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Estimation and Compensation of IQ Imbalance in Millimeter-Wave OFDM UWB System

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Abstract. A new estimation and compensation method for I/Q imbalance based on joint time and frequency domain is proposed in this paper, which is well applicable to orthogonal frequency division multiplexing (OFDM) ultra-wideband (UWB) millimeter-wave (mm-Wave) communications. Firstly, the method makes full use of the characteristics of I and Q signals in time domain, which have identical power and are uncorrelated. Amplitude imbalance factor and phase imbalance factor are estimated using preamble symbols. Secondly, a set of special pilots are designed in the frequency domain, and LS algorithm is utilized to estimate the residual imbalance factors to further reduce IQ imbalance. Simulation results show that IQ imbalance can be well estimated and compensated with low complexity.

Keywords: frequency domain, IQ imbalance, mm-Wave, OFDM-UWB, time domain

1 Introduction

Millimeter-wave communication system which operates at frequencies between 30GHz to 300GHz [1], is recognized as a key technology in 5G due to several hundred MHz bandwidth. Compared with traditional microwave communication with relatively narrow bandwidth, hardware impairments in mm-Wave communication creates more negative impact on system performance [2]. IQ imbalance in mm-Wave OFDM-UWB system is discussed in this paper.

Radio Frequency (RF) plays an important role in wireless communications system. There are two types of Traditional RF receiver, one is super heterodyne receiver and the other is zero-intermediate frequency (zero-IF) receiver. Compared with super heterodyne receiver, the zero-IF receiver has been widely used in wireless communications [3] with the advantage of small in size, simple in architecture, easy to integrate, energy conservation and low-cost. However, the advantage of simple implementation also brings serious IQ imbalance in Zero-IF receiver [4]. The overall performance will rapidly deteriorate without IQ imbalance estimation and compensation [5].

The effect of IQ imbalances on OFDM systems and the performance degradation have been investigated [6]. The existence of IQ imbalance in OFDM system is deduced [7]. A time domain estimation and compensation method without feedback mechanism is proposed [8]. A new IQ imbalance compensation method for OFDM systems using pilot signals inserted in frequency domain is proposed

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[9]. Some researchers have studied IQ imbalance estimation and compensation in OFDM system with carrier-frequency offset (CFO). Barhumi and Moonen proposed a frequency-domain equalization technique for OFDM transmission over frequency-selective channels [10]. They consider the case where the receiver analog front-end suffers from IQ-imbalance and the local oscillator suffers from CFO. Oka, Ahn, Omori and Hashimoto proposed novel IQ imbalance and CFO estimation schemes [11]. Wu, Li, Zhao proposed two novel preamble structures and the corresponding estimation algorithms that can treat the CFO and TX/RX IQ imbalance together in mm-Wave communication system [12].

For mm-Wave OFDM-UWB system, since the signal bandwidth is much larger compared with the narrowband system, the nonlinearity of RF transceiver is the main bottleneck limiting the performance of the communications. A new estimation and compensation method based on joint time and frequency domain is proposed to combat IQ imbalance problem.

This paper is organized as follows. The IQ imbalance theoretical analysis are discussed in section 2, including mathematical models and performance analysis in the zero-IF receiver. The principle of estimation and compensation method is discussed in section 3. Simulation results are shown in section 4. Finally, the summaries of the paper are given in section 5.

2 Theoretical Analysis of IQ Imbalance

2.1 System Model

The baseband signal in OFDM system can be expressed as:

$$x(t) = \frac{1}{N}\sum_{k=-N/2}^{N/2} R_k e^{j2\pi k f_s t} \quad \mathbf{(1)}$$

In the above formula, R_k is the modulation signal on the k th subcarrier, f_s is the adjacent subcarrier frequency interval. The signal bandwidth of UWB system discussed in this paper is 528 MHz, where $f_s = 4.125MHz$, N is the sub-carrier numbers of IFFT/FFT.

RF receiving signal can be defined as:

$$r_{RF}(t) = \mathrm{Re}\{r(t)e^{j2\pi f_c t}\} = r_I(t)\cos(2\pi f_c t) - r_Q(t)\sin(2\pi f_c t) \quad \mathbf{(2)}$$

where f_c is the frequency of Local Oscillator (LO), $w(t)$ is the additive white Gaussian noise (AWGN).

Zero-IF receiver architecture in UWB system is shown in Fig. 1. Where, LNA is Low-Noise Amplifier, VGA is Variable-Gain Amplifier, and LPF is Low-Pass Filter. Local Oscillator produces the in-phase component and quadrature component.

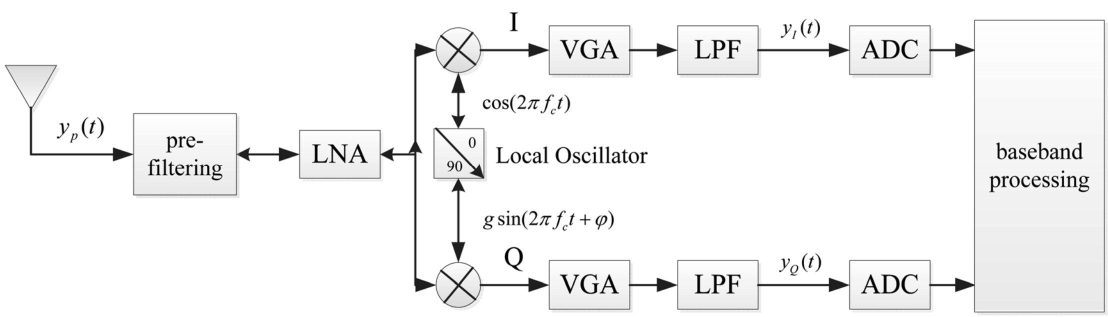

Fig. 1. Schematic of zero-IF receiver with IQ imbalance

Amplitude imbalance and phase imbalance are represented by g and θ in the Fig. 1. IQ Local Oscillator signals are expressed as:

$$x_{LO,I}(t) = \cos(2\pi f_c t) \quad \mathbf{(3)}$$

$$x_{LO,Q}(t) = g\sin(2\pi f_c t + \theta) \quad \mathbf{(4)}$$

Taking into account of the influence of IQ imbalance, the in-phase component of baseband signal $y_I(t)$ is expressed as:

$$\begin{aligned} y_I(t) &= r_{RF}(t)\cos(2\pi f_c t) \\ &= [r_I(t)\cos(2\pi f_c t) - r_Q(t) \\ &\times \sin(2\pi f_c t)]\cos(2\pi f_c t) \\ &= r_I(t)[1+\cos(4\pi f_c t)] \\ &-r_Q(t)\sin(4\pi f_c t). \end{aligned} \quad \textbf{(5)}$$

A low pass filter (LPF) is designed to eliminate the high frequency component in the in-phase component, then in-phase component can be expressed as:

$$y_I(t) = r_I(t) \quad \textbf{(6)}$$

Similarly, taking into account of the influence of IQ imbalance, the quadrature component of the baseband signal can be expressed as:

$$\begin{aligned} y_Q(t) &= r_{RF}(t)\cdot g\sin(2\pi f_c t+\theta) \\ &= [r_I(t)\cos(2\pi f_c t) + r_Q(t) \\ &\times \sin(2\pi f_c t)]\cdot g\sin(2\pi f_c t+\theta) \\ &= gr_I(t)[\sin(4\pi f_c t+\theta)+\sin\theta] \\ &+gr_Q(t)[\cos(4\pi f_c t-\theta)-\cos\theta]. \end{aligned} \quad \textbf{(7)}$$

A same LPF is designed to eliminate the high frequency component in the quadrature component, and then quadrature component can be expressed as:

$$y_Q(t) = gr_I(\mathrm{t})\sin(\theta) - gr_Q(\mathrm{t})\cos(\theta) \quad \textbf{(8)}$$

After processing by the orthogonal mixer and LPF, the signal can be expressed as:

$$\begin{aligned} y(t) &= y_I(t) - jy_Q(t) \\ &= y_I(t) - jg\{r_I(t)\sin(\theta) - r_Q(t)\cos(\theta)\} \\ &= \frac{1}{2}[1+g\cos(\theta)-jg\sin(\theta)](r_I(t)-jr_Q(t)) \\ &+\frac{1}{2}[1-g\cos(\theta)-jg\sin(\theta)](r_I(t)+jr_Q(t)) \\ &= \frac{1+ge^{-j\theta}}{2}r(t)+\frac{1-ge^{j\theta}}{2}r^*(t) \\ &= \alpha r(t)+\beta r^*(t). \end{aligned} \quad \textbf{(2)(9)}$$

where, α and β are defined as:

$$\alpha = \frac{1\text{+}ge^{-j\theta}}{2}, \quad \beta\text{=}\frac{1\text{-}ge^{-j\theta}}{2} \quad \textbf{(10)}$$

The discrete signal can be expressed as:

$$y_i(n) = \alpha\cdot r(n) + \beta\cdot r^*(n) \quad \textbf{(11)}$$

2.2 Performance Analysis of IQ Imbalance Effects

After converting time domain signals to frequency domain signals using Fast Fourier Transform (FFT), the signal on the k-th subcarrier can be represented as:

$$R_k^{'} = \alpha R_k + \beta R_{-k}^{*} \quad \textbf{(12)}$$

As can be seen from the above formula, the existence of IQ imbalance brings Signal of Image Interference (SOII) on received signals. The impact of IQ imbalance on received signals is mainly embodied in two aspects: one is a complex factor α which brings multiplicative distortion, the other is a complex factor β which generates SOII. For the zero-IF receiver, the SOII is the signal itself, namely IQ cross modulation signal, as shown in Fig. 2, where Δ represents the center frequency difference of adjacent channel and Signal of Interest (SOI).

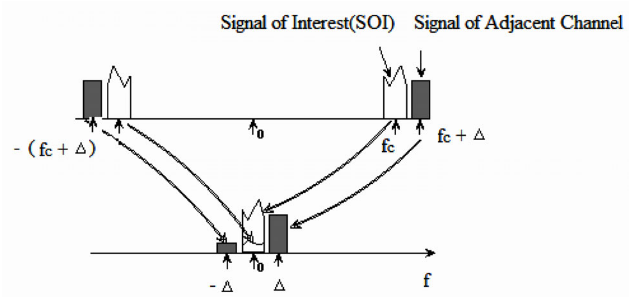

Fig. 2. SOII in Zero-IF receiver

As can be seen from equation (12), the power gain of SOI and its SOII are α^2 and β^2 respectively caused by amplitude imbalance and phase imbalance. Image rejection ratio (IRR) can be defined as:

$$L_{QUAD} = \frac{\alpha^2}{\beta^2} = \frac{\left(1+g^2\right)+2g\cos\theta}{\left(1+g^2\right)-2g\cos\theta} = \frac{1+\beta^2+2\beta\cos\theta}{1+\beta^2-2\beta\cos\theta} \quad \textbf{(13)}$$

where $\beta \triangleq \frac{1+\alpha/2}{1-\alpha/2}$ 。

IRR is a two-dimensional function with respect to amplitude error and phase error, the relationship between them is shown in Fig. 3.

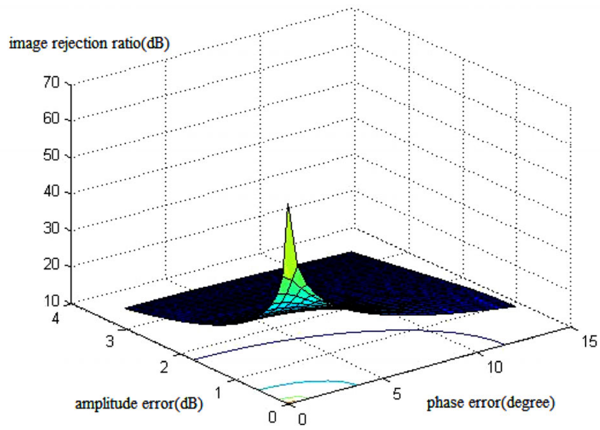

Fig. 3. The relationship between image rejection ratio and amplitude/phase factor in orthogonal mixer

Restricted to non-ideal factors of analog components, the analog orthogonal mixer cannot eliminate IQ imbalance fundamentally. Although with decades of development, analog orthogonal mixer still introduces non-ideal IQ imbalance factor. When amplitude imbalance factor is equal to 1.5 and phase imbalance factor is equal to 20 degrees, analog orthogonal mixer can only provide 14dB IRR according to equation (13). SOII result in a sharp decline in the performance of the wireless system without efficient IQ compensation [13]. Meanwhile, the spectrum density of received signal is usually very low for UWB receiver, and therefore if there is a strong SOII in the system, it is necessary to estimate and compensate IQ imbalance caused by analog orthogonal mixer.

In UWB system, the IRR of RF receiver is required to achieve 40dB or more, and therefore, the receiver needs to have the ability of no more than 1% of amplitude imbalance factor and no more than 1 degree of phase imbalance factor according to equation (1). However, limited by the level of integrated circuit technology, RF receiver cannot achieve this performance currently.

3 IQ Imbalance Compensation Algorithm in OFDM-UWB System

3.1 Compensation in Time Domain

The time-domain signals $t_I(n)$ and $t_Q(n)$ with QPSK code modulation has the following characteristics:

$$E\left\{t_I^2(n)\right\} = E\left\{t_Q^2(n)\right\} \tag{14}$$

$$E\left\{t_I(n)t_Q(n)\right\} = 0 \tag{15}$$

which means $t_I(n)$ and $t_Q(n)$ are a pair of IQ signals with identical power, zero mean, and orthogonality. $t_I(n)$ and $t_Q(n)$ are sent to IFFT module to generate OFDM symbols. Since the influence of IQ imbalance on signals is linear, the existence of IQ imbalance does not change identical power and orthogonality of IQ signals [14-15]. Amplitude/phase imbalance factors can be estimated by using the characteristics, the specific algorithm is as follows:

I/Q signals have identical power and are uncorrelated according to equation (14) and (15), it can be concluded that:

$$E\left\{y_Q^2\right\} = E\left\{(gr_Q\cos\theta - gr_I\sin\theta)^2\right\} = g^2E\left\{y_I^2\right\} \tag{16}$$

The estimation value of amplitude imbalance factor g can be represented as:

$$\hat{g} = \sqrt{\frac{E\left\{y_Q^2(n)\right\}}{E\left\{y_I^2(n)\right\}}} \tag{17}$$

According to orthogonality of IQ signals:

$$E\left\{y_I(n)y_Q(n)\right\} = E\left\{r_I(n)\cdot[gr_Q(n)\cos\theta - gr_I(n)\sin\theta]\right\} = -g\sin\theta E\left\{y_I^2(n)\right\} \tag{18}$$

Hence, $\hat{\theta}$ can be expressed as follows：

$$\hat{\theta} = -\arcsin\frac{E\left\{y_I(n)y_Q(n)\right\}}{\sqrt{E\left\{y_I^2(n)\right\}E\left\{y_Q^2(n)\right\}}} \tag{19}$$

In practical application, the mathematical expectation in the above formula can be replaced by mean value of the finite samples:

$$\hat{g} = \sqrt{\frac{\sum_{n=1}^{M}\left\{y_Q^2(n)\right\}}{\sum_{n=1}^{M}\left\{y_I^2(n)\right\}}} \tag{20}$$

$$\hat{\theta} = -\arcsin \frac{\sum_{n=1}^{M}\{y_I(n)y_Q(n)\}}{\sqrt{\sum_{n=1}^{M}\{y_I^2(n)\}}\sqrt{\sum_{n=1}^{M}\{y_Q^2(n)\}}} \quad \textbf{(21)}$$

where M represents samples. In this paper, two OFDM preamble symbols are used as the training sequence in time domain. FFT/IFFT length is 128, CP length is 36. Therefore, M = 2*(128+36) = 328.

Finally, signals in time domain can be compensated as follows utilizing estimation values $\hat{g}$ and $\hat{\theta}$ ：

$$y_I^{'}(n) = y_I(n) \text{ ，} \ y_Q^{'}(n) = \frac{y_Q(n) + \hat{g}\sin\hat{\theta}y_I(n)}{\hat{g}\cos\hat{\theta}} \quad \textbf{(22)}$$

3.2 Compensation in Frequency Domain

However, for one thing, under the frame structure in OFDM-UWB system where only a few preamble symbols exist, there is a lot of residual IQ imbalance in UWB system after time-domain compensation. For another, since there is a time selective fading characteristics in the wireless channel, the performance of OFDM-UWB receiver will deteriorate if only using few preamble symbols to estimate and compensate IQ imbalance, especially for those OFDM symbols located in the behind portion of radio frame structure.

The pilots in frequency domain within each OFDM symbol is used to further eliminate the residual IQ imbalance. In AWGN channel, equation (12) can be rewritten as:

$$R_k^{'} = \alpha R_k + \beta R_{-k}^{*} + N_k \quad \textbf{(23)}$$

The pilot deployment in this paper is as follows:

$$P_k = \begin{cases} A(k) & k > 0 \\ 0 & k \le 0 \end{cases} \quad \textbf{(24)}$$

where k is the number of subcarrier, P_k is the k-th pilot subcarrier, $A(k)$ is a constant.

We can get：

$$P_k^{'} = \alpha P_k + N_k \text{ ，} \ P_{-k}^{'} = \beta P_k^{*} + N_{-k} \quad \textbf{(25)}$$

where $P_k^{'}$ is the measured value of P_k at receiver，P_k^{*} is the conjugate of P_k. According to the principle of least squares (LS), the objective function is defined as follows:

$$J = (P_k - P_k^{'})^{*}(P_k - P_k^{'}) \quad \textbf{(26)}$$

In order to get $\widehat{\alpha_k}$ (LS estimation value of α), the objective function J needs to be minimized. Let $\frac{\partial J}{\partial \alpha} = 0$, accordingly, $\widehat{\alpha_k}$ can be expressed as:

$$\widehat{\alpha_k} = \frac{P_k^{'}}{P_k} = \alpha + \frac{N_k}{P_k} \quad \textbf{(27)}$$

The above formula shows that the estimation variance is inversely proportional to signal-to-noise ratio(SNR). The larger the SNR, the better the estimation performance. Estimation variance is defined as:

$$\delta^2 = \frac{1}{SNR} \quad \textbf{(28)}$$

Suppose there are K forward pilots in each OFDM symbol, the number of $\widehat{\alpha_k}$ are also K. The K estimation values are further processed by Maximum Likelihood (ML) estimation:

$$\alpha^{'} = \frac{1}{K}\sum_{K\in S_P}\widehat{\alpha_k} \quad \textbf{(29)}$$

where S_P is the set of forward pilots in OFDM symbols. $\alpha^{'}$ is the mean value of $\widehat{\alpha_k}$. Estimation variance processed by ML estimation can be expressed as:

$$\delta^{'2} = \frac{1}{K}\delta^2 \quad \textbf{(30)}$$

Estimation variance is further reduced by $\frac{1}{K}$ via ML estimation. In this paper, there are 12 pilots in each OFDM symbol, where the number of forward pilots is 6.

Similarly，$\beta^{'}$ (estimation value of β) can be expressed as:

$$\beta^{'} = \frac{1}{K}\sum_{K\in S_P}\widehat{\beta_k} \quad \textbf{(31)}$$

$\alpha^{'}$ and $\beta^{'}$ are taken to the formula, R_k (the correction value of $R_k^{'}$) can be obtained as follows:

$$R_k = \frac{(\alpha^{'})^* R_k^{'} - \beta^{'}(R_{-k}^{'})^*}{|\alpha^{'}|^2 - |\beta^{'}|^2} \quad \textbf{(32)}$$

4 Simulation

For the performance evaluation of the method proposed in this paper, a system simulation platform has been established.

The simulation conditions are as follows: SNR = 30dB, IQ amplitude imbalance factor is 1.5, phase imbalance factor is 20 degrees, and we adopt the frequency-dependent IQ imbalance model in wideband scenarios [16].

The influence of IQ imbalance on OFDM symbols constellation is shown in Fig. 4. IQ imbalance has not only led to the rotation of the constellation, but also causes inter-symbol interference (ISI). After estimation and compensation in time domain, the improved constellation is shown in Fig. 5. In the proposed method for OFDM-UWB system, 2 OFDM preamble symbols are used as the training sequence in time domain followed by estimation and compensation in frequency domain to eliminate residual IQ imbalance. The post-processed constellation using estimation and compensation method both in time domain and frequency domain is shown in Fig. 6. The bit error rate (BER) performances of the proposed method and traditional time-domain method are shown in Fig. 7. We can see a significant improvement using our proposed method.

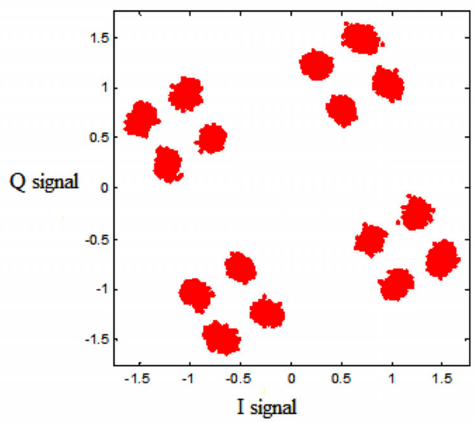

Fig. 4. Constellation without compensation

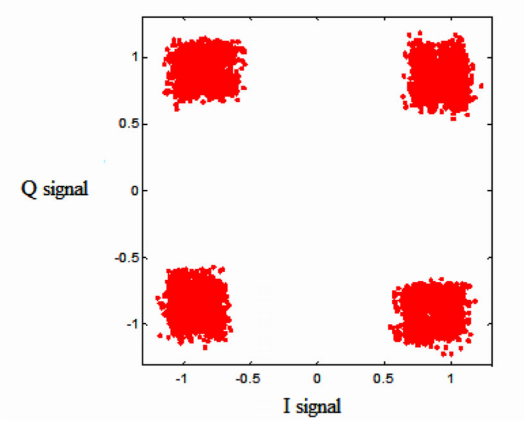

Fig. 5. Constellation after compensation in time domain

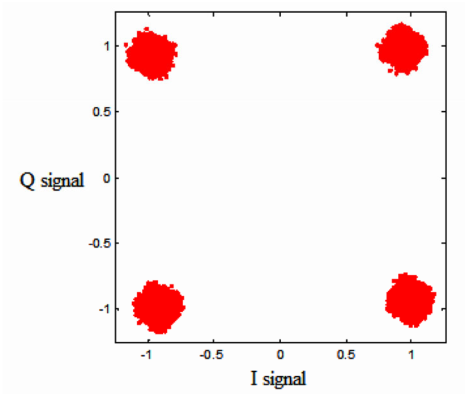

Fig. 6. Constellation after compensation in time domain and frequency domain

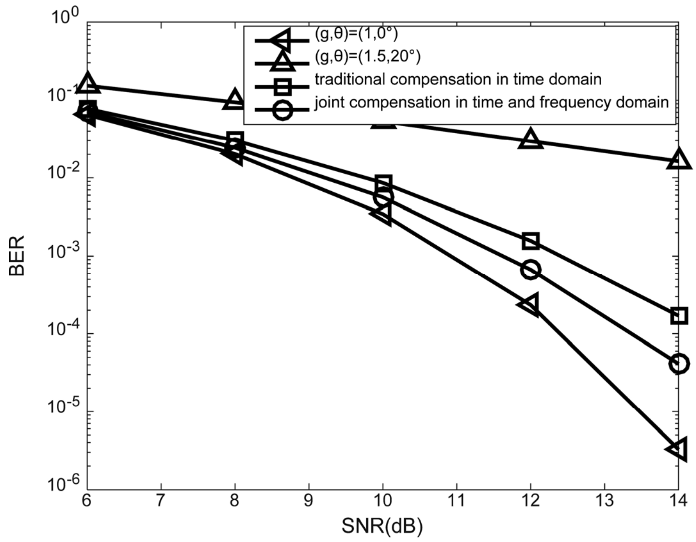

Fig. 7. BER of the proposed method and traditional time-domain method

5 Conclusion

A new method for estimation of IQ imbalance based on time domain and frequency domain is proposed in this paper, which well applicable for mm-Wave OFDM-UWB communication system. The system model and performance analysis of IQ imbalance effects on the wireless communications system are discussed in this paper firstly, followed by the estimation and compensation method. Compensation in time domain makes full use of the properties of I and Q signals. As for frequency domain method, a set of special pilots are designed, and LS algorithm is utilized to estimate the residual imbalance factors to further reduce IQ imbalance. Simulation results prove the effectiveness of the proposed method.

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