Signal Design to Mitigate the Impact of RF Impairment in OFDM Communication Systems

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***Abstract*—Orthogonal frequency division multiplexing (OFDM) signals are sensitive to the mismatching errors between the in-phase (I) and quadrature (Q) branches in the up and down-conversions. These mismatching errors including phase and amplitude mismatches make the signal constellation expand and rotate, which severely degrades the performance of OFDM systems. In this paper, a method of signal design for OFDM communication system is proposed in order to mitigate the impact of IQ mismatching errors. A simple quasi-symmetric conjugate (QSC) structure of signal in frequency domain designed at the transmitter side can completely remove the self-interference caused by IQ mismatching errors. At the receiver, the estimation and the compensation for IQ mismatch are not necessary. Analytic and simulation results can show the efficiency of QSC method in IQ mismatch mitigation compared to other techniques such as Adjacent Symbol Repetition (ASR), Adjacent Conjugate Symbol Repetition (ACSR), Symmetric Symbol Repetition (SSR), or Symmetric Conjugate Symbol Repetition (SCSR), respectively.**

I. INTRODUCTION

OFDM is an attractive modulation technique in wireless applications by dividing a frequency-selective channel into several frequency-flat sub-channels, which provides good immunity to the multi-path fading. Due to its promising advantages, OFDM has been adopted in several modern communication systems such as wireless local area network (WLAN) IEEE 802.11a [1], wireless metropolitan area network (WMAN) IEEE 802.16a [2], digital audio broadcasting (DAB), and digital video broadcasting (DVB-T) [3]. Recently, OFDM has been considered in draft standard IEEE 802.11p for vehicular communications, which allows for data communication between vehicles and a vehicle and infrastructure (known as V2X) [4]. However, OFDM signals are sensitive to impairments of radio frequency (RF) front-end components. A major source of impairments is the mismatching error between IQ components of the signal [5], [6], [7].

The impact of IQ mismatching error on the performance of an OFDM system has been investigated in several previous studies [8], [9], [10]. In RF communication system, the up and down-conversion of OFDM signal requires both cosine and sine waveforms of carrier. Due to manufacturing inaccuracies, the cosine and sine waveforms often do not have the same waveform and the phase shift between them is often not 90°. This problem is called IQ mismatch or IQ imbalance. These mismatching errors including phase and amplitude mismatches make the signal constellation expand and rotate, which result in the significant degradation of the Bit Error Rate (BER) performance of OFDM systems.

IQ mismatch compensation techniques can be divided into two types: analog domain and digital domain techniques. IQ mismatch can be calibrated in analog domain by some image-reject receiver structures. However, perfect IQ matching is not possible in the analog domain, especially when low-cost fabrication technologies are used. Because IQ mismatch vary negligible with time, compensation techniques can be digitally implemented. In [11], authors propose a digital pre-compensation structure for IQ modulator. This technique requires extra analog hardware and which needs to be carefully designed in order not to introduce any IQ imbalance itself. In several papers [12], [13], [14], IQ distortion can be estimated and compensated along with the channel estimation and equalization procedure in the digital domain. Adaptive techniques can be developed in the digital domain to track and eliminate imbalances. In [12], [13], authors proposed an estimation technique for calculating mismatching error parameters. Estimated parameters were used to calibrate the receiver mismatching error. IQ mismatching error and several other impairments such as phase noise and frequency offset were also investigated in [12], [13]. These papers considered additional effects from channel estimation on IQ compensation and the procedure to compensate. Signal design at transmitter method for OFDM to reduce inter-carrier interference (ICI) by IQ mismatch and phase noise regardless to channels or mismatch errors estimation is considered in [15]. However, the existing ASR, ACSR, SSR, SCSR methods are not efficient for IQ mismatches mitigation.

In this paper, we propose an IQ mismatch mitigation technique by signal design at transmitter side. A simple quasi-symmetric conjugate (QSC) structure of signal in frequency domain can completely remove the self-interference caused by IQ mismatching errors. This method does not need channel and mismatch errors estimation or a complex receiver design. Analytic and simulation results can show the efficiency of QSC method in IQ mismatch mitigation compared to other techniques such as ASR, ACSR, SSR, SCSR, respectively.

II. SYSTEM DESCRIPTION

A block diagram of the OFDM transmitter is illustrated in Fig. 1. Let $X = [X_0, X_1, \ldots, X_{N-1}]^T$ denote the input data after the serial to parallel (S/P) converter. The inverse fast Fourier transform (IFFT) will convert a signal from the frequency domain to the time domain.

After the IFFT, the complex base-band OFDM signal is

$$x(t) = \frac{1}{N}\sum_{n=0}^{N-1} X_n e^{j2\pi\Delta f t}, \qquad 0 \le t \le NT \tag{1}$$

where T is the data period, NT is the OFDM symbol duration, and $\Delta f = \frac{1}{NT}$ is the sub-carrier spacing. The time domain OFDM signal is then converted form parallel to serial (P/S) before the transmission.

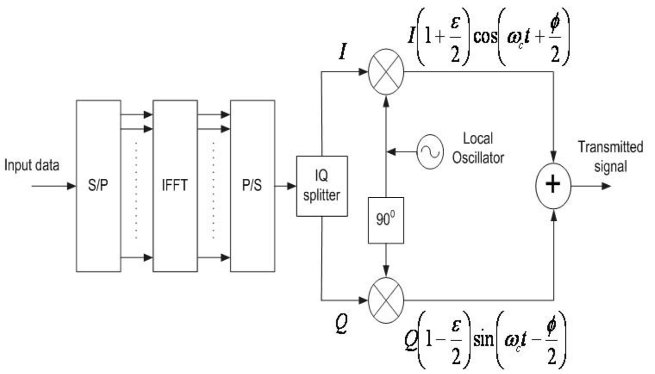

Fig. 1. An OFDM transmitter with IQ mismatching errors.

The carrier modulation of a signal to the RF is often implemented by the quadrature modulation method. Let us use I(t) and Q(t) to denote the I component and Q component of *x(t)*, respectively. A local oscillator (LO) can be employed to generate the sine waveform for the I branch and phase shifted by 90° to generate the cosine waveform for the Q branch. Ideally, the transmitted RF signal without the IQ mismatching error is given by

$$s(t) = I(t)\cos\omega_c t + Q(t)\sin\omega_c t \tag{2}$$

where ω_c is the carrier angle frequency. As shown in [7], the mismatching error between the I and Q branches often occurs.

Fig. 1 demonstrates an OFDM transmitter with both amplitude and phase IQ mismatching errors. In this case, the transmitted RF signal derived in [7] is given by

$$\hat{s}(t) = I(t)\left(1+\frac{\varepsilon}{2}\right)\cos\left(\omega_c t + \frac{\phi}{2}\right) + Q(t)\left(1-\frac{\varepsilon}{2}\right)\sin\left(\omega_c t - \frac{\phi}{2}\right) \tag{3}$$

where ε and ϕ denote the amplitude and phase mismatching errors, respectively.

At the receiver side, the corresponding quadrature demodulation is applied. The I and Q components of the received signal are multiplied with the recovered carriers $\cos\omega_c t$ and $\sin\omega_c t$, respectively. After low-pass filtering, the quadrature components of the signal are then combined at the IQ combiner. Under the assumption of a noise-free channel, the output signal of the IQ combiner is

$$\begin{aligned} r(t) &= \left[I\left(1+\frac{\varepsilon}{2}\right)\cos\frac{\phi}{2} - Q\left(1+\frac{\varepsilon}{2}\right)\sin\frac{\phi}{2}\right] + \\ &\quad j\left[-I\left(1-\frac{\varepsilon}{2}\right)\sin\frac{\phi}{2} + Q\left(1-\frac{\varepsilon}{2}\right)\cos\frac{\phi}{2}\right] \end{aligned} \tag{4}$$

After some calculations, we have

$$r(t) = \left(\cos\frac{\phi}{2} + j\frac{\varepsilon}{2}\sin\frac{\phi}{2}\right)x(t) + \left(\frac{\varepsilon}{2}\cos\frac{\phi}{2} - j\sin\frac{\phi}{2}\right)x^*(t) \tag{5}$$

where $x(t) = I(t) + jQ(t)$ and $x^*(t)$ denotes the complex conjugate of $x(t)$. Note that we can also rewrite Eq. (5) as

$$r(t) = \alpha_1 x(t) + \alpha_2 x^*(t) \tag{6}$$

with

$$\alpha_1 = \cos\frac{\phi}{2} + j\frac{\varepsilon}{2}\sin\frac{\phi}{2} \tag{7}$$

$$\alpha_2 = \frac{\varepsilon}{2}\cos\frac{\phi}{2} - j\sin\frac{\phi}{2} \tag{8}$$

After the down-conversion, the complex base-band signal $r(t)$ is sent to the OFDM demodulation. The discrete form of $r(t)$ is then converted from serial to parallel, denoting as $r = [r_0, r_1, \ldots, r_{N-1}]^T$. Taking the Fast Fourier Transform (FFT) operation, we have

$$R = \alpha_1 X + \alpha_2 X^\sharp \tag{9}$$

where $R = FFT(r) = [R_0, R_1, \ldots, R_{N-1}]^T$, $X = FFT(x) = [X_0, X_1, \ldots, X_{N-1}]^T$, and $X^\sharp = FFT(x^*) = [X_0^*, X_{N-1}^*, \ldots, X_{N/2}^*, X_{N/2-1}^*, \ldots, X_1^*]^T$.

The received signal is scaled by α_1 and interfered by the mirror image (complex conjugate is scaled by α_2). The second component of the right-hand side of Eq. (9) is called the self-interference and reduces the noise margin. Consequently, the BER performance of the system will be degraded.

III. IQ Mismatch Mitigation by QSC Method

The analysis in previous part shows that the received signal at the receiver side is interfered by the image self-interference. This interference makes BER performance of system to degrade. The closed-form expression for the probability of bit error for an OFDM system with the BPSK or QPSK modulation scheme affected by IQ mismatch and Additive White Gaussian Noise (AWGN) channel is derived in [16]

$$P_b = \frac{1}{2}erfc\left(\sqrt{\frac{(\cos^2\phi/2 + \varepsilon^2/4\sin^2\phi/2)E_b/N_0}{(\varepsilon^2/4\cos^2\phi/2 + \sin^2\phi/2)E_b/N_0 + 1}}\right) \tag{10}$$

where

$$erfc(x) = 1 - \frac{2}{\sqrt{\pi}}\int_0^x e^{-\frac{t^2}{2}}dt$$

Our target in signal designing is to eliminate this interference.

A. Previous signal design techniques

In previous study [15], before OFDM modulation process, signal design methods construct a special form of input data replace for conventional data $X = [X_0, X_1, \ldots, X_{N-1}]^T$.

- Adjacent symbol repetition (ASR)

By repeating the same symbol with opposite polarity on two adjacent subcarriers, the data block is

$$X = [X_0, -X_0, X_1, -X_1, \ldots, X_{N/2-1}, -X_{N/2-1}]^T$$

The received signal corrupted by IQ mismatch is given by

$$\begin{aligned} R &= [R_0, R_1, \ldots, R_{N-1}]^T = \alpha_1 X + \alpha_2 X^\sharp \\ &= \alpha_1 [X_0, -X_0, X_1, -X_1, \ldots, X_{N/2-1}, -X_{N/2-1}]^T + \\ &\quad \alpha_2 [X_0^*, -X_{N/2-1}^*, X_{N/2-1}^*, \ldots, X_1^*, -X_0^*]^T \end{aligned}$$

At the receiver, a decision variable at sample k^{th} is computed in frequency domain by

$$\begin{aligned} d_k &= R_k - R_{k+1} = [2\alpha_1 X_0 + \alpha_2 (X_0^* + X_{N/2-1}^*), \ldots, \\ &\quad 2\alpha_1 X_{N/2-1} + \alpha_2 (X_0^* + X_1^*)]^T \end{aligned}$$

- Adjacent conjugate symbol repetition (ACSR)

This is a modification of ASR method. Data modulated on two adjacent subcarriers k^{th} and $(k+1)^{th}$ are complex conjugate instead of opposite polarity. Data block will be

$$X = [X_0, X_0^*, X_1, X_1^*, \ldots, X_{N/2-1}, X_{N/2-1}^*]^T$$

The received signal at receiver side given by

$$\begin{aligned} R &= [R_0, R_1, \ldots, R_{N-1}]^T = \alpha_1 X + \alpha_2 X^\sharp \\ &= \alpha_1 [X_0, X_0^*, X_1, X_1^*, \ldots, X_{N/2-1}, X_{N/2-1}^*]^T + \\ &\quad \alpha_2 [X_0^*, X_{N/2-1}, X_{N/2-1}^*, \ldots, X_1^*, X_0]^T \end{aligned}$$

Decision variable is computed at receiver is

$$d_k = R_k + R_{k+1}^* = [(\alpha_2 + \alpha_2^*) X_0^* + \alpha_1 X_0 + \alpha_1^* X_{N/2-1}, \ldots]^T$$

- Symmetric symbol repetition (SSR)

In this scheme, the same data with opposite polarity are modulated on two symmetric subcarriers k^{th} and $(N-k-1)^{th}$. The data block is

$$X = [X_0, X_1, \ldots, X_{N/2-1}, -X_{N/2-1}, \ldots, -X_1, -X_0]^T$$

The received signal is

$$\begin{aligned} R &= [R_0, R_1, \ldots, R_{N-1}]^T = \alpha_1 X + \alpha_2 X^\sharp \\ &= \alpha_1 [X_0, X_1, \ldots, X_{N/2-1}, -X_{N/2-1}, \ldots, -X_1, -X_0]^T + \\ &\quad \alpha_2 [X_0^*, -X_0^*, \ldots, -X_{N/2-1}^*, X_{N/2-1}^*, \ldots, X_2^*, X_1^*]^T \end{aligned}$$

Decision variable is computed from two symmetric subcarriers at receiver

$$\begin{aligned} d_k &= R_k - R_{k+1} = [2\alpha_1 X_0 + \alpha_2 (X_0^* - X_1^*), \ldots, \\ &\quad 2\alpha_1 X_{N/2-1} - 2\alpha_2 X_{N/2-1}^*]^T \end{aligned}$$

- Symmetric conjugate symbol repetition (SCSR)

Complex conjugate data are modulated on two symmetric subcarriers. The data block will be

$$X = [X_0, X_1, \ldots, X_{N/2-1}, X_{N/2-1}^*, \ldots, X_1^*, X_0^*]^T$$

The received signal is

$$\begin{aligned} R &= [R_0, R_1, \ldots, R_{N-1}]^T = \alpha_1 X + \alpha_2 X^\sharp \\ &= \alpha_1 [X_0, X_1, \ldots, X_{N/2-1}, X_{N/2-1}^*, \ldots, X_1^*, X_0^*]^T + \\ &\quad \alpha_2 [X_0^*, X_0, \ldots, X_{N/2-1}, X_{N/2-1}^*, \ldots, X_2^*, X_1^*]^T \end{aligned}$$

Decision variable is computed at receiver side in similar way with ACSR method

$$d_k = R_k + R_{k+1}^* = [(\alpha_1 + \alpha_1^*) X_0 + \alpha_2 X_0^* + \alpha_2^* X_1, \ldots]^T$$

In all given methods, the desired signal still corrupted by interference. Each data in subcarrier is interfered by itself image and/or from other subcarriers (intercarrier interference). It can not avoid degradation in the performance of system.

B. *Proposed signal design technique*

Our proposed technique is based on the analysis in Eq. (9). From Eq. (9), image self-interference in frequency domain is a shifting and mirror complex-conjugate of data. Data block is designed to have a quasi-symmetric characteristic instead of fully symmetric in SSR or SCSR methods. The data at indexes 0^{th} and $(N/2)^{th}$ are set to zero, or more precisely are real signals (instead of complex). Data at these indexes are known as null frequency and are often set to zero in communications design to avoid DC component. Generally, we modulate signal at indexes 0^{th} and $(N/2)^{th}$ with real data. The data vector before OFDM modulation is given by

$$X = [X_0, X_1, \ldots, X_{N/2-1}, X_{N/2}, X_{N/2-1}^*, \ldots, X_2^*, X_1^*]^T \tag{11}$$

The image self-interference component caused by IQ mismatch is

$$X^\sharp = [X_0^*, X_1, \ldots, X_{N/2-1}, X_{N/2}^*, X_{N/2-1}^*, \ldots, X_2^*, X_1^*]^T \tag{12}$$

Because X_0 and $X_{N/2}$ are real data, $X_0 = X_0^*$ and $X_{N/2} = X_{N/2}^*$. We have $X^\sharp = X$

The received signal is

$$R = [R_0, R_1, \ldots, R_{N-1}]^T = \alpha_1 X + \alpha_2 X^\sharp = (\alpha_1 + \alpha_2) X$$

In this case, the image self-interference is completely removed. The received signal is only scaled by a complex factor $(\alpha_1 + \alpha_2)$. Because this scale factor varies negligibly with time, the received signal can be corrected at receiver side without any degradation.

All above analysis shows that QSC designing method can completely eliminate the image interference caused by IQ mismatch. This method outperforms other signal design methods such as ASR, ACSR, SSR, SCSR.

IV. Numerical Results and Discussions

In this section, the BER performance of the OFDM system with IQ mismatching errors is carried out by simulations to verify the derived analytical results. The deployed OFDM system uses the QPSK constellation and has 64 sub-carriers, i.e., N=64. In Fig. 2, Fig. 3 and Fig. 4, solid curves are the BER performance of the system with IQ mismatching error but no mitigation method.

Fig. 2 shows the BER performance of the OFDM system versus Eb/N0 with only the phase IQ mismatching error, i.e., $\varepsilon = 0$. BER curves are degraded as $\phi = 30^\circ$. Previous design techniques as ASR, ACSR, SSR, SCSR are not efficient in IQ mismatch mitigation. There is no improvement in performance when using these techniques. Otherwise, QSC method can get the same performance of system without IQ mismatch errors.

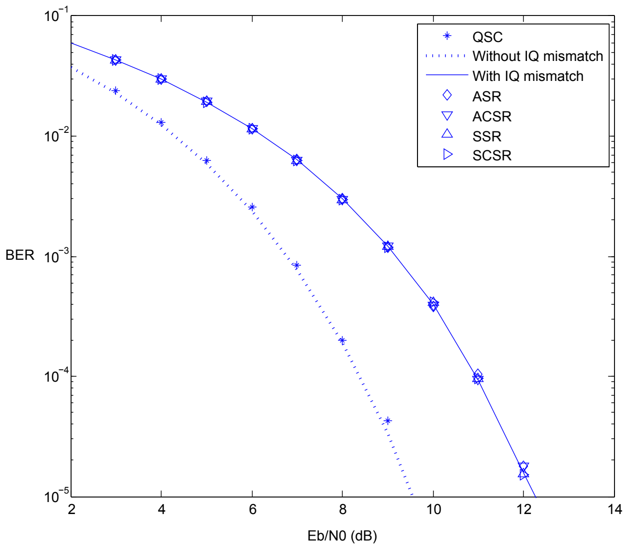

Fig. 2. BER of the OFDM system with $\phi = 30^\circ, \varepsilon = 0$.

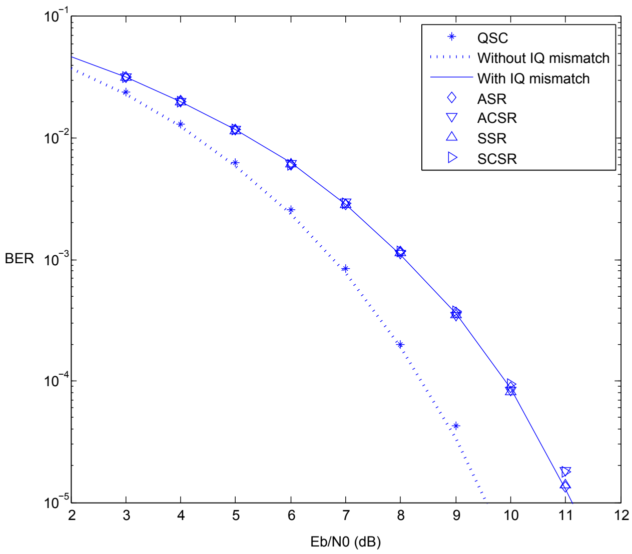

Fig. 3. BER of the OFDM system with $\phi = 0^\circ, \varepsilon = 0.4$.

Simulation results prove that QSC is an efficient technique for IQ mismatch mitigation.

Fig. 3 illustrates the BER performance of the OFDM system when only the amplitude IQ mismatching error is considered. The amplitude mismatching errors $\varepsilon = 0.4$ requires the additional Eb/N0 of 1.62 dB at BER=10^{-5}. QSC method outperforms other methods and reaches ideal case (without IQ mismatch) performance.

Fig. 4 demonstrates the BER performance of the OFDM system when both amplitude and phase mismatching errors are taken into account. When $\phi = 20^\circ$, additional SNR (Eb/N0) of 3.74 dB is required for $\varepsilon = 0.4$, at BER=10^{-5}.

In all the cases Figs. 2-4, the simulation results of the BER performance show that QSC is always an efficient technique for the OFDM system with IQ mismatching errors.

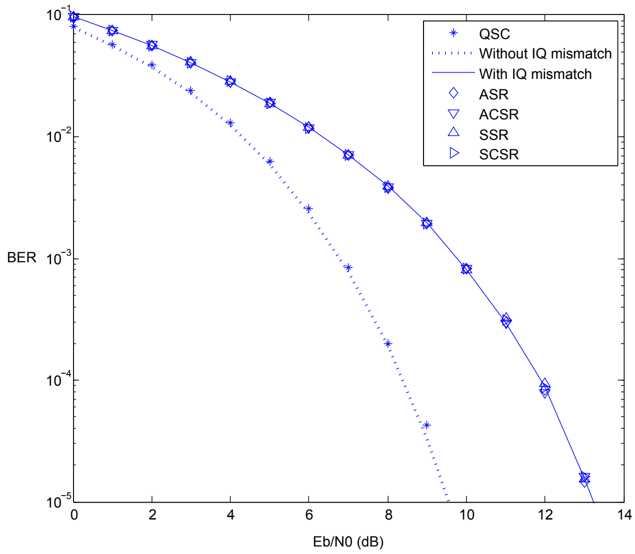

Fig. 4. BER of the OFDM system with $\phi = 20^\circ, \varepsilon = 0.4$.

V. Conclusion

The RF impairments result in the BER degradation of OFDM systems. The mismatching error between I and Q branches of up-conversion can cause degradation in BER performance. In this paper, a signal design technique is proposed to cope with the effect of IQ mismatching errors on OFDM systems. Without any channel or mismatching error estimation, a simple quasi symmetric conjugate (QSC) structure of signal at transmitter can completely remove effects of IQ mismatch. The efficiency of QSC technique is proved by both analytical and simulation results, which show that QSC outperforms other techniques ASR, ACSR, SSR, SCSR in IQ mismatch mitigation. Because of repeating the same symbol, like the previous techniques, however, QSC suffers a penalty of the half rate transmission.

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