AN EFFICIENT CFO ESTIMATION AND ICI REDUCTION IN MC-CDMA SYSTEM THROUGH CONJUGATE WEIGHTED MUSIC BASED RPRCC SCHEME

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***Abstract*— Multicarrier code division multiple access (MC-CDMA) is one of the most attractive method for future broadband wireless systems and long term evolution (LTE) standard. The performance of MC-CDMA systems is greatly deteriorated by carrier frequency offset (CFO) which is due to oscillator instability and Doppler shifts. CFO leads to loss of orthogonality between the subcarriers and introduces intercarrier interference (ICI). Among the numerous ICI cancellation techniques, the proposed receiver phase rotated conjugate cancellation (RPRCC) offers greater ICI reduction compared to other methods. The distributed nature of networks and concurrent transmission from multiple users in uplink, RPRCC needs multiple frequency offset estimation at the receiver. Multiple signal classification (MUSIC) algorithm is the best suited CFO estimation technique in multiuser environment. However the performance of MUSIC algorithm is inferior for closely spaced CFOs. To achieve precise CFO estimation and greater ICI reduction, RPRCC with conjugate weighted MUSIC based CFO estimation is proposed in this paper. The simulation results depict that the ICI power reduction capability and BER performance of the suggested method outperforms the conventional techniques in both properly and closely spaced CFOs.**

***Keywords*— CFO, Conjugate weighted MUSIC, ICI, MUSIC, MC-CDMA, RPRCC.**

I. INTRODUCTION

MC-CDMA combines the best features of orthogonal frequency division multiplexing (OFDM) and CDMA. It supports multimedia services such as audio, video, image and data due to its high data rate, robustness to multipath fading and easy implementation using fast Fourier transform (FFT) and inverse FFT (IFFT). The most popular 4G standard such as LTE and 5G, a real wireless world utilizes the features of OFDM and MC-CDMA (Kumar and Saxena, 2015; Hu *et al*., 2012). MC-CDMA system allows multiple users to access the channel simultaneously by means of frequency domain spreading. With several ICI cancellation schemes, self-cancellation (Zhao and Haggman, 2001) is the simple and low complexity method compared to other methods. Conjugate cancellation (CC) is the second method to mitigate the effect of ICI. It offers time diversity by transmitting signal in two independent paths, in which first path carries the standard MC-CDMA signal and the second path carries the conjugate of first path signal. The conjugate operation at the receiver for second path signal mutually cancels out the ICI effects. However the carrier to interference ratio (CIR) of CC technique is inferior for high value of CFOs compared to normal MC-CDMA system (Yeh *et al*., 2007; Khedr *et al*., 2011). Third method is the phase rotated CC (PRCC) in which the phase rotation is introduced at the transmitter to tune the transmitted signal such that the ICI effects could be cancelled mutually at the receiver. The amount of phase rotation is calculated by estimating CFO at the receiver and feeding back to transmitter (Wang and Huang, 2010). It increases communication overhead and estimation error for time varying channel. To overcome the above shortcomings and for effective utilization of bandwidth in a multiuser environment, RPRCC technique is proposed. It employs CFO estimation and phase rotation at the receiver side.

The commonly used CFO estimation algorithms for multiuser environment are maximum likelihood (ML) and MUSIC. Due to the discontinuity of arc tangent and noise, CFO acquisition range of ML algorithm is limited in $-0.5 \le \varepsilon \le 0.5$ (Mohseni and Matin, 2012; Morelli and Moretti, 2012). It becomes inadequate and furthermore the estimate is no longer unbiased. The estimation range can be extended by using shorter training symbols; however the estimation accuracy is reduced (Schmidl and Cox, 1997). MUSIC algorithm is the Eigen value decomposition (EVD) based CFO estimation technique which extends the estimation range above 0.5.

For low SNR conditions and with closely spaced CFOs, (variation in CFO among users is less) MUSIC algorithm fails to distinguish the contiguous peaks. Hence the original peak location of one user is extended into neighboring users range and severely distorts the actual peak location (Sun and Lin, 2012). As a result, some user CFOs are estimated incorrectly and some of them may be lost. Hence, conjugate weighted MUSIC algorithm is proposed to improve the performance of RPRCC particularly for closely spaced CFOs.

II. MULTIUSER RPRCC

The basic principle of MC-CDMA system is to spread the *m*-th user ($1 \le m \le M$ where M is the number of users)

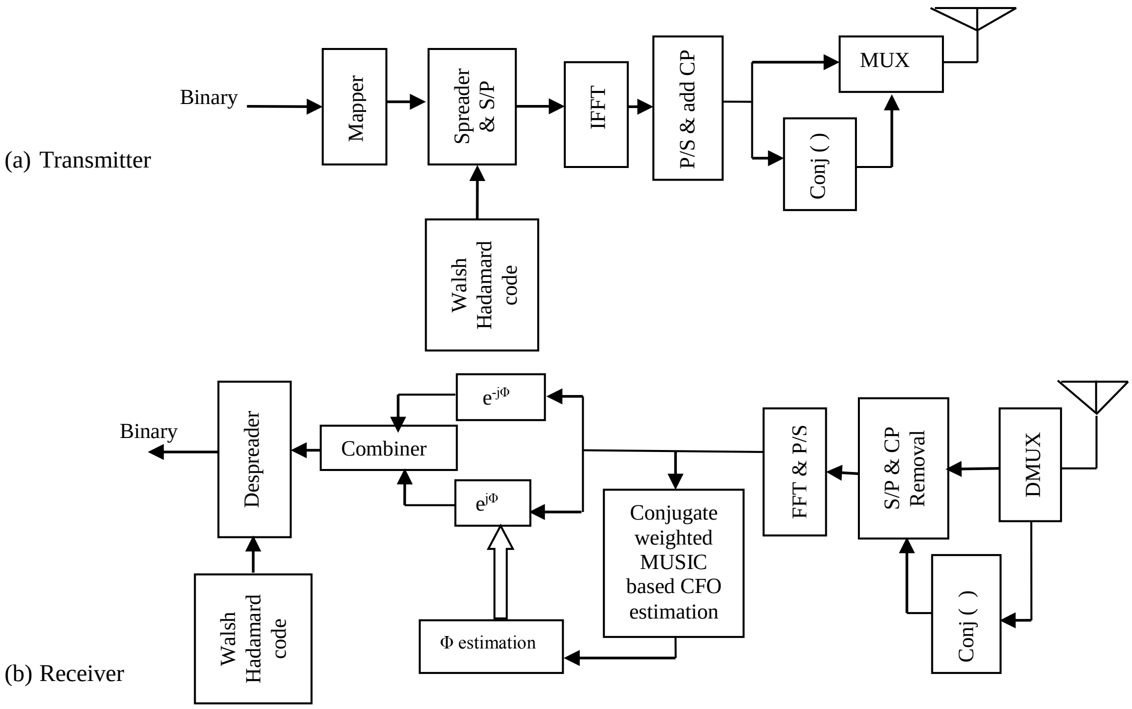

Fig. 1. Block diagram of RPRCC with conjugate weighted MUSIC based CFO estimation (a) Transmitter (b) Receiver

binary data sequence b^m using spreading sequence $C_k^{(m)}$ ($0 \le k \le N$-1, where N is the number of subcarriers). The composite CDMA signals of all the M users are subsequently mapped to N subcarriers using OFDM technique (Fazel and Kaiser, 2008; Hara and Prasad, 1997). The block diagram of RPRCC with conjugate weighted MUSIC based CFO estimation is illustrated in Fig.1.

The k-th chip CDMA signal corresponding to m-th user is expressed as

$$X_k^{(m)} = b^{(m)} C_k^{(m)} \quad k = 0, 1, 2, \cdots, N-1 \tag{1}$$

The complex MC-CDMA signal of m-th user after IFFT block is given by

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

where n=0, 1, 2,…, N-1. The intersymbol interference (ISI) due to multipath channel is reduced by adding cyclic prefix (CP) is with MC-CDMA symbols.

The CP extended MC-CDMA symbol is given by

$$x_n^{(m)} = \frac{1}{N} \sum_{k=0}^{N-1} b^{(n)} C_k^{(m)} \exp(j2\pi nk/N) \tag{3}$$

where n= $-N_c$, $-N_c$+1, ..., 0,1,…,N and N_c is the length of CP. RPRCC technique employed two path transmission such as CC technique at the transmitter in which second path signal is the conjugate of first path signal. The Time division duplexing (TDD) is employed to transmit signals over two transmission paths and are expressed as

$$\begin{aligned} y_n^{(1)} &= x_n \\ y_n^{(2)} &= (x_n)^* \end{aligned} \tag{4}$$

The induced CFO across two successive paths is assumed as same since the channel is slowly time variant.

The channel with transfer function is

$$H_k = \sum_{l=0}^{L-1} h_l \exp(-j2\pi kl/N)$$

where L is the number of multipath components and h_l is the channel impulse response of l-th component. The signal corresponding to one MC-CDMA symbol in uplink receiver is the superposition of all the M user signals. It is assumed that all the M user signals are time synchronized and transmitted over multipath fading channel in which the fading coefficients are constant for one MC-CDMA block.

After the removal of CP, two path noisy received symbols in the presence of multiuser CFO are given as

$$r_n^{(1)} = \frac{1}{N} \sum_{m=1}^{M} \sum_{k=0}^{N-1} H_k^{(m)} b^{(m)} C_k^{(m)} \exp(j2\pi nk/N) \times \exp(j2\pi n\varepsilon^{(m)}/N) + w_n^{(1)} \tag{5}$$

where n=1, 2,…, N and $\varepsilon^{(m)}$ is the m-th user normalized frequency offset.

$$r_n^{(2)} = \frac{1}{N} \sum_{m=1}^{M} \sum_{k=0}^{N-1} H_k^{(m)} b^{(m)} C_k^{(m)} \exp(-j2\pi nk/N) \times \exp(j2\pi n\varepsilon^{(m)}/N) + w_n^{(2)} \tag{6}$$

where $w_n^{(1)}$ and $w_n^{(2)}$ are additive white Gaussian noise (AWGN) in two paths.

In RPRCC, the first path signal component is phase rotated by $-\phi$ and the conjugate of second path signal is phase by ϕ (Wang *et al.*, 2011). The frequency domain representation of two path signals at the output of FFT block are represented by

$$R_p^{(1)} = \sum_{n=0}^{N-1} \frac{1}{N} \sum_{m=1}^{M} \sum_{k=0}^{N-1} H_k^{(m)} b^{(m)} C_k^{(m)} \exp(-j\phi) \times \exp(-j2\pi n(p-k-\varepsilon^{(m)})/N) + w_n^{(1)} \exp(-j2\pi np/N) \tag{7}$$

$$R_p^{(2)} = \sum_{n=0}^{N-1} \frac{1}{N} \sum_{m=1}^{M} \sum_{k=0}^{N-1} (H_k^{(m)})^* b^{(m)} C_k^{(m)} \exp(j\phi) \times \exp(-j2\pi n(p-k+\varepsilon^{(m)})/N) + w_n^{(2)} \exp(-j2\pi np/N) \quad (8)$$

The combined output of both the paths becomes

$$S_p = R_p^{(1)} + R_p^{(2)} \quad (9)$$

Due to oscillator instabilities and Doppler shifts, every user in uplink has its own timing and frequency offsets. The multiple signal classification (MUSIC) algorithm is the spectral estimation method suitable for estimating each user's CFO in the multiuser environment (Wang and Ryu, 2013). MUSIC algorithm is based on EVD of covariance matrix of a received signal where signal and noise subspaces are separated. The assumption in MUSIC algorithm is that all the user CFOs are well spaced (Sun and Lin, 2012).

III. CONJUGATE WEIGHTED MUSIC BASED CFO ESTIMATION

The received wideband multiuser signal is the composition of number of narrowband signal components. The proposed method utilizes non-data aided technique for multiuser CFO estimation. For the multiuser scenario, transmission of training sequences greatly reduces data rate. For CFO estimation, training symbols are extracted from the transmitted sequence and their relative phase is calculated that make the estimation process complex. The received signal corresponding to m-th user is expressed as

$$r_n^{(m)} = \frac{1}{N} \sum_{k=0}^{N-1} H_k^{(m)} b^{(m)} C_k^{(m)} \exp(j2\pi nk/N) \times \exp(j2\pi n\varepsilon^{(m)}/N) \quad (10)$$

At the receiver, sum of all the user signals is represented by

$$r_n = \frac{1}{N} \sum_{m=1}^{M} \sum_{k=0}^{N-1} H_k^{(m)} b^{(m)} C_k^{(m)} \exp(j2\pi nk/N) \times \exp(j2\pi n\varepsilon^{(m)}/N)$$

Hence the noisy received signal corresponding to M users is expressed as

$$r_n = \sum_{m=1}^{M} \alpha_n^{(m)} \exp(j2\pi n\varepsilon^{(m)}) + w_n \quad (11)$$

where

$$\alpha_n^{(m)} = \frac{1}{N} \sum_{m=1}^{M} \sum_{k=0}^{N-1} H_k^{(m)} b^{(m)} C_k^{(m)} \exp(j2\pi nk/N)$$

and w_n is the additive white Gaussian noise (AWGN).

Consider the time window of size L, Eq. 11 can be written in vector form as

$$\mathbf{r_n} = \sum_{m=1}^{M} \alpha_n^{(m)} \mathbf{a_m} \mathbf{e}^{j2\pi n\varepsilon^{(m)}} + \mathbf{w_n} \quad (12)$$

where

$\mathbf{a_m} = \left[1, \mathbf{e}^{j2\pi\varepsilon^{(m)}}, \cdots, \mathbf{e}^{j2\pi(L-1)\varepsilon^{(m)}}\right]^T$, $\mathbf{a} = [\mathbf{a}_1, \mathbf{a}_2, \cdots, \mathbf{a}_M]^T$

$\mathbf{r_n} = [r_n, r_{n+1}, \cdots, r_{n+L-1}]^T$, $\mathbf{w_n} = [w_n, w_{n+1}, \cdots, w_{n+L-1}]^T$.

The first step in MUSIC based CFO estimation is to determine the covariance matrix of the received signal, which is given by

$$\mathbf{R_r} = E[\mathbf{r_n}\mathbf{r_n}^H] \quad (13)$$

where $\mathbf{r_n}^H$ is the Hermition of $\mathbf{r_n}$.,

$$\mathbf{R_r} = \sum_{m=1}^{M} \left|\alpha_n^{(m)}\right|^2 \mathbf{a_m}\mathbf{a_m}^H + \sigma_w^2 \mathbf{I}_L,$$

$\mathbf{I}_L$ is the $L\times L$ identity matrix and σ_w^2 is the variance of noise.

The Eigen decomposition of $\mathbf{R_r}$ is expressed as

$$\mathbf{R_r} = \sum_{i=1}^{L} \lambda_i \mathbf{V}_i \mathbf{V}_i^H \quad (14)$$

where the λ_i are the eigenvalues arranged in descending order and the $\mathbf{V}_i$ are is the corresponding eigenvectors.

Eigenvalues in Eq. 14 can be written as sum of signal power and noise power

$$\lambda_i = L|\alpha_i|^2 + \sigma_i^2 \qquad \text{for} \qquad i \le M. \quad (15)$$

The remaining eigenvalues are due to noise alone

$$\lambda_i = \sigma_i^2 \qquad \text{for} \qquad i > M. \quad (16)$$

Hence covariance matrix can be partitioned in terms of signal and noise eigenvectors

$$\mathbf{R_r} = \sum_{i=1}^{L} [L|\alpha_i|^2 + \sigma_i^2] \mathbf{V}_i \mathbf{V}_i^H + \sum_{i=M+1}^{L} \sigma_i^2 \mathbf{V}_i \mathbf{V}_i^H \quad (17)$$

For each eigenvector $\mathbf{V}_i$, the noise and signal subspaces are orthogonal to each other *i.e.*

$\mathbf{a}_m^H \mathbf{V}_i = 0$ for $m = 1, 2, \cdots, M$ and $i = M+1, M+2, \cdots, L$

The MUSIC estimates corresponding to M frequency offsets (Wen *et al*., 2014) are determined by applying a one-dimensional search of M local maxima.

$$\hat{\varepsilon} = \arg\max_{\varepsilon} \left(\mathbf{a}_m^H \mathbf{V}_n \mathbf{V}_n^H \mathbf{a}_m\right)^{-1} \quad (18)$$

where $\mathbf{V}_n = [\mathbf{V}_{M+1}, \mathbf{V}_{M+2}, \cdots, \mathbf{V}_L]$.

For an ideal case, the noise of channel transfer function is white and has the same eigenvalues. For CFO estimation, covariance matrix is calculated for time window of length L (Wang, 2013). Due to the limited data length, noise eigenvalues is slightly different which causes error in peak search process. To adjust the difference of that noise eigenvalues and to improve the estimation accuracy for closely spaced CFOs, a conjugate weighted MUSIC algorithm is proposed in this paper. The real valued MUSIC estimate of CFO is obtained by minimizing the orthogonality error between $\mathbf{a}$ and $\mathbf{V}_i$

$$\hat{\varepsilon} = \arg\max_{\varepsilon} \left\|\mathbf{a}^H \mathbf{V}_i\right\|^2 \quad (19)$$

Consequently, the non-distinctiveness of columns of $\mathbf{V}_i$ and for any linear combination of these vectors still extents the noise subspace. To analyze their statistical properties, the cost function in Eq. 19 is reformulated with a different but equivalent form as

$$\hat{\varepsilon} = \arg\max_{\varepsilon} \left\|\mathbf{a}^H \mathbf{V}_i \mathbf{V}_i^H\right\|^2 \quad (20)$$

where each row of $\mathbf{a}^H$ is the signal vector corresponding to one of M users. The orthogonal error vector corresponding to each user is given by

$$\boldsymbol{\psi} = vec\left(\mathbf{a}^H \mathbf{V}_i \mathbf{V}_i^H\right)^2. \quad (21)$$

The CFO estimation is carried out at minimum variance in error vector.

$$\hat{\varepsilon} = \arg\max_{\varepsilon}\left(\mathbf{\Psi}^H\mathbf{\Psi}\right). \tag{22}$$

The error vector $\mathbf{\Psi}$ is zero, if the signal and noise subspaces are orthogonal; otherwise there is a significant amount of variance that should be normalized by noise eigenvalues.

Since the noise Eigen values determined for limited data length is slightly different, those noise Eigen values are used to normalize the changes between themselves and are used to maintain the orthogonality between signal and noise subspaces. In order to minimize the orthogonal error between signal and noise subspaces, the conjugate weight matrix is calculated as

$$\boldsymbol{\mu} = 1/\lambda_i \left\|\left(\mathbf{a}^H\mathbf{V}_i\mathbf{V}_i^H\right)^*\right\|^2 \tag{23}$$

where λ_i the noise eigenvalues for is i=M+1, …, L constitutes an orthogonality error. The norm in the above equation returns the Euclidean length of error vector which is given by

$$\boldsymbol{\mu} = \sum_{i=M+1}^{L} 1/\lambda_i \left|\mathbf{a}^H\mathbf{V}_i\mathbf{V}_i^H\right|^2 . \tag{24}$$

The weight matrix $\boldsymbol{\mu}$ is used to reduce orthogonality error in the interval M+1, …, L. The m-th user CFO estimation using conjugate weighted MUSIC algorithm is given by

$$\begin{aligned}\hat{\varepsilon} &= \arg\min_{\varepsilon}\left(\mathbf{a}_m^H\mathbf{V}_n\boldsymbol{\mu}\mathbf{V}_n^H\mathbf{a}_m\right)\\ &= \arg\max_{\varepsilon}\left(\mathbf{a}_m^H\mathbf{V}_n\boldsymbol{\mu}\mathbf{V}_n^H\mathbf{a}_m\right)^{-1}.\end{aligned} \tag{25}$$

The optimum phase rotation for the proposed RPRCC scheme at the receiver is given by

$$\phi = 2\times\pi\times\hat{\varepsilon}\,. \tag{26}$$

The conjugate weighted MUSIC algorithm outperforms conventional MUSIC especially when the number of significant data points at the receiver is relatively small. Further the computational complexity of MUSIC and conjugate weighted MUSIC algorithms are analyzed. The number of operations such as multiplications and additions required for MUSIC estimate are M×[(2L-1)(M[L-M]+M^2)+(ML(2[L-M]-1))].

However conjugate weighted MUSIC algorithm adds M×([L-M](2L-1)+[L-M]-1+L-(M+1)) extra operations for weight matrix calculation to nullify orthogonality error between noise and signal subspaces. The proposed algorithm depicts an improvement in CFO estimation and ICI reduction at the cost of 11.4% increase in computational complexity. The values of M and L considered for complexity analysis are 4 and 16 respectively. Let the channel is slowly time variant, received signal of m-th user is expressed as sum of desired signal and interference. Under perfect channel equalization, the two combined paths output of m-th user is given by

$$\begin{aligned}S_p^{(m)} = {}& X_p^{(m)}(\exp(j\phi)I(\varepsilon^{(m)}) + \exp(-j\phi)I(-\varepsilon^{(m)})) + \\ & \sum_{k=0,k\neq p}^{N-1} X_k^{(m)}[\exp(j\phi)I(p-k+\varepsilon^{(m)}) + \\ & \exp(-j\phi)I(p-k+\varepsilon^{(m)})] + W_1 + W_2\end{aligned} \tag{27}$$

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

The first term in Eq. 27 represents the desired signal term, second term is the ICI and third term is AWGN. The CIR of RPRCC for m-th user is expressed as

$$\mathrm{CIR}_{RPRCC}^{(m)} = \frac{\left|\exp(j\phi)I(\varepsilon^{(m)}) + \exp(-j\phi)I(-\varepsilon^{(m)})\right|^2}{\sum_{k=1}^{N-1}\left|\exp(j\phi)I(k+\varepsilon^{(m)}) + \exp(-j\phi)I(k-\varepsilon^{(m)})\right|^2} . \tag{28}$$

IV. RESULTS AND DISCUSSION

Figure 2 illustrates the Pseudo spectrum estimation using classic MUSIC algorithm. The received signal consists of four CFOs f_1=-0.1, f_2=0.4, f_3=0.42 and f_4=0.6; where two are well-spaced (f_1=-0.1 and f_4=0.6) and two are closely spaced (f_2=0.4 and f_3=0.42). The MUSIC estimate results in two distinct peaks at the CFOs -0.1 and 0.6. However the peaks corresponding to f_2=0.4 and f_3=0.42 have converged, making it impossible to distinguish the two closely spaced CFOs.

Figure 3 illustrates the performance of conjugate weighted MUSIC based CFO estimation algorithm for four CFOs f_1=-0.1, f_2=0.4, f_3=0.42 and f_4=0.6.

The weight matrix in the proposed MUSIC algorithm minimizes orthogonality error between signal and noise subspaces. It normalizes the changes between noise Eigen values which is slightly different from σ_i^2 and minimizes the orthogonality error between signal and noise subspaces

Figure 4 illustrates BER performance comparison of the proposed RPRCC with MLE based RPRCC, MU-SIC based RPRCC and normal MC-CDMA system. The simulation is carried out for four users with randomly considered normalized CFOs of 0.23, 0.21, 0.15 and0.1. The performance is analyzed using QAM modula-

Table 1. Simulation parameters

Parameter	Value
Number of data symbols	62000
Number of subcarriers	64
Number of users	4
Spreading code	Walsh Hadamard
Modulation	QAM
Channel	AWGN, Rayleigh, Rician
Normalized CFO	-1 to 1

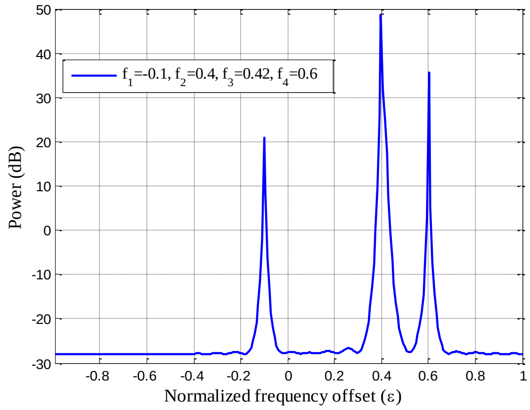

Fig. 2. Illustration of CFO estimation using MUSIC algorithm for f_1=-0.1, f_2=0.4, f_3=0.42 and f_4=0.6

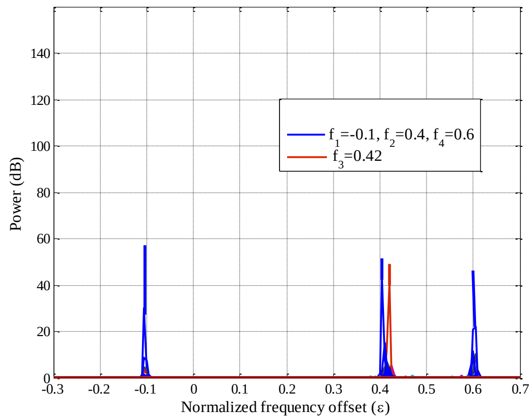

Fig. 3. CFO estimation of the proposed method.

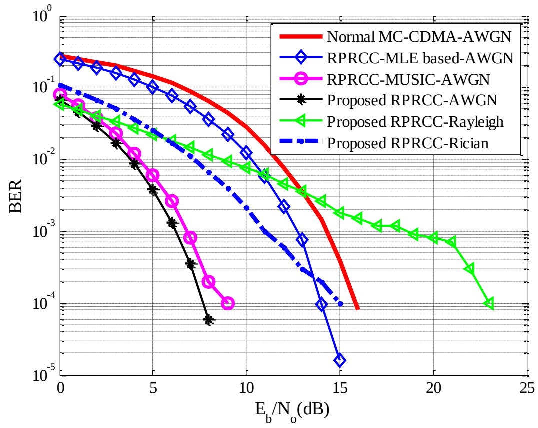

Fig. 4. BER comparison of the proposed method with MUSIC based RPRCC and MLE based RPRCC

tion technique under AWGN, multipath Rayleigh and Rician fading channels (Patil and Bhosle, 2011). The graph depicts that the BER of 10^{-4} is achieved at 7.5 dB, 9 dB and 14 dB in RPRCC with conjugate weighted MUSIC, MUSIC based RPRCC and MLE based RPRCC respectively. The same performance can be achieved at 15 dB and 23 dB for Rician and Rayleigh channels. Due to the precise CFO estimation and greater ICI reduction, the proposed RPRCC outperformed for any kind of CFOs.

Figure 5 and 6 depicts the performance of MUSIC and conjugate weighted MUSIC algorithm for closely spaced CFOs of 0.1, 0.11, 0.12, 0.13, 0.14 and 0.15. The peaks corresponding to ε=0.1 to 0.15 in conventional MUSIC algorithm, has congregated at ε=0.1 and produced high estimation error. However the proposed conjugate weighted MUSIC algorithm produced six peaks corresponding to ε=0.1 to 0.15.

Figure 7 illustrates ICI power comparison of the proposed conjugate weighted MUSIC and conventional MUSIC based CFO estimation for closely spaced CFOs in between 0.1 and 0.15. The proposed method shows improvement in ICI reduction compared to conventional MUSIC algorithm particularly for closely spaced CFOs. In the conventional MUSIC algorithm, peaks corresponding to ε=0. 1 to 0.15 has converged, making it impossible to distinguish the CFOs.

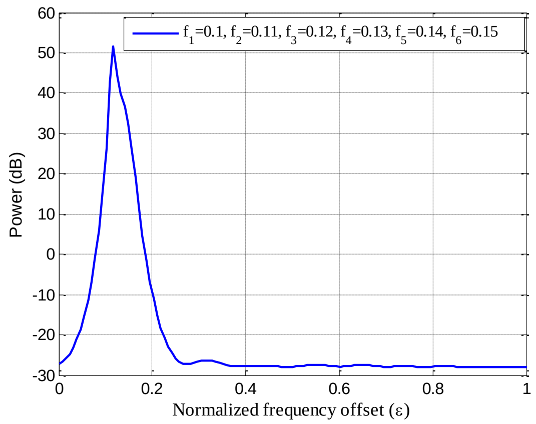

Fig. 5. CFO estimation using MUSIC for closely spaced CFOs of ε=0.1 to 0.15.

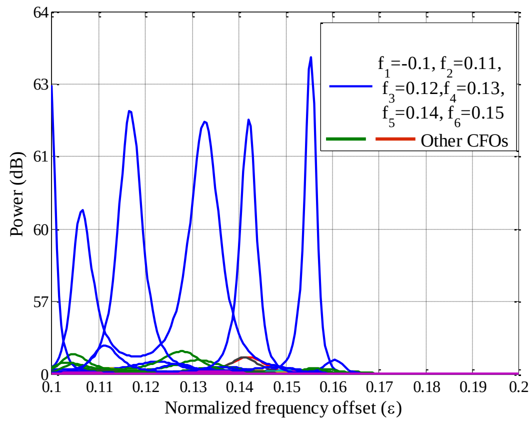

Fig. 6. CFO estimation using conjugate weighted MUSIC for closely spaced CFOs of ε=0. 1 to 0.15.

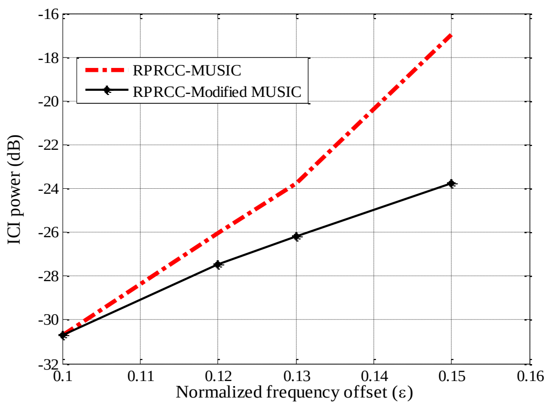

Fig. 7. ICI power comparison of proposed MUSIC with classic MUSIC for closely spaced CFOs.

Hence the CFO estimation corresponds to ε=0.1 to 0.15 is only 0.1 and the phase rotation at the receiver is corresponding to 0.1. Thus the estimation error obtained for ε=0.15 is greater than 0.11, resulting in high ICI power at high CFOs.

Figure 8 illustrates ICI power comparison of the proposed MUSIC based RPRCC technique with MUSIC based RPRCC, MLE based RPRCC and normal MC-CDMA technique for a single user (*m*-th) among M users under the normalized frequency offset values from

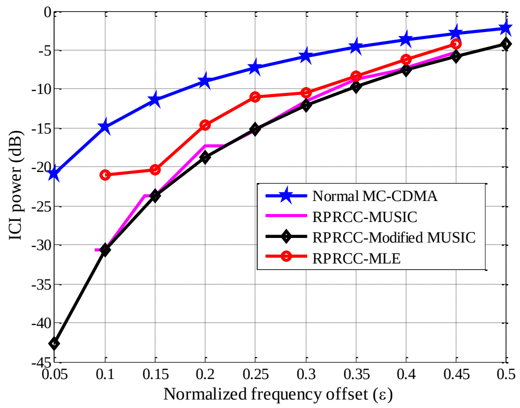

Fig. 8. ICI power comparison of the proposed method with MUSIC and MLE based RPRCC.

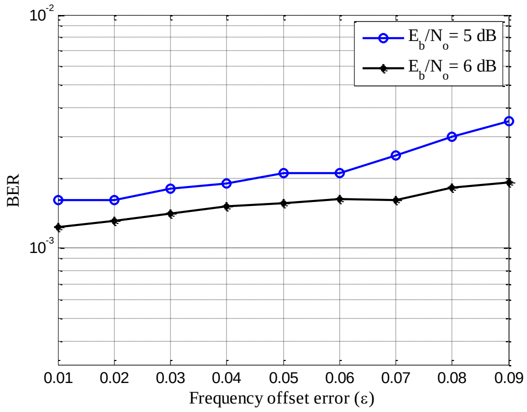

Fig. 9. BER performance of the proposed RPRCC with frequency offset estimation error.

0.05 to 0.5. The desired signal is demodulated from the composite signal of M users with M different CFOs. The self-ICI power of m-th user is plotted in Fig.8. The graph shows that MUSIC algorithm provides the same ICI power for CFOs 0.09 and 0.1, 0.14 and 0.15 as well as 0.2 and 0.22. However the proposed method offered distinct ICI power irrespective of the CFO spacing. However the performance of the proposed algorithm is similar to MUSIC algorithm for well-spaced CFOs.

Figure 9 illustrates the BER performance of the proposed RPRCC with frequency offset estimation error. At the receiver, frequency offset is precisely estimated using conjugate weighted MUSIC algorithm. The maximum estimation error considered for simulation is 0.09 with E_b/N_o of 5 dB and 6 dB (Wen *et al.*, 2014). The number of iterations is 25. The curves clearly depict that the proposed technique carried out CFO estimation under minimum orthogonality error condition and offered high estimation accuracy.

V. CONCLUSIONS

RPRCC with conjugate weighted MUSIC based CFO estimation suitable for multiuser mobile environment is proposed. Compared with MUSIC and MLE algorithms, the proposed method greatly distinguishes closely spaced CFOs and improved the estimation accuracy. The phase rotation at the receiver reduces communication overheads as well as the delay problem encountered in transmitter PRCC technique. Due to the accurate CFO estimation and greater ICI compression, the proposed conjugate weighted MUSIC based RPRCC technique is the best choice to meet the requirements of future multiuser mobile environment.

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