IEICE TRANS. COMMUN., VOL.E94–B, NO.1 JANUARY 2011

LETTER

MCFO Compensation and Performance Analysis for Localized DFT-S-OFDM Uplink Cooperative System

Zhiyan ZHANG[†a)], *Nonmember*, Jianhua ZHANG[†], *Member*, Wei XU[†], Yanyan ZHANG[†], *Nonmembers*, *and* Yi LIU[†], *Student Member*

SUMMARY In the localized Discrete Fourier Transform-Spread-Orthogonal Frequency Division Multiplexing (DFT-S-OFDM) uplink cooperative system, multiple carrier frequency offsets (MCFO), arising from the nodes' separate oscillators and Doppler spreads, drastically degrade the performance of the receiver. To solve the problem, this letter proposes an efficient MCFO compensation method which fully exploits the diversity gain of space frequency block coded (SFBC) and the characteristic of inter-carrier interference (ICI). Moreover, the bit error ratio (BER) lower bound of the proposed algorithm is theoretically derived. Simulation results validate the theoretical analysis and demonstrate that the proposed MCFO compensation method can achieve robust BER performance in a wide range of MCFO in the multipath Rayleigh fading channel.

key words: *DFT-S-OFDM, MCFO compensation, SFBC, BER lower bound*

1. Introduction

Cooperative communication and single carrier frequency division multiple access (SC-FDMA) have attracted much attention in wireless communication in recent years. Cooperative communication creates a virtual antenna array which obtains spatial diversity and enhances bandwidth efficiency, power efficiency and reliability [1]. SC-FDMA combines the desirable characteristics such as low peak-to-average power ratio (PAPR), robustness against the frequency-selective channel and simple implementation. As one implementation of SC-FDMA in Evolved Universal Terrestrial Radio Access (E-UTRA), Discrete Fourier Transform-Spread-Orthogonal Frequency Division Multiplexing (DFT-S-OFDM) has been specified in the 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE) [2].

Frequency synchronization is a major challenge in multiuser uplink cooperative system. Since each transmitting node has a separate local oscillator and independent Doppler spread, multiple carrier frequency offsets (MCFO) exist at the destination and result in inter-carrier interference (ICI) and multiple access interference (MAI). Frequency synchronization for DFT-S-OFDM uplink cooperative system is achieved via MCFO estimation and compensation. The former is rather straightforward: the methods in [3], [4] can be applied. However, there has been very few work focused on MCFO compensation so far. In [5], a minimum mean square error (MMSE) decision feedback equalizer (DFE) is employed at the receiver, where matrix inversion calculation is required. The MCFO compensation methods of [6] and [7] limit the range of the normalized frequency offset among every node within less than 0.1.

A novel MCFO compensation algorithm for DFT-S-OFDM uplink cooperative system is proposed in this letter. It can achieve robust the bit error ratio (BER) performance in a wide range of MCFO, while matrix inversion calculation is avoided. Furthermore, the effect of MCFO on the BER performance for the proposed algorithm is analyzed and the BER lower bound in the multipath fading channel is also derived.

2. System Model

2.1 DFT-S-OFDM Cooperative System Model

In this letter, the uplink cooperative system consists of Q source nodes, one relay node and one destination node. We employ the transmit diversity protocol proposed by 802.16j in [8] involving two phases within each frame. More specifically, in the listening phase the sources only transmit message to the relay and the relay is assumed to detect the message from the sources perfectly. During the cooperation phase, the relay re-encodes the message and transmits it cooperatively with the sources with a structure of the distributed Alamouti space frequency block coded (SFBC). Hence, the decode-and-forward (DF) relaying scheme is adopted. This process is illustrated in Fig. 1.

The DFT-S-OFDM operation consists of DFT, sub-carrier mapping, inverse fast Fourier transform (IFFT) and cyclic prefix (CP) insertion. Consider multiuser DFT-S-

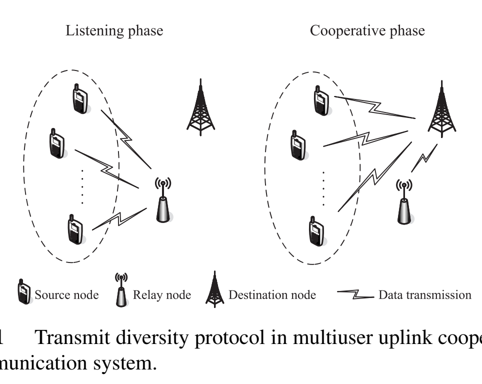

Fig. 1 Transmit diversity protocol in multiuser uplink cooperative communication system.

Manuscript received April 7, 2010.
Manuscript revised August 11, 2010.

[†]The authors are with the Wireless Technology Innovation Institute, Beijing University of Posts and Telecommunications, Beijing, 100876, P.R. China.
a) E-mail: zhangzhiyanwti@gmail.com

DOI: 10.1587/transcom.E94.B.285

OFDM cooperative system consisting of N subcarriers and Q users. N subcarriers are divided into Q subchannels, and each subchannel has $P = N/Q$ subcarriers. Each user transmits its data only in its exclusive subchannel. In this letter, the localized carrier assignment scheme is employed and $\Gamma_q = \{(q-1)P, (q-1)P+1, \ldots (q-1)P+P-1\}$, $q = 1, \ldots, Q$ denotes the subcarrier set assigned to user q.

2.2 Signal Model

In the cooperation phase, for the q-th user, the IFFT output of either source or relay node can be written as

$$x_{\alpha}^{(q)}(n) = \frac{1}{\sqrt{N}} \sum_{u=(q-1)P}^{(q-1)P+P-1} X_{\alpha,u}^{(q)} e^{j2\pi un/N}, 0 \le n \le N-1 \quad (1)$$

where signal associated with the source node is subscripted with sd and similarly for the relay node. $X_{\alpha,u}^{(q)}, \alpha = \{sd, rd\}$ are the modulated signals of user q at subcarrier u at the source or relay terminal respectively, which are encoded by SFBC coder as

$$\begin{aligned} \mathbf{X}_{sd}^{(q)} &= \left[X_{(q-1)P}^{(q)}, -X_{(q-1)P+1}^{*(q)}, \cdots, X_{(q-1)P+p-2}^{(q)}, -X_{(q-1)P+p-1}^{*(q)}\right]^T \\ \mathbf{X}_{rd}^{(q)} &= \left[X_{(q-1)P+1}^{(q)}, X_{(q-1)P}^{*(q)}, \cdots, X_{(q-1)P+p-1}^{(q)}, X_{(q-1)P+p-2}^{*(q)}\right]^T \end{aligned} \quad (2)$$

where $\left[X_{(q-1)P}^{(q)}, X_{(q-1)P+1}^{(q)}, \cdots, X_{(q-1)P+p-2}^{(q)}, X_{(q-1)P+p-1}^{(q)}\right]^T$ is the signal transmitted from the source node in the listening phase.

The time-variant multipath fading channel between the transmitter and the receiver is characterized by

$$h_{\alpha}^{(q)}(\tau, n) = \sum_{l=1}^{L} h_{\alpha,l}^{(q)}(n)\, \delta\left(\tau - \tau_{\alpha,l}^{(q)}\right) \quad (3)$$

where L is the maximal path number of all links, $h_{\alpha,l}^{(q)}$ and $\tau_{\alpha,l}^{(q)}, \alpha = \{sd, rd\}$ are the channel impulse response (CIR) and time delay of the l-th path.

At the destination node, the received signal is the mixture of the signals from all nodes and the noise. Therefore, assuming perfect time synchronization and CP removing, it can be written as

$$r(n) = \sum_{q=1}^{Q} \gamma_{sd}^{(q)}(n) + \gamma_{rd}^{(R)}(n) + w(n) \quad (4)$$

where $w(n)$ is the complex additive white Gaussian noise (AWGN) with zero-mean and variance of σ_w^2.

$$\begin{aligned} \gamma_{sd}^{(q)}(n) &= e^{j2\pi\xi^{(q)}n/N} \frac{1}{\sqrt{N}} \sum_{u=(q-1)P}^{(q-1)P+P-1} X_{sd,u}^{(q)} H_{sd,u}^{(q)} e^{j2\pi un/N} \\ \gamma_{rd}^{(R)}(n) &= e^{j2\pi\xi^{(R)}n/N} \frac{1}{\sqrt{N}} \sum_{q=1}^{Q} \sum_{u=(q-1)P}^{(q-1)P+P-1} X_{rd,u}^{(q)} H_{rd,u}^{(q)} e^{j2\pi un/N} \end{aligned} \quad (5)$$

where $\xi^{(q)}$ is the normalized CFO between user q and the destination, and $\xi^{(R)}$ is defined similarly. The channel transfer function (CTF), $H_{\alpha}^{(q)}$, is the FFT of $h_{\alpha}^{(q)}, \alpha \in \{sd, rd\}$.

3. Proposed MCFO Compensation Algorithm

In order to eliminate ICI and MAI caused by MCFO in DFT-S-OFDM uplink cooperative system, an efficient MCFO compensation algorithm is proposed in this section. Figure 2 shows the algorithm architecture. Channel knowledge including MCFO at the destination node is assumed to be available, through the pilot sequence (see [3], [4] and references therein). For the sake of simplicity, the algorithm will be only explained for user q, and it will be the same for other users.

1) MCFO correcting: At the destination, for user q, the received signal is interfered by both $\xi^{(q)}$ and $\xi^{(R)}$. In order to utilize the diversity gain of SFBC fully, the received signal $r(n)$ is corrected with the estimated CFO of each link respectively, and two sets of signals are obtained.

$$\begin{aligned} y_{sd}^{(q)}(n) &= r(n) e^{-j\frac{2\pi\xi^{(q)}n}{N}} \\ y_{rd}^{(q)}(n) &= r(n) e^{-j\frac{2\pi\xi^{(R)}n}{N}} \end{aligned} \quad (6)$$

2) FFT and subcarrier selecting: The corrected signals $y_{\alpha}^{(q)}(n), \alpha \in \{sd, rd\}$ are decomposed into subcarriers by FFT.

$$Y_{\alpha}^{(q)}(k) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} y_{\alpha}^{(q)}(n) e^{-j2\pi nk/N}, 0 \le k \le N-1 \quad (7)$$

Then $Y_{\alpha}^{(q)}(k), (q-1)P \le k \le (q-1)P+P-1$ are selected for user q. After subcarrier separation, there is almost no inter-user interference, which is beneficial for frequency compensation.

3) Equal Gain Combining (EGC): Combining with formula (2), the corrected signals in frequency domain can be rewritten as

$$\begin{aligned} Y_{sd}^{(q)}(k) &= X_k^{(q)} H_{sd,k}^{(q)} + \beta X_{k+1}^{(q)} H_{rd,k}^{(q)} + \Xi_{sd}^{(q)}(k) \\ Y_{sd}^{(q)}(k+1) &= -X_{k+1}^{*(q)} H_{sd,k+1}^{(q)} + \beta X_k^{*(q)} H_{rd,k+1}^{(q)} + \Xi_{sd}^{(q)}(k+1) \end{aligned} \quad (8)$$

$$\begin{aligned} Y_{rd}^{(q)}(k) &= \beta^* X_k^{(q)} H_{sd,k}^{(q)} + X_{k+1}^{(q)} H_{rd,k}^{(q)} + \Xi_{rd}^{(q)}(k) \\ Y_{rd}^{(q)}(k+1) &= -\beta^* X_{k+1}^{*(q)} H_{sd,k+1}^{(q)} + X_k^{*(q)} H_{rd,k+1}^{(q)} + \Xi_{rd}^{(q)}(k+1) \end{aligned} \quad (9)$$

where $\Xi_{\alpha}^{(q)}(k)$ and $\Xi_{\alpha}^{(q)}(k+1)$ denote the interference plus

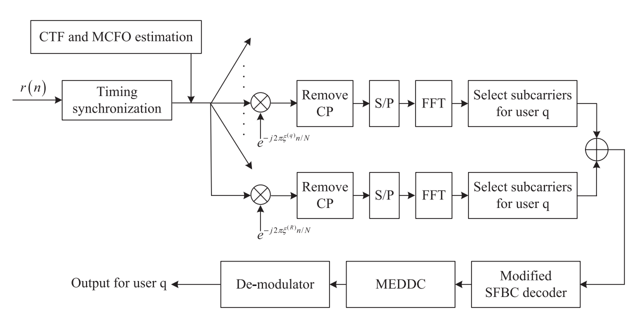

Fig. 2 Receiver architecture of proposed MCFO compensation algorithm in DFT-S-OFDM uplink cooperative system.

noise component on subcarrier k and $k+1$. β is the ICI/MAI coefficient caused by MCFO, and it is defined as

$$\beta = \frac{1}{N} e^{j\pi \frac{N-1}{N}\left(\xi^{(R)}-\xi^{(q)}\right)} \frac{\sin\left(\pi\left(\xi^{(R)}-\xi^{(q)}\right)\right)}{\sin\left(\pi\frac{\left(\xi^{(R)}-\xi^{(q)}\right)}{N}\right)} \tag{10}$$

According to the Alamouti SFBC structure, CTF is assumed to remain constant during at least two neighboring subcarriers, i.e. $H_{\alpha,k}^{(q)} = H_{\alpha,k+1}^{(q)}, \alpha \in \{sd, rd\}$. Neither $Y_{sd}^{(q)}(k)$ nor $Y_{rd}^{(q)}(k)$ is accurate enough. However, the ICI items of $\Xi_{sd}^{(q)}(k)$ and $\Xi_{rd}^{(q)}(k)$ can be partially canceled through combination. Therefore, combining (8) and (9), we can get:

$$\begin{aligned} Y^{(q)}(k) &= \gamma^* X_k^{(q)} H_{sd,k}^{(q)} + \gamma X_{k+1}^{(q)} H_{rd,k}^{(q)} + \Xi^{(q)}(k) \\ Y^{(q)}(k+1) &= -\gamma^* X_{k+1}^{*(q)} H_{sd,k}^{(q)} + \gamma X_k^{*(q)} H_{rd,k}^{(q)} + \Xi^{(q)}(k+1) \end{aligned} \tag{11}$$

where $\gamma = \frac{(1+\beta)}{2}$, $\Xi^{(q)}(k) = \frac{\Xi_{sd}^{(q)}(k)+\Xi_{rd}^{(q)}(k)}{2}$, $\Xi^{(q)}(k+1) = \frac{\Xi_{sd}^{(q)}(k+1)+\Xi_{rd}^{(q)}(k+1)}{2}$.

4) Modified SFBC decoding: A modified SFBC decoder is employed, in which the decoded signals on two neighboring subcarriers are respectively given by

$$\begin{aligned} \hat{X}^{(q)}(k) &= \frac{\gamma H_{sd,k}^{*(q)} Y^{(q)}(k) + \gamma H_{rd,k}^{(q)} Y^{*(q)}(k+1)}{\left(|\gamma|^2 \left|H_{sd,k}^{(q)}\right|^2 + |\gamma|^2 \left|H_{rd,k}^{(q)}\right|^2\right)} \\ \hat{X}^{(q)}(k+1) &= \frac{\gamma^* H_{rd,k}^{*(q)} Y^{(q)}(k) - \gamma^* H_{sd,k}^{(q)} Y^{*(q)}(k+1)}{\left(|\gamma|^2 \left|H_{sd,k}^{(q)}\right|^2 + |\gamma|^2 \left|H_{rd,k}^{(q)}\right|^2\right)} \end{aligned} \tag{12}$$

5) Minimum Euclidean distance decision criterion (MEDDC): The Euclidean distances from $\hat{X}^{(q)}(k)$ to all constellation points are compared. Then, the constellation point with the smallest Euclidean distance is chosen.

$$\hat{X}_{MEDDC}(k) = \arg\min_{\vartheta_i}\left(\left\|\hat{X}^{(q)}(k) - \vartheta_i\right\|\right) \tag{13}$$

where ϑ_i is the coordinate of the ith constellation point and $i = 1, 2, \cdots, M$ for M-ary modulation and $\|\cdot\|$ is the Euclidean norm.

4. BER Performance Analysis

In this section, the BER lower bound of the proposed algorithm in the multipath Rayleigh channel will be derived. By utilizing the modified SFBC decoder, the decoded signals can be expressed as

$$\begin{aligned} \hat{X}^{(q)}(k) &= X^{(q)}(k) + \frac{\gamma H_{sd,k}^{*(q)} \Xi^{(q)}(k) + \gamma H_{rd,k}^{(q)} \Xi^{*(q)}(k+1)}{\left(|\gamma|^2 \left|H_{sd,k}^{(q)}\right|^2 + |\gamma|^2 \left|H_{rd,k}^{(q)}\right|^2\right)} \\ \hat{X}^{(q)}(k+1) &= X^{(q)}(k+1) + \frac{\gamma^* H_{rd,k}^{*(q)} \Xi^{(q)}(k) - \gamma^* H_{sd,k}^{(q)} \Xi^{*(q)}(k+1)}{\left(|\gamma|^2 \left|H_{sd,k}^{(q)}\right|^2 + |\gamma|^2 \left|H_{rd,k}^{(q)}\right|^2\right)} \end{aligned} \tag{14}$$

Then the instantaneous signal to interference and noise ratio (SINR) of the kth subcarrier is depicted as

$$SINR_k = \frac{\sigma_x^2 (|\gamma|^2 \left|H_{sd,k}^{(q)}\right|^2 + |\gamma|^2 \left|H_{rd,k}^{(q)}\right|^2)}{\xi(k) \cdot \sigma_x^2 + \sigma_W^2} \tag{15}$$

where $\xi(k)$ denotes the nonnegative ICI/MAI power coefficient, which is the function of $H_{\alpha,u}^{(l)}, l = 1, \cdots, Q, u \neq k$.

According to [9], the instantaneous BER of the kth subcarrier conditioned on $H_{\alpha,k}^{(q)}$, is approximately given by

$$\begin{aligned} P_{con}(k) &\simeq \frac{2}{\log_2 M} Q\left(\sin\frac{\pi}{M}\sqrt{2 \cdot SINR_k}\right) \\ &= \frac{2}{\log_2 M} Q\left(\sqrt{2\sin^2\frac{\pi}{M} \cdot \frac{\sigma_x^2|\gamma|^2(\left|H_{sd,k}^{(q)}\right|^2 + \left|H_{rd,k}^{(q)}\right|^2)}{\xi(k)\cdot\sigma_x^2 + \sigma_W^2}}\right) \end{aligned} \tag{16}$$

$P_{con}(k)$ is a monotonically increasing function with respect to $\xi(k)$ and $\xi(k)$ is nonnegative, therefore $SINR_k$ can be upper bounded as

$$SINR_k \le SINR_{HB} = \frac{\sigma_x^2 |\gamma|^2 (\left|H_{sd,k}^{(q)}\right|^2 + \left|H_{rd,k}^{(q)}\right|^2)}{\sigma_W^2} \tag{17}$$

and then the lower bound of $P_{con}(k)$ can be expressed as

$$P_{con}(k) \ge P_{LB}(k) = \frac{2}{\log_2 M} Q\left(\sqrt{2\varsigma\left(\left|H_{sd,k}^{(q)}\right|^2 + \left|H_{rd,k}^{(q)}\right|^2\right)}\right) \tag{18}$$

where $\varsigma = \sin^2\left(\frac{\pi}{M}\right) \cdot \frac{|\gamma|^2\sigma_x^2}{\sigma_W^2}$.

Therefore, the average BER lower bound for the kth subcarrier can be expressed as

$$P_{b,LB}(k) = \int_0^\infty p(z_k) P_{LB}(k) dz_k \tag{19}$$

where $z_k = \left|H_{sd,k}^{(q)}\right|^2 + \left|H_{rd,k}^{(q)}\right|^2$, $H_{\alpha,k}^{(q)}, \alpha \in \{sd, rd\}$ are independent Rayleigh random variables. z_k can be modeled as a chi-square random variable of freedom degrees-4 with expectation of $2\sigma_H^2$. In consequence, the probability density function (PDF) of z_k can be expressed as

$$p(z_k) = \frac{1}{4\sigma_H^4} \cdot z_k \cdot e^{-z_k/2\sigma_H^2}, z_k \ge 0 \tag{20}$$

Therefore the formula (19) can be rewritten as

$$\begin{aligned} P_{b,LB}(k) &= \frac{2}{\log_2 M} \int_0^\infty p(z_k) \int_{\sqrt{2\varsigma z_k}}^\infty \frac{1}{\sqrt{2\pi}} e^{-y^2/2} dy dz_k \\ &= \frac{1}{\log_2 M} \cdot \left(1 - \frac{\left(2\varsigma\sigma_H^2\right)^{1/2}\left(4\varsigma\sigma_H^2 + 3\right)}{2\left(2\varsigma\sigma_H^2 + 1\right)^{3/2}}\right) \end{aligned} \tag{21}$$

where $P_{b,LB}(k)$ is constant with respect to k. Then, we average over all subcarriers and obtain the general BER as

$$P_{b,LB} = \frac{1}{N}\sum_{k=0}^{N-1} P_{b,LB}(k) = P_{b,LB}(k) \tag{22}$$

5. Analytical and Simulation Results

To evaluate the performance of the proposed MCFO compensation algorithm for uplink DFT-S-OFDM cooperative system, simulations are performed in this section. The basic simulation parameters, referring to 3GPP LTE, are summarized in Table 1. To simulate the practical wireless channel and mobile environment, Spatial Channel Model (SCM) is employed. The frequency offsets are chosen to be independent random variables with the uniform distribution in the interval $\left[-\frac{\xi_{\max}}{2}, \frac{\xi_{\max}}{2}\right]$, i.e. $\left|\xi^{(q)} - \xi^{(l)}\right| \le \xi_{\max}, \left|\xi^{(q)} - \xi^{(R)}\right| \le \xi_{\max}$, $l = 1, \cdots, Q, l \neq q$. Sreedhar's MCFO compensation method introduced in [7] is also simulated for comparison.

Figure 3 illustrates the comparison between derived theoretical BER lower bound and simulated BER performance. The options of $\xi^{(q)} = \xi^{(R)}$ and $\xi^{(q)} \neq \xi^{(R)}$ are both considered. It can be observed that the derived BER lower bound can match the simulated curves. Furthermore, with the increase of $\left|\xi^{(q)} - \xi^{(R)}\right|$, either theoretical BER lower bound or simulated BER performance degrades. It can be explained: due to the power leakage caused by MCFO, SINR decreases, which leads to the degradation of BER performance.

Figure 4 compares the uncoded BER performance of traditional SFBC decoder, Sreedhar's method with parallel interference canceling (PIC) and proposed MCFO compensation algorithm. It can be seen that although Sreedhar's method can improve the BER performance when $\xi_{\max}$ is 0.2, both traditional SFBC decoder and Sreedhar's method are invalid when $\xi_{\max}$ gets larger, e.g. 0.4. When $\xi_{\max}$ is 0.2 and 0.4, simulation curves of the proposed MCFO method are very close, which means that ICI and MAI caused by MCFO can be greatly eliminated and the BER performance degradation can be effectively reduced.

Table 1 Simulation parameters.

Parameter	Value	Parameter	Value
Center frequency	2 GHz	Sampling frequency	7.68 MHz
Band width	5 MHz	Subcarrier number	512
Subcarrier spacing	15 kHz	OFDM length	76.12 μs
CP length	4.69 μs	Modulation	QPSK
Channel model	SCM	Scenario	urban macro
Path number	6	Drop number	200000

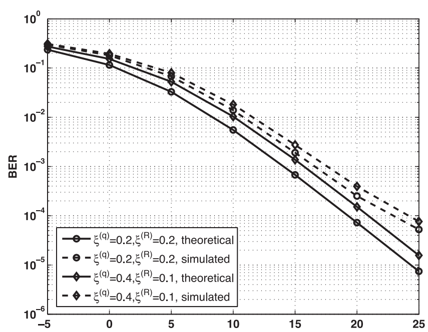

Fig. 3 Comparison between derived theoretical BER lower bound and simulated BER performance.

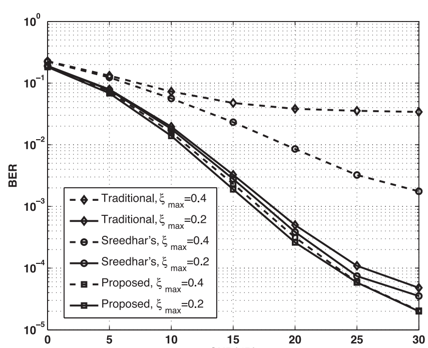

Fig. 4 Uncoded BER performance among traditional SFBC decoder, Sreedhar's method and proposed MCFO compensation algorithm in uplink cooperative communication system.

6. Conclusion

This letter proposes an efficient MCFO compensation algorithm consisting of MCFO correcting, EGC, modified SFBC decoder and MEDDC to eliminate ICI and MAI caused by MCFO for localized DFT-S-OFDM uplink cooperative system. Furthermore, the BER lower bound of the proposed algorithm is analysed and derived. By utilizing the proposed algorithm, the BER performance degradation can be reduced to be ignorable with the extension of MCFO range in the multipath Rayleigh channel, which demonstrates the robustness of the proposed algorithm. Therefore, the proposed MCFO compensation algorithm can be applied in multiuser cooperative communication system even if the frequency offsets are large.

Acknowledgment

This work was supported by National Natural Science Foundation of China under Grant NO. 60772113, and China 863 Program under Grant NO. 2009AA011502.

References

[1] S.J. Lee, J.S. Yoon, and H.K. Song, "Carrier frequency offset mitigation using MSE-OFDM in cooperative communications," Proc. Australasian Telecommunication Networks and Applications Conference ATNAC 2008, pp.76–79, Dec. 2008.
[2] S. Sesia, I. Toufik, and M. Baker, LTE-The UMTS Long Term Evolution: From Theory to Practice, John Wiley & Sons, 2009.
[3] P.A. Parker, D.W. Bliss, P. Mitran, and V. Tarokh, "Adaptive frequency synchronization for collaborative communication systems," Proc. 27th International Conference on Distributed Computing Systems Workshops ICDCSW'07, pp.82–82, June 2007.
[4] P.A. Parker, P. Mitran, D.W. Bliss, and V. Tarokh, "On bounds and algorithms for frequency synchronization for collaborative communication systems," IEEE Trans. Signal Process., vol.56, no.8, pp.3742–3752, Aug. 2008.
[5] N. Benvenuto, S. Tomasin, and D. Veronesi, "Multiple frequency offsets estimation and compensation for cooperative networks," Proc. IEEE Wireless Communications and Networking Conference WCNC 2007, pp.891–895, March 2007.

[6] Z. Li, W. Zhang, and G. Zhu, "On detection of distributed STBC-OFDM system with multiple carrier frequency offsets," Proc. VTC 2006-Spring Vehicular Technology Conference IEEE 63rd, pp.2130–2134, May 2006.
[7] D. Sreedhar and A. Chockalingam, "ICI-ISI mitigation in cooperative SFBC-OFDM with carrier frequency offset," Proc. IEEE 18th International Symposium on Personal, Indoor and Mobile Radio Communications PIMRC 2007, pp.1–5, Sept. 2007.
[8] C.G. Kang and H.S. Ryu, "Cooperative diversity schemes for multi-hop relay system," July 2006.
[9] S. Wilson, Digital Modulation and Coding, Prentice Hall, 1996.