Performance Analysis of An Improved ICI-Cancellation Scheme with I/Q imbalance Compensation in TFI-OFDM Systems

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***Abstract*—The inter-carrier interference (ICI) caused by carrier frequency offset (CFO) and inphase and quadrature (I/Q) imbalance at the tranceiver will bring about serious problems in high-speed OFDM systems since the orthogonality among subcarriers is destroyed and it has great impact on the system performance. Various techniques have been developed to combat the effects of the CFO and the IQ imbalance in the analog front-end. However, these methods are either too complicated or use a large number of pilot signals. A system that less sensitive to CFO and I/Q imbalance is required at the receiver for LTE-advanced system. In this paper, the ICI self-cancellation (ICI SC) scheme is proposed to mitigate the CFO effect in a general implementation framework with I/Q imbalance compensation. ICI and optimum CIR (carrier to interference power ratio) are derived and discussed. Moreover, by utilizing time-frequency interferometry (TFI) pilot signal and energy clipping method, through analysis and simulations, we can determine the predefined weighting coefficients to achieve the best BER performance. It is demonstrated by the computer simulations that the proposed scheme can make improvement of the BER performance compared to the conventional ICI SC methods.**

***Index Terms*—ICI, ICI SC, CFO, I/Q imbalance, TFI-OFDM**

I. Introduction

ORTHOGONAL frequency division multiplexing (OFDM) has been considered as a promising technology in wideband digital communication for high data rate applications. Due to higher spectrum efficiency and robustness to multipath fading channels, it has been adopted in various communication standards such as worldwide interoperability for microwave access (WiMAX), wireless local area networks (WLAN), and digital terrestrial video broadcasting (DVB-T). OFDM is sensitive to the distortion associated with the carrier signal [1] including mismatches between I and Q branches in the OFDM direct conversion receivers and the CFO due to Doppler frequency or the physically inherent nature of the oscillators. In this case, the orthogonality between subcarriers is destroyed, which implies a subcarrier frequency component is affected by other subcarrier frequency components that leads to ICI. To mitigate the disadvantage, numerous algorithms have been developed in improving the system performance including schemes with improved decoding reliability [2], windowing function in the time domain [3], diversity-based ICI cancellation approach [4], frequency-domain equalization [5], carrier frequency offset estimation and compensation methods [6]-[9]. However, these methods require high implementation complexity and there has been almost no consideration for the possible influence of I/Q imbalance. On the other hand, some of the existing compensation methods for I/Q imbalance are without considering CFO [17]-[19]. It is critical to have an efficient and convenient way to solve the CFO problems in the presence of I/Q imbalance. Recently, the ICI self-cancellation (ICI SC) techniques that it is less sensitive to CFO have been extensively investigated. The basic idea of the general ICI SC schemes is that the same data symbol is mapped onto two subcarriers with predefined weighting coefficients to cancel the ICI components. Zhao et al. [10] presented a simple yet effective way for ICI SC that modulate the same data symbol on two adjacently located subcarriers with predefined inversed phase coefficients and the ICI components can be eliminated to some extent either using first-order constant method or first-order linear method. Plural weighted data-conversion algorithm in [11] can mitigate phase error compared to [10] and robust to the impact of frequency offset at low CFO. ICI SC of data-conjugate method is studied to reduce ICI effectively in [12]. Since the received signal is considered as the circular convolution of transmitted signal, the symmetric conjugate weighting coefficients are used to eliminate the effect of phase noise in [13]. This technique can tolerate phase noise of 7 deg with a BER of 10^{-3} [16] and CIR performance is improved. The methods in [14]-[15] utilize weighted conjugate transformation with different phase angles. However, it lacks theoretical analysis to determine rotated phases. To analyze the CIR and BER in a generalized frame work, we proposed a real constant and plural weighted data-conjugate scheme in the transmitter, furthermore, the modulation mode of desired signal after I/Q imbalance compensation is discussed in receiver. In the proposed schemes, different data allocation is used to modulate one data symbol onto the next subcarrier with predefined weighting coefficients to mitigate the phase error after I/Q imbalance compensation.

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In the following section, TFI-OFDM system and the effect of ICI are introduced. In Section III, a joint I/Q imbalance compensation and ICI SC schemes are proposed in TFI-OFDM system. In section IV, the simulation results are shown. Finally, a conclusion is given in section V.

II. OFDM SIGNAL MODEL AND ANALYSIS OF ICI

A. Signal Model

In this paper, we use the TFI-OFDM system model to clarity the benefit of the proposed method [20]-[23]. The transmitter block diagram of TFI-OFDM system is illustrated in Fig. 1. The received baseband signal with I/Q imbalance and CFO can be represented by

$$\bar{y}(t) = \zeta e^{-j\Delta\omega t} y(t) + \xi e^{j\Delta\omega t} y^{*}(t) \tag{1}$$

where

$$\begin{cases} \zeta = \cos(\phi) - j\Delta\sin(\phi) \\ \xi = \Delta\cos(\phi) + j\sin(\phi) \end{cases} \tag{2}$$

Δ and ϕ are amplitude and phase mismatches. $y(t)$ is the baseband received signal.

$$y(t) = \int_{-\infty}^{\infty} h(\tau,t)x(t-\tau)d\tau + n(t) \tag{3}$$

where h and τ are the complex channel gain and the time delay, respectively. $n(t)$ is additive Gaussian noise process with a single side-band power spectrum of N_0 and $x(t)$ is transmitted baseband OFDM signal.

$$\begin{aligned} x(t) = \sum_{i=0}^{N_p+N_d-1} g(t-iT)\cdot\Big\{\sqrt{\frac{2S}{N_c}}\sum_{k=0}^{N-1} u(k,i) \\ \cdot\exp[j2\pi(t-iT)k/T_s]\Big\} \end{aligned} \tag{4}$$

where N_d and N_p are the number of data and pilot symbols, T_s is the sampling time. T is the OFDM symbol length. N is the total number of subcarriers, S is average transmitting power, $g(t)$ is the transmission pulse, respectively. After the FFT operation, Eq. (1) becomes

$$\begin{aligned} \tilde{Y}(k,i) = \sqrt{\frac{2S}{N}}\Big[\zeta H(k,i)X(k,i)S(0) + \xi H^{*}(N-1-k,i) \\ \cdot X^{*}(N-1-k,i)S(0)^{*} + \sum_{l\neq k}\zeta H(l,i)X(l,i)S(l-k) \\ + \sum_{l\neq N-1-k}\xi H^{*}(N-1-l,i) \\ \cdot X^{*}(N-1-l,i)S(N-1-l-k)\Big] + \omega(k,i) \end{aligned} \tag{5}$$

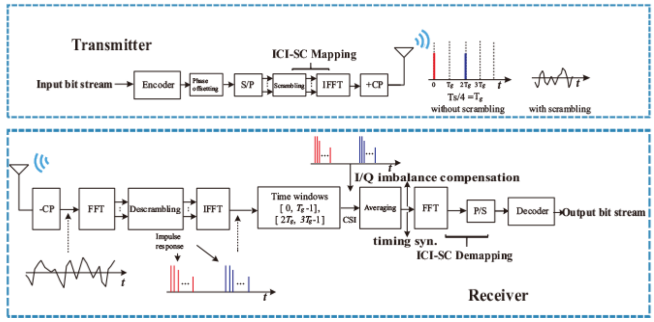

Fig. 1. The Block diagram of ICI SC scheme in the tranceiver

where $\tilde{Y}(k,i)$ is received signal in frequency domain. In the presence of the I/Q imbalance, the subcarriers will be interfered by frequency mirror-image subcarriers. The ICI due to both the CFO and the I/Q imbalance will lead to CIR degradation. Here, $S(l-k)$ is defined as the complex coefficient for the ICI components between l^{th} and k^{th} subcarriers, which can be expressed as

$$S(l-k) = \frac{\sin[\pi(l+\varepsilon-k)]}{N\sin[\pi(l+\varepsilon-k)/N]}\cdot e^{j\pi(l+\varepsilon-k)(N-1)/N} \tag{6}$$

where ε is normalized frequency offset. To reduce the effect of I/Q imbalance and ICI due to CFO, proper estimation and compensation methods are necessary.

B. ICI Analysis

For convenience, I abbreviate $X(k,i)$, $H(k,i)$, $\omega(k,i)$, $\tilde{Y}(k,i)$ to $X(k)$, $H(k)$, $\omega(k)$, $\tilde{Y}(k)$ respectively. Here we assume that the accurate CSI (channel state information) is known and $\zeta = 1, \xi = 0$ when the two paths are exactly in quadrature. The received frequency-domain symbol stream with CFO can be rewritten as follows

$$Y(k) = X(k)S(0) + \sum_{l=0,l\neq k}^{N-1} X(l)S(l-k) + \omega(k) \tag{7}$$

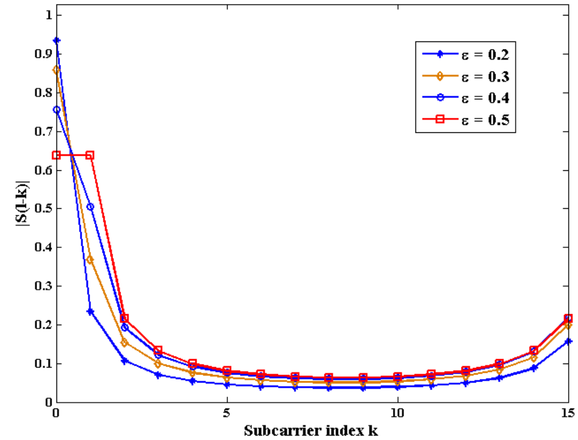

Fig. 2. ICI coefficients for the subcarriers from k=0 to N-1. (N=16, l=0)

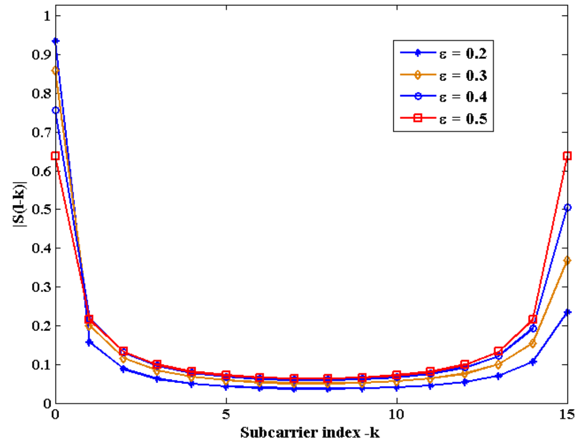

Fig. 3. ICI coefficients for the subcarriers from -k=0 to N-1. (N=16, l=0)

In order to analyze the influence of ICI from other subcarriers into k^{th} subcarrier, we assume the normalized carrier frequency offset values from 0.2 to 0.5 and $N = 16$. The complex ICI coefficients $\left|S\left(l-k\right)\right|$ are plotted for all subcarriers in Fig. 2 and Fig. 3, respectively.

The two figures indicate that the weight of the desired signal component $S(0)$ decreases whereas the undesired weights of the ICI components increase for a larger ε. Note that the adjacent carrier has the maximum contribution to the ICI. The CIR is an indicator that used as a measure of the carrier component power to the interference components power. Here we assume that the modulated data symbol $X(k)$ is statistically independent and identically distributed, and the CIR of standard OFDM transmission is given by

$$CIR = \frac{E\left[\left|C(k)\right|\right]}{E\left[\left|ICI(k)\right|\right]} = \frac{E\left[\left|X(k)\right|^2\right]\cdot E\left[\left|S(0)\right|^2\right]}{E\left[\left|X(l)\right|^2\right]\sum_{l=0,l\neq k}^{N-1}\left|S(l-k)\right|^2} = \frac{\left|S(0)\right|^2}{\sum_{l=1}^{N-1}\left|S(l)\right|^2} \quad (8)$$

Equations (6), (8) show that CIR depends upon subcarrier number N and carrier frequency offset ε. Furthermore, the CIR has a maximum change of 0.068 dB when $N \geq 8$. Therefore, the CIR of normal OFDM systems can be considered as relation of the normalized frequency offset approximately.

III. Proposed Joint I/Q Imbalance Compensation and ICI SC Schemes

In this paper, we use the I/Q Imbalance estimation method based on TFI-OFDM to achieve an accurate compensation with small number of pilot symbols [23]. we define $V\left(k\right)$ in pilot symbol as

$$V(k) = \begin{cases} \dfrac{\tilde{Y}^*(N-1-k)}{\tilde{Y}(k)} & k \text{ for odd} \\ \dfrac{\tilde{Y}^*(k)}{\tilde{Y}(N-1-k)} & k \text{ for even.} \end{cases} \quad (9)$$

We can obtain $\sum_{k=0}^{N-1} X(k) = \{1, 0, \cdots, 1, 0\}$ as the pilot signal and separate the desired and mirror signals. Assuming that the noise power and ϕ are small and can be ignored, Eq. 9 can be rewritten as

$$V(k) = \frac{\xi^*}{\zeta} \approx \Delta - j\tan\phi \quad (10)$$

As a result, we can obtain Δ and ϕ as

$$\begin{cases} \Delta = \mathrm{Re}\{V(k)\} \\ \phi = \arctan\left[-\mathrm{Im}\{V(k)\}\right]. \end{cases} \quad (11)$$

I/Q imbalance compensation is easy to implement in time domain [24] by using

$$\hat{y}_{com}(t) = \frac{\zeta^*\bar{y}(t) - \xi\bar{y}^*(t)}{|\zeta|^2 - |\xi|^2} \quad (12)$$

where $\hat{y}_{com}(t)$ is the compensated received signal in time domain. After I/Q imbalance compensation, a real constant and plural weighted data-conjugate ICI-Cancellation scheme is proposed. The data symbols are remapped as the form of

$$X'(k) = \alpha X(k), X'(k+1) = \beta e^{-j\varphi} X^*(k) \quad k \in \{0, 2, ..., N-2\}$$

All data symbol is mapped onto a pair of two adjacent subcarriers in frequency domain to achieve frequency diversity. Unlike the conventional methods, it can be proved that the proposed method is robust to the artificial phase rotation φ at any angel in the evaluation of CIR. Furthermore, the optimal values of α and β are achieved not only considering the CIR but also the BER performance, which is more important. Hence, the received data signal at the k^{th} *and* $(k+1)^{th}$ subcarriers are

$$Y'(k)=\sum_{l=0,l=even}^{N-2}\alpha X(l)S(l-k)+\beta e^{-j\varphi}X^*(k)S(l+1-k)+\omega(k) \tag{13}$$

$$Y'(k+1)=\sum_{l=0,l=even}^{N-2}\alpha X(l)S(l-k-1)+\beta e^{-j\varphi}X^*(k)S(l-k)+\omega(k+1) \tag{14}$$

After Combining the real constant and plural weighted coefficients, the received signal $Y''(k)$ is determined as

$$\begin{aligned}Y''(k)&=\frac{1}{\alpha-\beta}[Y'(k)-e^{-j\varphi}Y'^*(k+1)]\\&=\frac{1}{\alpha-\beta}\sum_{l=0,l=even}^{N-2}\{X(l)[\alpha S(l-k)-\beta S^*(l-k)]\\&+X^*(l)[\beta e^{-j\varphi}S(l+1-k)-\alpha e^{-j\varphi}S^*(l-k-1)]\}+\omega'(k)\\&=\frac{1}{\alpha-\beta}\{\underbrace{X(k)[\alpha S(0)-\beta S^*(0)]+X^*(k)[\beta e^{-j\varphi}S(1)-\alpha e^{-j\varphi}S^*(-1)]}_{C(k)}\\&+\underbrace{\sum_{l=0,l\neq k,l=even}^{N-2}\{X(l)[\alpha S(l-k)-\beta S^*(l-k)]+X^*(l)[\beta e^{-j\varphi}S(l+1-k)-\alpha e^{-j\varphi}S^*(l-k-1)]\}}_{ICI(k)}\\&+\omega'(k)\end{aligned} \tag{15}$$

Thus, CIR of proposed ICI SC scheme is given by

$$\begin{aligned}CIR_{\text{Pro.}}&=\frac{m(\alpha,\beta,\varphi)}{n(\alpha,\beta,\varphi)}\\&=\frac{\left|\alpha S(0)-\beta S^*(0)\right|^2+\left|\beta e^{-j\varphi}S(1)-\alpha e^{-j\varphi}S^*(-1)\right|^2}{\sum_{l=2,l=even}^{N-2}\left|\alpha S(l)-\beta S^*(l)\right|^2+\left|\beta e^{-j\varphi}S(l+1)-\alpha e^{-j\varphi}S^*(l-1)\right|^2}\end{aligned} \tag{16}$$

In order to get the optimum value of CIR at a given value of ε and *N*, we have to analysis the proper numerical coefficients α, β and the phase rotation factor φ. This is equivalent to finding the maximum value of the ternary function. Derivation process is as follows

$$\begin{aligned}m(\alpha,\beta,\varphi)&=[\alpha S(0)-\beta S^*(0)][\alpha S^*(0)-\beta S(0)]\\&+[\beta e^{-j\varphi}S(1)-\alpha e^{-j\varphi}S^*(-1)][\beta e^{j\varphi}S^*(1)-\alpha e^{j\varphi}S(-1)]\\&=(\alpha^2+\beta^2)\left|S(0)\right|^2-\alpha\beta(S^2(0)+S^{*2}(0)+S(1)S(-1)\\&+S^*(1)S^*(-1))+\alpha^2\left|S(-1)\right|^2+\beta^2\left|S(1)\right|^2\end{aligned} \tag{17}$$

Similarly,

$$\begin{aligned}n(\alpha,\beta,\varphi)=\sum_{l=2,l=even}^{N-2}&(\alpha^2+\beta^2)\left|S(l)\right|^2-\alpha\beta(S^2(l)+S^{*2}(l)+S(l+1)S(l-1)\\&+S^*(l+1)S^*(l-1))+\alpha^2\left|S(l-1)\right|^2+\beta^2\left|S(l+1)\right|^2\end{aligned} \tag{18}$$

take the partial derivative with respect to φ

$$\frac{\partial CIR}{\partial\varphi}=\frac{\frac{\partial m}{\partial\varphi}\cdot n-\frac{\partial n}{\partial\varphi}\cdot m}{n^2}=0 \tag{19}$$

where $\frac{\partial m}{\partial\varphi}=0,\frac{\partial n}{\partial\varphi}=0$. The specially designed modulation approach allows the phase rotation at any angel since there is no variable φ in (17) and (18). Next, take the partial derivative with respect to α , let

$$\frac{\partial CIR}{\partial\alpha}=\frac{\frac{\partial m}{\partial\alpha}\cdot n-\frac{\partial n}{\partial\alpha}\cdot m}{n^2}=0 \tag{20}$$

where

$$\begin{aligned}\frac{\partial m}{\partial\alpha}&=2\alpha\left|S(0)\right|^2-\beta(S^2(0)+S^{*2}(0)\\&+S(1)S(-1)+S^*(1)S^*(-1))+2\alpha\left|S(-1)\right|^2,\end{aligned} \tag{21}$$

$$\begin{aligned}\frac{\partial m}{\partial\alpha}=\sum_{l=2,l=even}^{N-2}&2\alpha\left|S(l)\right|^2-\beta(S^2(l)+S^{*2}(l)+S(l+1)S(l-1)\\&+S^*(l+1)S^*(l-1))+2\alpha\left|S(l-1)\right|^2.\end{aligned} \tag{22}$$

After substituting the values from (21) and (22) into (20) , we have

$$C_0\alpha^3+C_1\alpha^2+C_2\alpha+C_3=0 \tag{23}$$

where

$$\begin{cases} C_0 = 0 \\ C_1 = (S^2(0)+S^{*2}(0)+S(1)S(-1)+S^*(1)S^*(-1)) \sum_{l=2,l=even}^{N-2} (|S(l)|^2+|S(l-1)|^2) \\ \quad -(|S(0)|^2+|S(-1)|^2) \sum_{l=2,l=even}^{N-2} S^2(l)+S^{*2}(l)+S(l+1)S(l-1)+S^*(l+1)S^*(l-1) \\ C_2 = 2\beta\{(|S(0)|^2+|S(-1)|^2) \sum_{l=2,l=even}^{N-2} |S(l+1)|^2 + (|S(-1)|^2-|S(1)|^2) \sum_{l=2,l=even}^{N-2} |S(l)|^2 \\ \quad -(|S(0)|^2+|S(1)|^2) \sum_{l=2,l=even}^{N-2} |S(l-1)|^2\} \\ C_3 = \beta^2\{(|S(0)|^2+|S(1)|^2) \sum_{l=2,l=even}^{N-2} S^2(l)+S^{*2}(l)+S(l+1)S(l-1)+S^*(l+1)S^*(l-1) \\ \quad -(S^2(0)+S^{*2}(0)+S(1)S(-1)+S^*(1)S^*(-1)) \sum_{l=2,l=even}^{N-2} |S(l)|^2+|S(l+1)|^2\} \end{cases} \tag{24}$$

In the same way, take the partial derivative with respect to β,

$$\frac{\partial CIR}{\partial \beta} = \frac{\frac{\partial m}{\partial \beta}\cdot n - \frac{\partial n}{\partial \beta}\cdot m}{n^2} = 0 \tag{25}$$

where

$$\frac{\partial m}{\partial \beta} = 2\beta|S(0)|^2 - \alpha(S^2(0)+S^{*2}(0)+S(1)S(-1) + S^*(1)S^*(-1)) + 2\beta|S(1)|^2, \tag{26}$$

$$\frac{\partial m}{\partial \beta} = \sum_{l=2,l=even}^{N-2} 2\beta|S(l)|^2 - \alpha(S^2(l)+S^{*2}(l)+S(l+1)S(l-1) + S^*(l+1)S^*(l-1)) + 2\beta|S(l+1)|^2. \tag{27}$$

Substituting (26) and (27) into (25**),** after calculation, it can be formulated as

$$C_0^{'}\beta^3 + C_1^{'}\beta^2 + C_2^{'}\beta + C_3^{'} = 0 \tag{28}$$

where

$$\begin{cases} C_0^{'} = 0, \\ C_1^{'} = (S^2(0)+S^{*2}(0)+S(1)S(-1)+S^*(1)S^*(-1)) \sum_{l=2,l=even}^{N-2} (|S(l)|^2+|S(l+1)|^2) \\ \quad -(|S(0)|^2+|S(1)|^2) \sum_{l=2,l=even}^{N-2} S^2(l)+S^{*2}(l)+S(l+1)S(l-1)+S^*(l+1)S^*(l-1) \\ C_2^{'} = 2\alpha\{(|S(0)|^2+|S(1)|^2) \sum_{l=2,l=even}^{N-2} |S(l-1)|^2 + (|S(1)|^2-|S(-1)|^2) \sum_{l=2,l=even}^{N-2} |S(l)|^2 \\ \quad -(|S(0)|^2+|S(-1)|^2) \sum_{l=2,l=even}^{N-2} |S(l+1)|^2\} \\ C_3^{'} = \alpha^2\{(|S(0)|^2+|S(-1)|^2) \sum_{l=2,l=even}^{N-2} S^2(l)+S^{*2}(l)+S(l+1)S(l-1)+S^*(l+1)S^*(l-1) \\ \quad -(S^2(0)+S^{*2}(0)+S(1)S(-1)+S^*(1)S^*(-1)) \sum_{l=2,l=even}^{N-2} |S(l)|^2+|S(l-1)|^2\} \end{cases} \tag{29}$$

Though the analysis of Eqs.(23) and (28), we can find the approximate optimal solution of $\alpha = 0.5, \beta = -0.5$ from the above equations at a given ε under $\alpha \neq 0$ and $\beta \neq 0$. In fact, we can see the relative variation regularity from Figs. 4 and 5. The optimum CIR are taken with the approximately inverted signs of α and β for normalized $CFO \in [0, 0.15]$.

Here we emphasize the novelty of the proposed scheme with respect to the existing method.

- The mapping form of previous ICI SC methods is directly given without numerical analysis [11]–[15]. In this paper, we present the generalized framework and the derivation process to determine the predefined weighting coefficients.
- The proposed model is robust to the artificial phase rotation φ, which will greatly reduce the sensitivity of the random phase noise in the transmitter.
- Here we consider a special case, if $\varphi = 0$, we have $X^{'}(k) = 0.5X(k)$, $X^{'}(k+1) = -0.5X^*(k)$, this appears to be equivalent to the data conjugate algorithm in [12]. Similarly, if $\varphi = \pi/2$, $X^{'}(k) = 0.5X(k)$, $X^{'}(k+1) = -0.5e^{j\pi/2}X^*(k)$, this seems to be equivalent to the fixed plural weighted data-conjugate algorithm A in [14]. However, it is different because the amplitude limiting is operated in the transmitter rather than in the receiver in the proposed method. Furthermore, we can get the conclusion by simulations that the reduction of signal energy in the transmitter are much more effective than the manipulation between adjacent subcarriers in the receiver.
- From our work, we know that the proposed method has relatively better CIR and the best BER performance compared to the conventional methods.

IV. SIMULATION RESULTS

In this section, Monte Carlo simulations have been conducted to evaluate the performance of proposed scheme compared to the existing methods. Here, the convolution codes (rate $R=1/2$, constraint length $\kappa=7$) with bit interleaving are used. The packet consists of $N_p=1$ pilot symbol and $N_d=20$ data symbols. The subcarriers of 256 samples ($N=256$) and CP length of 16 samples ($N_{cp}=16$) are considered. Modulation type is QPSK and unless stated otherwise, the simulation is run by 1000 trials. The system performance is evaluated in terms of BER besides CIR. As mentioned above, $\alpha=0.5$, $\beta=-0.5$ are chosen respectively. The conventional algorithms were also implemented for the purpose of comparison. In this project, the simulations were performed in an AWGN channel model and it can be easily adapted to a flat-fading channel with channel estimation. The

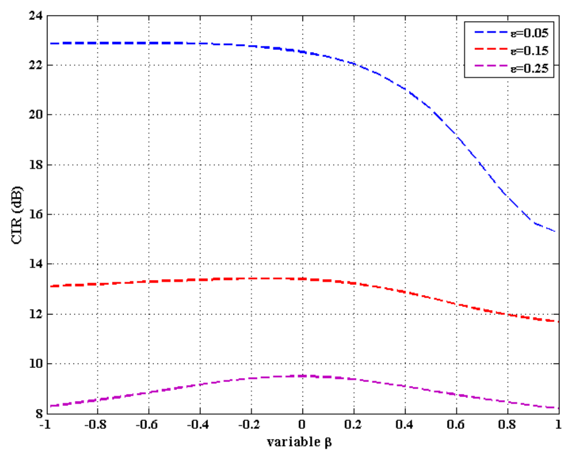

Fig. 4. CIR versus β . ($N=256, \alpha=1$)

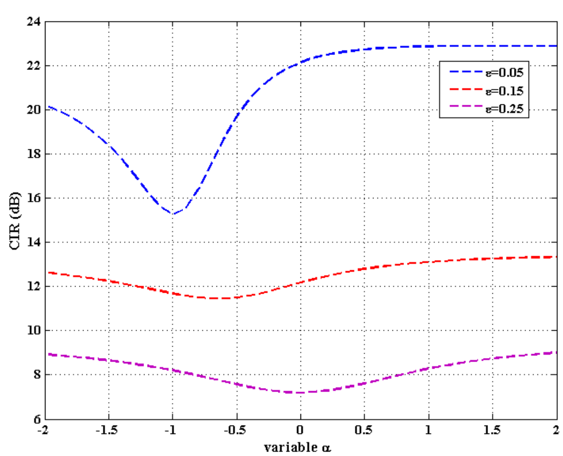

Fig. 5. CIR versus α . ($N=256, \beta=-1$)

self cancellation schemes have widely been used because it does not require very complex hardware or software for implementation. Table.1 shows the simulation parameters.

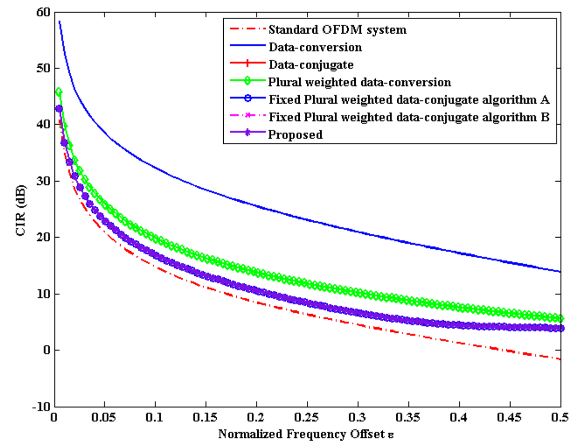

Fig. 6. CIR for the conventional and proposed algorithm versus Normalized frequency offset ε in flat-fading channels($\alpha=1, \beta=-1$).

The theoretical CIR curve of conventional and the proposed ICI SC schemes are shown in Fig. 6. Algorithms in [10]-[11] were labeled as data-conversion, plural weighted data-conversion, algorithms in [12]-[13] were labeled as data-conjugate, symmetric data-conjugate, and algorithms in [14]-[15] were labeled as fixed plural weighted data-conjugate algorithm A and B, respectively. The CIR performance of ICI SC scheme is found to be better than that of the standard-OFDM system. Furthermore, it can be seen that the CIR performance of proposed scheme is inferior than the methods in [10], [11], but higher than the normal OFDM and has nearly identical performance as the methods in [13], [14], and [15]. From Fig. 6, we know, in general, the data conversion methods have better CIR performance than conjugate methods. Note that CIR is one indicator of system performance, we also have to evaluate the BER performance. There are some relationship between CIR and BER from the analysis of previous methods but no datas to indicate that they are directly related to the each other.

TABLE I
SIMULATION PAREMETERS

Data Modulation	QPSK
FEC	Convolutional code ($R=1/2, \kappa=7$)
Frame size	21 symbol ($N_p=1, N_d=20$)
FFT size	256
Number of subcarrier	256
Guard interval	16 sampel times
Applicable channel model	AWGN, flat-fading
The gain mismatch Δ Phase mismatch ϕ	0.2 10°
Weighted coefficients α , β	0.5 and -0.5
CFO ε	0.001, 0.05, 0.1, 0.15

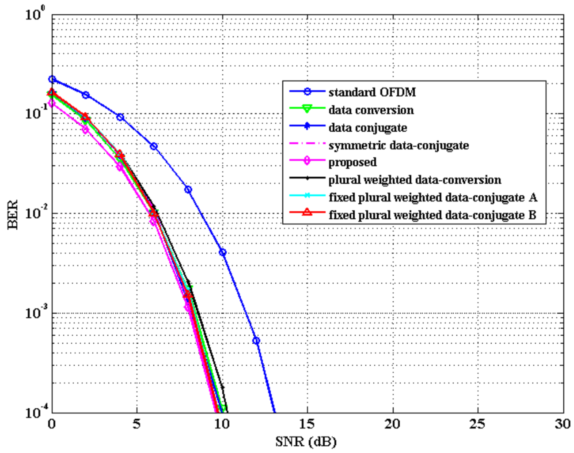

Fig. 7. BER for the conventional and proposed algorithm versus SNR with I/Q imbalance compensation ($N = 256, \varepsilon = 0.001$)

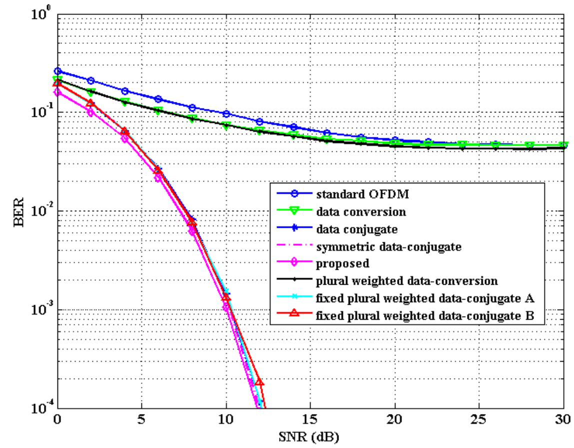

Fig. 9. BER for the conventional and proposed algorithm versus SNR with I/Q imbalance compensation ($N = 256, \varepsilon = 0.1$)

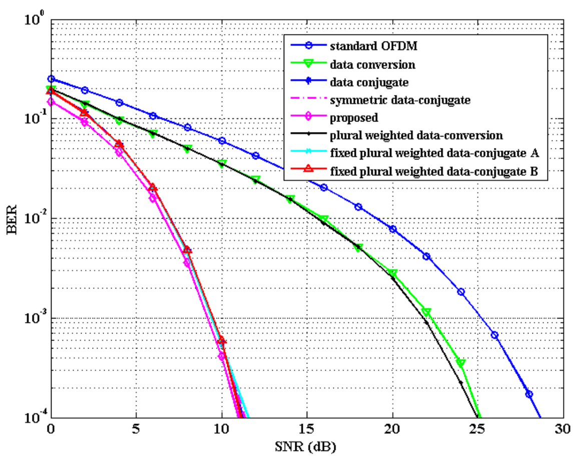

Fig. 8. BER for the conventional and proposed algorithm versus SNR with I/Q imbalance compensation ($N = 256, \varepsilon = 0.05$)

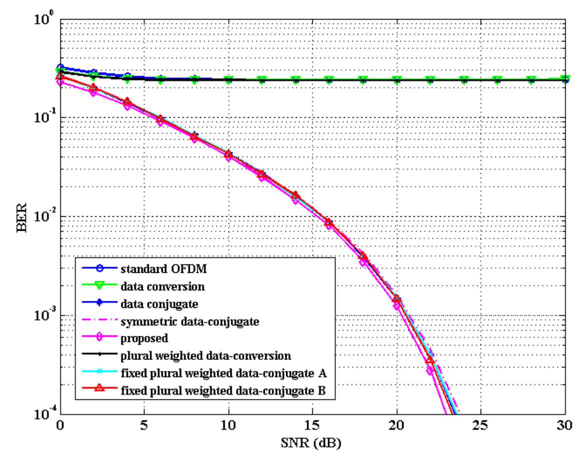

Fig. 10. BER for the conventional and proposed algorithm versus SNR with I/Q imbalance compensation ($N = 256, \varepsilon = 0.15$)

Fig. 7-Fig. 10 show the BER performance of proposed method compared to the conventional method after I/Q imbalance compensation. As seen in these figures, the proposed algorithm performs better than the others for different values of CFO. It depends on the design of the data allocation in the transmitter and the demodulation scheme in the receiver. When CFO is very small as shown in Fig. 7, except for proposed scheme and plural weighted data-conversion method, the data-conversion method outperforms the others at a low SNR below 6dB while inferior than others when SNR is greater than it. From Fig. 8-Fig. 10, we know that both the data-conversion method and plural weighted data-conversion method are inferior than the other approaches. Among the comparatively good schemes, fixed plural weighted data-conjugate algorithm A exhibits better performance than B when SNR is less than 10dB in Fig.8 whereas B is superior than A when SNR is less than 10dB in Fig.9. As described in [15], data-conjugate algorithm B gives better BER than A as ε increases. Overall, symmetric data-conjugate scheme and data-conjugate scheme have almost the same performance.

To make clear what are the effectiveness of proposed method when considering the actual OFDM, the system of 2GHz 3GPP and 2.3GHz mobile wimax are considered here. The subcarrier spacing are 15kHz and 9.769kHz respectively. The proposed algorithm can support the moving velocity up to 409km/h and 229km/h if the 10^{-3} BER is required when SNR equals 10dB. Analytical and simulation results show that the algorithm achieves better performance than other algorithms due to its higher utilizability and more robust property to normalized CFO.

V. Conclusion

In this paper, an improved ICI SC scheme has been presented in the presence of I/Q imbalance to improve the system performance in TFI-OFDM systems. The proposed ICI cancellation scheme repeats the data symbol with phase rotation and constant weighted data-conjugate over a pair of subcarriers. Unlike conventional methods, the designed transmission model is robust to phase rotation and it achieves relatively better CIR and the best BER performance for lower and higher values of CFOs. Due to the repetition symbols on adjacent subcarriers, it achieves frequency diversity by reducing bandwidth efficiency. However, the proposed scheme is effective for combating the impact of ICI and easy for hardware implementation since no further channel equalization is needed and the system complexity is not increased. The proposed scheme shows good property compared with conventional methods for practical application.

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REFERENCES

[1] T. L. Liu, W. H. Chung, S. Y. Yuan, and S. Y. Kuo, "ICI Self-Cancellation With Cosine Windowing in OFDM Transmitters Over Fast Time-Varying Channels," *IEEE Trans. Wireless Communs.*, vol.14, no.7, pp.3559-3570, July 2015.

[2] J. Armstrong, "Analysis of new and existing methods of reducing intercarrier interference due to carrier frequency offset in OFDM," *IEEE Trans. Commun*., vol. 47, no. 3, pp. 365-369, Mar. 1999.

[3] A. Seyedi and Gary J. Saulnier, "General ICI self-cancellation scheme for OFDM systems," *IEEE Trans. Veh. Technol.*, vol. 54, no. 1, pp.198–210, Jan. 2005.

[4] M.-X. Chang, "A novel algorithm of inter-subchannel interference selfcancellation for OFDM systems," *IEEE Trans. Wireless Communs*., vol.6, no. 8, pp. 2881–2893, Aug. 2007.

[5] W. G. Jeon, K.H. Chang, Y.S. Cho, "An Equalization Technique for Orthogonal Frequency-Division Multiplexing Systems in Time-Variant Multipath Channels," *IEEE Trans. on Commun*., vol.47, no.1, pp.27-32,Jan.1999.

[6] M. M. U. Gul, X. Ma, and S. Lee, "Timing and frequency synchronization for OFDM downlink transmissions using Zadoff-Chu sequences," *IEEE Trans. Wireless Communs.*, vol.14, no.3, 1716-1729. March 2015

[7] S. Lmai, A. Bourre, C. Laot, and S. Houcke, "An efficient blind estimation of carrier frequency offset in OFDM systems, " *IEEE Trans. Veh. Technol.*, vol.63, no.4, pp. 1945-1950, May 2014.

[8] H. C. Nguyen, E. De Carvalho, and R.Prasad, "Multi-user interference cancellation schemes for carrier frequency offset compensation in uplink OFDMA," *IEEE Trans. Wireless Communs*., vol.13, no.3, pp. 1164-1171, March 2014.

[9] H. Yang, W. J. Shin, S. Lee, and Y. H. You, "A robust estimation of residual carrier frequency offset with I/Q imbalance in OFDM systems, " *IEEE Trans. Veh. Technol*., vol.64, no. 3, pp. 1254-1259, March 2015.

[10] Y. Zhao and S.-G. H¨agggman, "Intercarrier interference self-cancellation scheme for OFDM mobile communication systems," *IEEE Trans. Commun*., vol. 49, pp. 1185–1191, July 2001.

[11] Yi. Peng , Y. Kuo , G. Lee , and J. Wen, "Performance Analysis of a New ICI-Self- Cancellation-Scheme in OFDM Systems," *IEEE Trans. Consum. Electron.*,vol.53, no.4, pp.1333-1338, 2007.

[12] H.G. Ryu, Y. Li, J.S. Park, "An Improved ICI Reduction Method in OFDM Communication System," *IEEE Trans. Broadcasting*, vol.5, no.3 pp.395-400, Sep.2005

[13] S. Tang, K. Gong, J. Song, C. Pan, and H. Yang, "intercarrier interference cancellation with frequency diversity for OFDM systems," *IEEE Trans. on Broadcasting*, vol. 53, no. 1, March 2007.

[14] Q. Shi, Y. Fang, and M. Wang, "A novel ICI self-cancellation scheme for OFDM systems," *Proc. of IEEE WiCom*, pp.1-4, 2009.

[15] A. bishnu , A. Jain, and A. Shrivastava, "A new scheme of ICI self-cancellation in OFDM system," *Proc. of IEEE CSNT*, pp.120-123, 2013.

[16] P. Singh, O.P.Sahu, "An overview of ICI self cancellation techniques in OFDM systems," *Proc. of IEEE CICT*, pp.299-302, 2015.

[17] D. Mattera, L. Paura, F. Sterle, "MMSE WL equalizer inpresence of receiver IQ imbalance," *IEEE Trans. Signal Process*., vol.56, no.4, pp. 1735-1740, April 2008.

[18] A. Schuchert, R. Hasholzner, "A novel IQ imbalance compensation scheme for the reception of OFDM signals," *IEEE Trans. Consum. Electron*., vol.47, no.3, pp. 313-318, Aug. 2001.

[19] A. Tarighat, A.H. Sayed, "MIMO OFDM receivers for systems with IQ imbalances," *IEEE Trans. Signal Process*., vol.53, no.9, pp. 3583-3596, Sept.2005.

[20] C. Ahn, S. Takahashi, and K. Haeiwa, "Time-frequency interferometry for OFDM," *Proc. of IEEE APCC*, pp.153-156, October 2007.

[21] C. Ahn, "Accurate channel identification with time-frequency interferometry for OFDM," *IEICE Trans. Fundamentals*, vol.E90-A, No.11, pp.2641-2645, November 2007.

[22] T. Yoshimura, C. Ahn, T. Omori, and K. Hashimoto, "Path-selection based adaptive guard interval for TFI-OFDM system," *Proc. of IEEE TENCON*, pp.549-553, November 2011.

[23] H. Oka, C. Ahn, T. Omori, and K. Hashimoto, "IQ Imbalance Estimation and Compensation Schemes using TFI-OFDM System," *Proc. of IEEE IWSDA*, pp.126-129, October 2013.

[24] Chiu, Yi-Jen, and S-P. Hung, "Estimation scheme of the receiver IQ imbalance under carrier frequency offset in communication system," *Communications, IET*, vol.4, no.11, pp.1381-1388, July 2010.