Blind frequency-dependent in-phase/quadrature imbalance compensation with constant norm algorithm and cascaded structure

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Abstract: Increasing carrier frequency and broadening bandwidth speeds up wireless communication, but at the price of a frequency-dependent imbalance between the in-phase/quadrature (IQ) signals in the quadrature modulator/demodulator. We propose a blind compensation system for correcting frequency-dependent IQ imbalance in orthogonal frequency division multiplexing (OFDM) systems. As the convergence characteristic of conventional blind adaptive algorithms limits their compensation performance, we introduce a constant-norm algorithm (CNA) and cascaded structure. Simulation results show that the proposed scheme improves bit error rate performance in a frequency-dependent IQ imbalance environment.

Keywords: Frequency-dependent IQ-imbalance, OFDM, CNA

Classification: Wireless communication technologies

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1 Introduction

Higher-speed wireless communication can be achieved by expanding the frequency bandwidth. For example, IEEE 802.11ay uses 8.64 GHz as the full bandwidth of the 60-GHz band [1]. However, a wider bandwidth causes a frequency-dependent imbalance, in which a gain error and phase error between the in-phase (I) and quadrature (Q) signals fluctuate at each frequency.

Tarighat et al. proposed a pilot-aided IQ imbalance compensation system [2]. Unfortunately, the pilot signals decrease the system’s data transmission rate. Blind (pilot-free) IQ imbalance compensation has therefore been proposed as an alternative [3]. Blind IQ imbalance compensation using second-order statistics is effective for frequency-independent IQ imbalance. Matsui et al. proposed a blind IQ imbalance compensation system using a constant modulus algorithm (CMA) for an orthogonal frequency division multiplexing (OFDM) system [4]. This system improves the bit error rate (BER) performance in phase-shift keying (PSK) because the CMA converges on a circular envelope [5]. Unfortunately, it degrades the performance in the case of quadrature amplitude modulation (QAM), which positions the signals on a rectangular shape.

To improve the compensation performance, we propose introducing an adaptive sixth-order constant-norm algorithm (CNA) [6] and a cascaded structure composed of two IQ imbalance compensators: one with a CNA that converges on a rectangular shape with rounded corners, the other using a signal compensated by the CNA as a reference to increase performance.

2 OFDM symbol with IQ imbalance

In the time domain, the received OFDM signal with frequency-dependent IQ imbalance is given by

\[ y(m, n) = g_1(n) \otimes r(m, n) + g_2(n) \otimes r^*(m, n), \]

where \( r(m, n) \) represents a received OFDM signal without IQ imbalance; \( m \) and \( n \) represent the symbol number and time index, respectively; \( * \) represents complex conjugation; and \( \otimes \) represents convolution. The parameters of IQ imbalance \( g_1(n) \) and \( g_2(n) \) are given by [4]

\[ g_1(n) = \{ h_I(n) + g \exp(-j\phi)h_Q(n) \}/2, \]

\[ g_2(n) = \{ h_I(n) - g \exp(-j\phi)h_Q(n) \}/2, \]

where \( h_I(n) \) and \( h_Q(n) \) are the impulse responses of the I/Q channels for the frequency-dependent component of the IQ imbalance, and \( g \) and \( \phi \) represent...
The amplitude and phase errors of the frequency-independent IQ imbalance. The received OFDM symbol, which is obtained by taking the fast Fourier transform (FFT), is given by

\[ Y(m, k) = G_1(k)R(m, k) + G_2(k)R^*(m, -k), \quad (3) \]

where \( k \) represents the subcarrier number; \( G_1(k) \) and \( G_2(k) \) are coefficients caused by the frequency-dependent IQ imbalance on the \( k \)-th subcarrier; \( R(m, k) \) is a received OFDM symbol without frequency-dependent IQ imbalance; and \( R(m, -k) \) is a received OFDM symbol without frequency-dependent IQ imbalance on the mirror subcarrier \(-k\) at the \( m \)-th symbol.

### 3 Proposed blind IQ compensation

Fig. 1 shows a block diagram of the proposed blind IQ imbalance compensation system. The proposed system is composed of a first IQ imbalance compensator using a CNA, a decision element, and a second IQ imbalance compensator using a least mean square (LMS) algorithm. The output symbol of the first IQ imbalance compensator is given by

\[ Z(m, k) = W_1(m, k)Y(m, k) + W_2(m, k)Y^*(m, k), \quad (4) \]

where \( W_1(k) \) and \( W_2(k) \) are the weights on the \( k \)-th subcarrier at the \( m \)-th symbol. An adaptive algorithm updates the weights. The conventional IQ imbalance compensation system uses a CMA that converges on a circular envelope [4]. Therefore, the conventional system degrades the compensation performance in the case of QAM, which has an envelope of rectangular shape.

We adopt a sixth-order CNA in the first IQ imbalance compensator. The cost function of the CNA \( J \) is defined by [6]

\[ J = \mathbb{E}[\| Z(m, k) \|_6^2 - \gamma]^2, \quad (5) \]

where \( \mathbb{E}[\cdot] \) is the expected value, \( \gamma \) represents the average power of the transmitted symbol, and the sixth order norm is

\[ \| Z(m, k) \|_6 = \sqrt[6]{|\text{Re}\{Z(m, k)\}|^6 + |\text{Im}\{Z(m, k)\}|^6}, \quad (6) \]

where \( \text{Re}\{\cdot\} \) and \( \text{Im}\{\cdot\} \) indicate the real and imaginary parts of a complex signal, respectively. The adaptive algorithms for \( W_1(k) \) and \( W_2(k) \) are given by the following equations from the partial derivative of \( J \):

\[
W_1(m+1, k) = W_1(m, k) - \mu_{\text{CNA}}(\| Z(m, k) \|_6^2 - \gamma) \\
\times \frac{\{\text{Re}\{Z(m, k)\}\}^5 + j\{\text{Im}\{Z(m, k)\}\}^5}{\| Z(m, k) \|_6^4}Y^*(m, k),
\]

\[
W_2(m+1, k) = W_2(m, k) - \mu_{\text{CNA}}(\| Z(m, k) \|_6^2 - \gamma) \\
\times \frac{\{\text{Re}\{Z(m, k)\}\}^5 + j\{\text{Im}\{Z(m, k)\}\}^5}{\| Z(m, k) \|_6^4}Y(m, k),
\]

where \( \mu_{\text{CNA}} \) is the step size. The CNA converges so that the envelope of the output symbol approaches a rounded rectangular shape. Therefore, the IQ
imbalance compensator using this CNA improves the compensation performance.

Next, we introduce an IQ imbalance compensator using an LMS algorithm, because a CNA that converges on a rounded rectangular envelope limits the compensation performance. The output symbol of the IQ imbalance compensator using an LMS algorithm is given by

$$Z'(m, k) = W_1'(m, k)Y(m, k) + W_2'(m, k)Y^*(m, -k),$$  \hspace{1cm} (8)

where $W_1'(k)$ and $W_2'(k)$ are weights. The error of the IQ imbalance compensator is expressed by

$$E(m, k) = D'(m, k) - Z'(m, k),$$  \hspace{1cm} (9)

where $D'(m, k)$ is the symbol estimated by the IQ imbalance compensator using a CNA and the decision element. The weights $W_1'(m, k)$ and $W_2'(m, k)$ converge in such a way that the mean square error $E[E^2(m, k)]$ is minimized by an LMS algorithm. The weights are updated as follows:

$$W_1'(m + 1, k) = W_1'(m, k) - \mu_{LMS}Y^*(m, k)E(m, k),$$

$$W_2'(m + 1, k) = W_2'(m, k) - \mu_{LMS}Y(m, k)E(m, k),$$  \hspace{1cm} (10)

where $\mu_{LMS}$ is the step size for the LMS algorithm.

![Fig. 1. Structure of proposed blind IQ imbalance compensation system.](image)

4 Simulation Results

The performance of the proposed system was evaluated using computer simulations. The channel was additive white Gaussian noise. The frequency-dependent IQ imbalance that was used in this simulation was generated by two low-pass filters (LPFs) and a frequency-independent IQ imbalance [4]. The received I and Q signals passed two LPFs with respective transfer functions given by

$$H_I(z) = \frac{1 + z^{-1}}{1 + 0.7162 \cdot z^{-1}},$$

$$H_Q(z) = \frac{1 + z^{-1}}{1 + 0.4602 \cdot z^{-1}}.$$  \hspace{1cm} (11)
Table I. Simulation parameters

| Parameter                | Value       |
|--------------------------|-------------|
| Modulation scheme        | QPSK, 16QAM |
| Number of samples        | 390         |
| Number of subcarriers    | 512         |
| Number of data subcarriers | 336       |
| Oversampling rate        | 2           |
| Stepsize for CSM         | 0.0002      |
| Stepsize for LMS, CMA, and CNA | 0.01     |

The amplitude and phase errors in the frequency-independent IQ imbalance were set to 0.3 dB and 3 degrees, respectively. Table I shows the parameters used in the simulation. The subcarrier placement that was used in this simulation followed the IEEE 802.11ad for the 60-GHz frequency band [7]. We compared the proposed system with conventional systems based on a pilot-aided approach [2], a conjugate signal model (CSM) [3], and CMA [4].

Fig. 2 shows the BER performance for quadrature phase-shift keying (QPSK) and 16QAM. Proposed systems 1 and 2 represent the results of the proposed system without and with the IQ imbalance compensator using an LMS algorithm, respectively. From Fig. 2(a), proposed system 2 improves $E_b/N_0$ by about 0.7 dB at BER $= 10^{-4}$ in comparison to the system using CMA and to proposed system 1; it obtains the same BER as pilot-aided IQ compensation. Fig. 2(b) shows the BER performance in the case of 16QAM. Both proposed systems 1 and 2 significantly improve the BER due to a CNA in comparison to the conventional systems. Furthermore, proposed system 2 obtains the same BER as the pilot-aided system. Simulation results shows that a CNA contributes to BER improvement for QAM. In addition, the IQ imbalance compensator using an LMS algorithm improves the performance degradation caused by discordance between the envelope of the modulation scheme and the convergence envelope of the adaptive algorithm.

5 Conclusion

We have proposed a blind IQ imbalance compensation system that uses a CNA and a cascaded structure. Conventional systems can compensate for frequency-dependent IQ imbalance in the case of PSK but are not suitable for QAM. Thus, the proposed system adopts a CNA that converges on a rectangular envelope with rounded corners to improve the compensation performance. Further improvement in compensation ability is achieved by adding an IQ imbalance compensator using an LMS algorithm. From the simulation results, the proposed system significantly improves the BER performance and is thus effective in compensating frequency-dependent IQ imbalance. In future work, we will investigate IQ imbalance compensation for multiple-input multiple-output OFDM systems.

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Fig. 2. BER performance with (a) QPSK and (b) 16QAM modulation schemes.