. IQ imbalance is viewed as the amplitude or gain mismatch and the phase mismatch yields an orthogonality mismatch between I and Q branches. The effect of IQ imbalance is recognized as the impaired signal constellation in the time domain. It will cause severe degradation of demodulation accuracy. An iterative IQ imbalance estimation and compensation is proposed to improve the demodulation performance. The reason for IQ imbalance is the signal components in I and Q channels which do not maintain orthogonality and power balance. The IQ estimation is carried out in two ways: gain mismatch and phase mismatch estimation.

The complex baseband equation for the received signal with IQ imbalance is given as

$$Y_I(k) = \cos\omega_c k$$
$$Y_Q(k) = g\sin(\omega_c k - \phi_{err}) \quad (22)$$

where g and ϕ_{err} are the relative mismatch in gain and phase. $Y_I(k)$ and $Y_Q(k)$ are the signals in I and Q branches. The carrier frequency at the receiver is ω_c.

Step 1: Initialize i=0, g=0 and ϕ_{err} =0

Step 2: Estimate the gain mismatch using

$$g_{est} = \sqrt{\frac{\sum_k Y_Q^2(k)}{\sum_k Y_I^2(k)}} \quad (23)$$

Step 3: Phase mismatch is estimated at the LPF.

$$\sin\phi_{est} = \frac{2Y_I Y_Q}{g} \text{ and } \phi_{est} = \sin^{-1}\left(\frac{2Y_I Y_Q}{g}\right) \quad (24)$$

Step 4: Compensate the IQ imbalances using

$$C_I(k) = \frac{1}{\cos\phi_{est}}\left[\cos\phi_{est} Y_I(k)\right] \quad (25)$$

$$C_Q(k) = \frac{1}{\cos\phi_{est}}\left[\sin\phi_{est} Y_I(k) + g_{est} Y_Q(k)\right] \quad (26)$$

Where $C_I(k)$ and $C_Q(k)$ are the corrected I & Q components. Iterate on the steps 2 to 4, until the algorithm converges.

4. RESULTS AND DISCUSSION

MC-CDMA system is analyzed with the binary phase shift keying (BPSK) modulation and quadrature PSK (QPSK). The CIR and BER performance of the proposed system is compared with MC-CDMA with CC technique and MC-CDMA with IQ imbalance.

The Simulation parameters are listed in Table 1.

Table 1: Simulation Parameters

Parameter	Value
Number of symbols	5200
Number of subcarriers	1024
Number of users	15
Spreading code	Walsh Hadamard
Modulation	BPSK,QPSK
Frequency offset	0.1,0.2,0.3,0.4,0.5
Gain imbalance	0.5, 1
Phase imbalance	5°, 10°
Channel	AWGN, Rayleigh

Figure 2 illustrates the CIR performance comparison of proposed technique with other ICI cancellation schemes in different normalized frequency offset values. The graph clearly shows that the maximum CIR obtained in the proposed method is 88.5 dB, the conventional CC technique is 76.6dB, CC technique with fixed phase rotation of -0.15 (maximum CIR at ε=0.05) at transmitter is 57.8 dB and the normal MC-CDMA system is 40.76dB. The CC technique gives good performance when the frequency offset is less than 0.25. When the frequency offset is greater than 0.25 the performance of normal MC-CDMA system is better than CC technique. Due to the receiver phase rotation, the RPRCC technique outperforms the conventional ICI cancellation methods in both low and high frequency offset conditions. The proposed method uses the frequency shifting property of Fourier transform. The property is the multiplication of signal $x(t)$ with $e^{j\omega t}$ shifts the frequency spectrum by ω, where ω is the angular frequency.

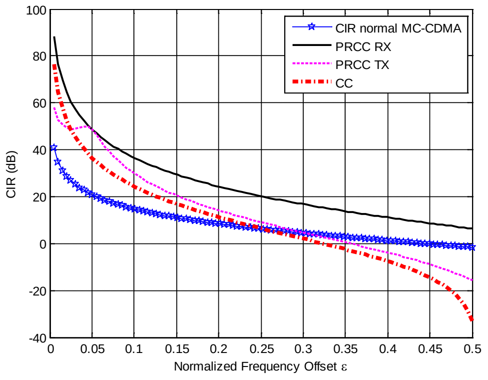


Figure 2: CIR Comparison of RPRCC with Normal MC-CDMA and CC under AWGN channel

Figure 3 compares the BER performance of RPRCC with and without IQ compensation. In Fig.3 the analysis is carried out with the normalized frequency offset 0.1, gain mismatch 1 and phase mismatch 10° and the number of data symbols is 5200. The graphs show that for the same number of data symbols, the BER of 10^{-3} is achieved at energy/noise spectral density (E_b/N_o) of around 3.5dB in the proposed method and at 4.5dB in RPRCC without IQ compensation and at 6dB in the proposed method with QPSK modulation and at 5.5dB in conventional CC method.

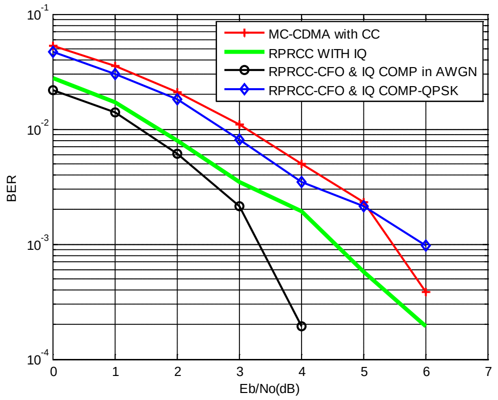


Figure.3: BER Comparison of RPRCC with and without CFO& IQ compensation

Figure 4 illustrates the BER comparison of the proposed technique for multiple users at ε=0.05, gain imbalance is 1 and phase imbalance is 10°. Results show that the simultaneous users experience little difference in their BER performance. This is due to the fact that when the number of simultaneous users is increased, the BER performance is gradually degraded. The graph shows that the BER of 10^{-3} is achieved at E_b/N_o of 3.5 dB for 5 users and at 3.8dB for 10 users and at 4 dB for 15 simultaneous users accessing the channel.

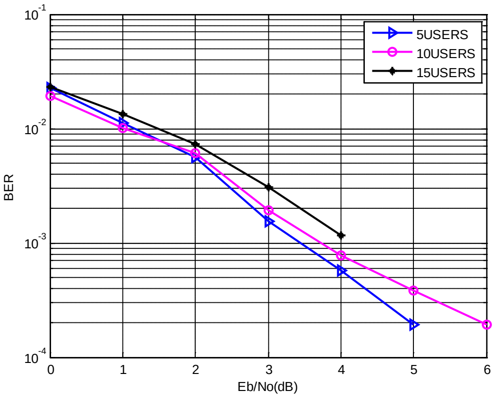


Figure 4: BER Performance of the Proposed Technique for Multiple Users in AWGN channel.

Figure 5 illustrates the performance of the proposed method in both AWGN and Rayleigh channel [14] with CFO values of 0.1 and 0.44.The result shows that when $\varepsilon=0.1$, gain imbalance is 0.5 and phase imbalance is 5°, to achieve the BER of around 10^{-3}, the proposed method needs E_b/N_o of 4.5dB and at $\varepsilon=0.44$, to achieve the same BER, the proposed method needs 5dB in AWGN channel and to achieve the same performance in Rayleigh fading channel the system needs more than 15dB. It is mainly due to the amplitude and phase distortion caused by frequency selective Rayleigh fading channel.

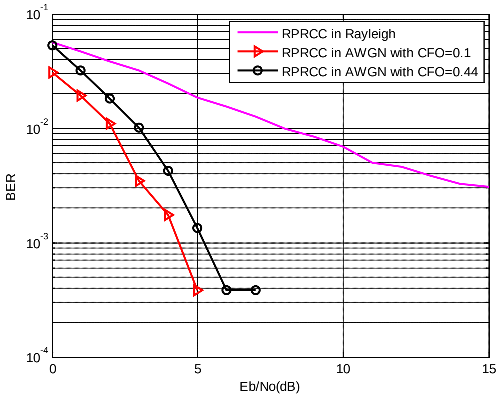


Figure 5: BER Performance of the Proposed Method in AWGN and Rayleigh channel.

5. CONCLUSION

The RPRCC technique with joint CFO and IQ compensation is proposed in this paper. The simulation results show that the CIR and BER performances of the proposed technique are better than the conventional CC technique in both low and high frequency offset conditions. Due to the presence of iterative CFO and IQ compensation, the proposed technique improves the detection accuracy with reduced ICI condition, which in turn reduces the MAI. This technique increases the capacity of MC-CDMA system by allowing many users to get the services simultaneously without any performance degradation. Thus the proposed technique can meet the requirements of future mobile radio communication systems.

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