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Joint Estimation of CSI and IQ Imbalance, and Compensation of IQ Imbalance in Spatialy Multiplexed MIMO-OFDM Receivers

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Abstract

This study presents a novel method for estimating Channel State Information (CSI) and IQ imbalance and compensating IQ imbalance in a spatially multiplexed MIMO OFDM receiver. Our approach integrates estimation of IQ imbalance with CSI estimation using an OFDM training frame, thus eliminating the need for additional pilot symbols for IQ imbalance estimation. This technique streamlines the process and avoids extra overhead. We conducted simulations on a 2×2 spatially multiplexed MIMO-OFDM system to evaluate the performance of our method. The findings reveal a substantial decrease in Bit Error Rate (BER), emphasizing the effectiveness of the proposed method in enhancing the precision and dependability of MIMO-OFDM systems. This improvement indicates that the approach can significantly boost communication quality in modern wireless systems. The method stands out by delivering these gains without introducing additional system complexity or consuming extra resources, making it an ideal solution for practical deployment. By maintaining efficiency and minimizing overhead, it supports better performance in real-world scenarios where resource constraints are critical. Overall, the results validate the approach as a reliable and scalable solution, contributing to the advancement of robust and efficient wireless communication technologies essential for meeting growing data demands and maintaining signal integrity.

Keywords: Multiple input multiple output orthogonal frequency division multiplexing (MIMO-OFDM), channel state information (CSI), in phase and quadrature-phase (IQ) imbalance

INTRODUCTION

Multiple Input Multiple Output-Orthogonal Frequency Division Multiplexing (MIMO-OFDM) based physical layer technologies have become a fundamental choice for modern wireless communication systems due to their high data rates, spectral efficiency, and robustness against multipath fading. These physical layer techniques are widely adopted in several major standards and technologies. For instance, MIMO-OFDM forms the basis of the physical layer for 3GPP Long Term Evolution (LTE), which supports high-speed mobile broadband. Similarly, Mobile WiMAX uses MIMO-OFDM to provide efficient wireless access over large areas. The International Mobile Telecommunications-Advanced (IMT-Advanced) standard, which defines requirements for 4G systems, also incorporates MIMO-OFDM. Furthermore, wireless local area networks (WLANs) such as IEEE 802.11a and IEEE 802.11n utilize MIMO-OFDM to enhance network performance and reliability.

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Unfortunately, the OFDM performance is greatly affected by IQ imbalance [1, 2]. Le and Nguyen proposed low complexity IQ imbalance compensation scheme for multiuser single input multiple output MU-SIMO system [3]. Marey *et al.* presented pilot based joint estimation is proposed, but it is for multiuser MIMO and not for spatially multiplexed MIMO [4]. Marey *et al.* proposed IQ imbalance estimation and compensation for MIMO-OFDM but it is Alomouti OFDM scheme where MIMO provides diversity and not spatial multiplexing [5]. The work by Marey *et al.* proposed an iterative method for compensating IQ imbalance in single-carrier OFDM systems. IQ imbalance, commonly present in practical transmitters and receivers, can significantly degrade system performance if not properly addressed. Marey *et al.* introduced a transmitter IQ imbalance compensation technique that achieves convergence within just a single OFDM training symbol, making it highly efficient for SISO-OFDM systems [6]. On the other hand, the method described by Jnawali *et al.* proposed a subcarrier-multiplexed preamble structure to handle IQ imbalance [7]. While effective, this approach has a drawback: it increases the dynamic range requirement of the analog-to-digital converter (ADC), which can pose hardware implementation challenges. Overall, both methods offer valuable solutions, but trade-offs exist between complexity, convergence speed, and hardware requirements.

To the best of our knowledge, the issue of compensating for IQ (In-phase and Quadrature) imbalance, particularly in the context of spatially multiplexed MIMO-OFDM (Multiple Input Multiple Output-Orthogonal Frequency Division Multiplexing) systems, has not been thoroughly or adequately addressed in existing literature. IQ imbalance, which arises due to imperfections in the analog front-end of wireless communication systems, can significantly degrade system performance by causing interference between the I and Q signal components. This becomes more critical in MIMO-OFDM systems, where the complexity of multiple parallel data streams and high data rates increases the vulnerability to such impairments. Despite its importance, limited attention has been given to robust compensation techniques that effectively mitigate the impact of IQ imbalance in these advanced systems. In this study, the method of estimating CSI and IQ imbalance shown by Marey *et al.* for SISO-OFDM receiver is extended and formulated for spatially multiplexed MIMO-OFDM receiver [6]. In our method, IQ imbalance as well as channel estimation and compensation of IQ imbalance is completed using OFDM training frame, without any extra overhead of pilots for IQ imbalance estimation and compensation.

MATHEMATICAL MODEL OF IQ IMBALANCE FOR SPATIALLY MULTIPLEXED MIMO-OFDM

With phase imbalance θ and amplitude imbalance ε, the impact of IQ imbalance on the OFDM signal can be represented as [1, 6]:

$$y = \alpha x + \beta x^* \tag{1}$$

Where, $*$ denotes complex conjugate, x represents ideal OFDM signal in time domain. And

$$\alpha = \cos(\theta) + j\varepsilon \sin(\theta) \tag{2}$$

$$\beta = \varepsilon \cos(\theta) - j \sin(\theta). \tag{3}$$

The effect of IQ imbalance post FFT, on i^{th} sub carrier is:

$$d_r = \alpha d + \beta (d)_m^* \tag{4}$$

Where, m indicates mirror subcarrier, $d = ac + n = a_i c_i + n_i$, $(d)_m^* = (a^* c^* + n^*)_m = a_{-i}^* c_{-i}^* + n_{-i}^*$, a_i is complex symbol on i^{th} sub-carrier, n_i is FFT component of noise $n(t)$. c_i is channel coefficient of i^{th} subcarrier.

Eq. (4) shows that, IQ imbalance creates a problem of image interference, where symbol (d) on each sub-carrier is interfered by, the complex conjugate of symbol on mirror subcarrier $(d)_m^*$. Thus IQ imbalance causes loss of orthogonality in OFDM.

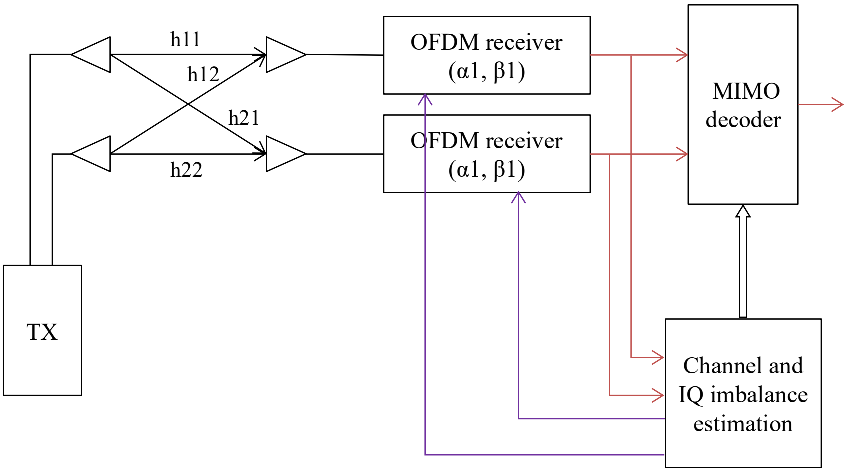

Figure 1. 2×2 spatially multiplexed MIMO-OFDM.

Figure 1 shows a 2×2 spatially multiplexed MIMO-OFDM; with IQ imbalance in OFDM receiver-1 (α_1, β_1) and in receiver-2 (α_2, β_2). The effect of IQ imbalance on i^{th} subcarrier for this 2×2 spatially multiplexed MIMO-OFDM can be represented as Eq. (5).

$$\begin{bmatrix} y1 \\ y2 \end{bmatrix}_k = \begin{bmatrix} \alpha_1 \\ \alpha_2 \end{bmatrix} \odot \begin{bmatrix} h11 & h12 \\ h21 & h22 \end{bmatrix}_k \begin{bmatrix} x1 \\ x2 \end{bmatrix}_k + \begin{bmatrix} \beta_1 \\ \beta_2 \end{bmatrix} \odot \begin{bmatrix} h11^* & h12^* \\ h21^* & h22^* \end{bmatrix}_{-k} \begin{bmatrix} x1^* \\ x2^* \end{bmatrix}_{-k} + \begin{bmatrix} z1 \\ z2 \end{bmatrix}_k \qquad (5)$$

Here, $\odot$ denotes Kronecker Product, $x1$, $x2$ represent ideal signals on kth subcarrier. $\begin{bmatrix} z1 \\ z2 \end{bmatrix}_k$ is independent AWGN vector with zero mean and unit variance.

Eq. (5) shows that, if IQ imbalance is present, then the decoded symbol on a subcarrier (k) will have interference from subcarrier (-k) of both OFDM frames. This result can be extended for any N×N spatially multiplexed MIMO-OFDM.

JOINT ESTIMATION OF CSI AND IQ IMBALANCE IN SM-MIMO-OFDM SYSTEM

We have performed estimation and compensation of IQ imbalance jointly with CSI estimation for spatially multiplexed MIMO-OFDM. For this we have considered IEEE 802.11n standard. In this standard, HTLTF (high throughput long training field) is used as a training OFDM frame for channel estimation. In this standard, the channel matrix for kth subcarrier is estimated by Eq. (6) [8].

$$\hat{H} = \begin{bmatrix} \hat{h}11 & \hat{h}12 \\ \hat{h}21 & \hat{h}22 \end{bmatrix}_k = \left(Y_{t1}^k \;\; Y_{t2}^k \right) P_{orth}^T \left(\frac{1}{HTLTF_k \; N_{LTF}} \right) \qquad (6)$$

Where,

Y_{t1}^k and Y_{t2}^k represent received signal vector $\begin{bmatrix} y1 \\ y2 \end{bmatrix}_k$ for transmitted training symbol on time t1 and on t2 respectively.

$P_{orth}^T = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$

$HTLTF_k$ is training symbol on kth subcarrier.

N_{LTF} is number of time training symbols transmitted. In case of 2×2 SM-MIMO-OFDM it is 2.

With IQ imbalance, as shown Figure 1, we have formulated the Least Squared estimated CSI for subcarrier k as:

$$\hat{H} = \begin{bmatrix} \hat{h}11 & \hat{h}12 \\ \hat{h}21 & \hat{h}22 \end{bmatrix}_k = \begin{bmatrix} \alpha_1 \\ \alpha_2 \end{bmatrix} \odot \begin{bmatrix} h11 & h12 \\ h21 & h22 \end{bmatrix}_k + \begin{bmatrix} \beta_1 \\ \beta_2 \end{bmatrix} \odot \begin{bmatrix} h11^* & h12^* \\ h21^* & h22^* \end{bmatrix}_{-k} \left(\frac{HTLTF_{-k}^*}{HTLTF_k} \right) \qquad (7)$$

As shown in Eq. (7) and in Figure 1, channel vectors $\hat{h}11$ and $\hat{h}12$ are affected by IQ imbalance (α_1, β_1) and $\hat{h}21$ and $\hat{h}22$ are affected by IQ imbalance (α_2, β_2).

Steps for Joint Estimation of Channel and IQ Imbalance, and Compensation for IQ Imbalance

1. Using the received training data, known as the preamble, an estimate of the channel matrix H^ for each subcarrier is obtained. This estimation process follows the procedure outlined in Eq. (6), which enables accurate characterization of the channel's effect on the transmitted signal for reliable communication.
2. Using these matrix estimates of all sub carriers, channel vectors $\hat{h}11$,$\hat{h}12$, $\hat{h}21$ and $\hat{h}22$ are obtained, *where each channel vector contains sub carriers' channel coefficients. These channel vectors have effect of IQ imbalance*.
3. (α_1, β_1) is estimated using channel vectors $\hat{h}11$ and $\hat{h}12$ as depicted in Eq. (6). The accuracy of estimates can be increased by using the average of estimates resulting from $\hat{h}11$ and $\hat{h}12$. similarly, (α_2, β_2) is estimated using channel vectors $\hat{h}21$ and $\hat{h}22$.
4. Using estimated IQ imbalance $(\hat{\alpha}_1, \hat{\beta}_1)$ and $(\hat{\alpha}_2, \hat{\beta}_2)$, the correct channel matrix for subcarrier k is obtained by Eq. (8).
5. Using estimated IQ imbalance $(\hat{\alpha}_1, \hat{\beta}_1)$ and $(\hat{\alpha}_2, \hat{\beta}_2)$, compensation of IQ imbalance for OFDM data frames is performed in time domain (pre FFT compensation), as shown in functional block diagram in Figure 1 [6]. And Equalization is performed post FFT using $\widehat{H}_{corr}{}^{k}$ for each sub carrier data symbol.

$$\widehat{H}_{corr}{}^{k} = \begin{bmatrix} 1/(\hat{\alpha}_1{}^2 - \hat{\beta}_1{}^2) \\ 1/(\hat{\alpha}_2{}^2 - \hat{\beta}_2{}^2) \end{bmatrix} \odot \left[\begin{pmatrix} \hat{\alpha}_1{}^* \\ \hat{\alpha}_2{}^* \end{pmatrix} \odot \widehat{H}^{k} - \begin{pmatrix} \hat{\beta}_1{}^* \\ \hat{\beta}_2{}^* \end{pmatrix} \odot \widehat{H}_c{}^{-k} HTLTF_k HTLTF_{-k} \right] \qquad (8)$$

Where, * denotes complex conjugate, k denotes kth subcarrier, -k denotes -kth subcarrier, $\widehat{H}_c{}^{-k}$is element wise complex conjugate of $\widehat{H}^{-k}$.

SIMULATIONS AND RESULTS

The simulation has been carried out for 2×2 spatially multiplexed MIMO-OFDM with the multipath channel models D and E [8]. The maximum delay spread for channels D and E are 390 and 730 ns respectively [8]. These models were largely used to compare proposals during the development of the (IEEE 802.11n) standard [8]. The IQ imbalance considered for simulation is: $(\varepsilon_1 = 0.1, \theta_1 = 10^{o})$, $(\varepsilon_2 = 0.1, \theta_2 = 10^{o})$. The simulation parameters are as shown in Table 1.

The sample channel vectors h11, h12, h21 and h22 of one OFDM frame, for channel model E which we have used in our simulation, are shown in Figures 2–5 respectively. The black plots represent

Table 1. Simulation parameters.

IEEE 802.11N standard: (2×2 SM-MIMO-OFDM)	
Useful OFDM symbol period (Tu)	3.2×10^{-6} s
Baseband elementary period	Tu/64
Guard interval	1/4×Tu
Total OFDM symbol period (T)	4×10^{-6} s
Total number of subcarriers	64
Useful subcarriers	56
Null subcarriers	8
IFFT/FFT length	64

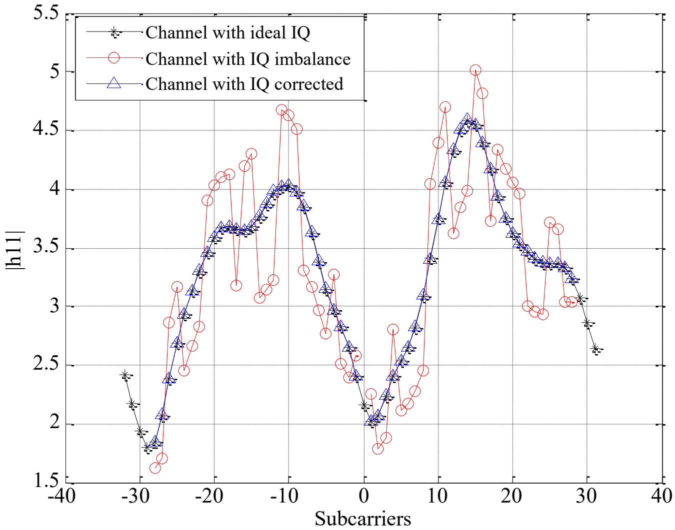

Figure 2. Channel vector h11.

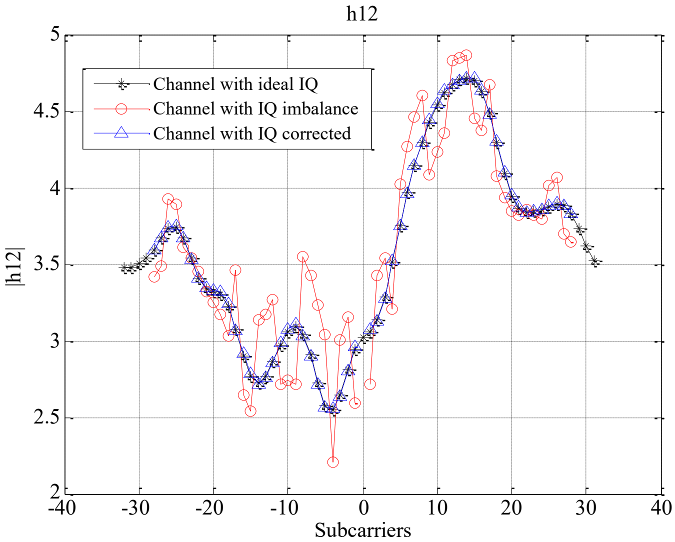

Figure 3. Channel vector h12.

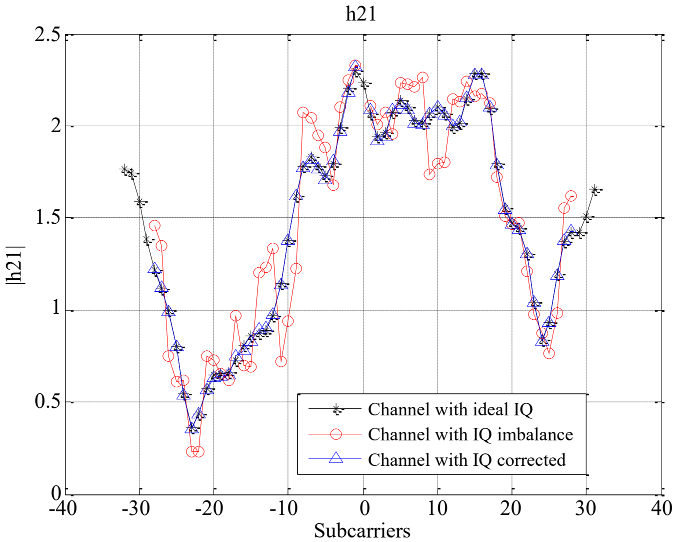

Figure 4. Channel vector h21.

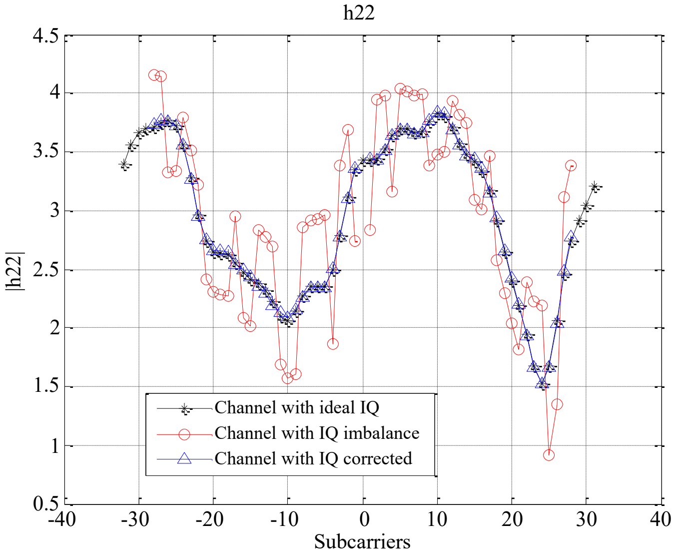

Figure 5. Channel vector h22.

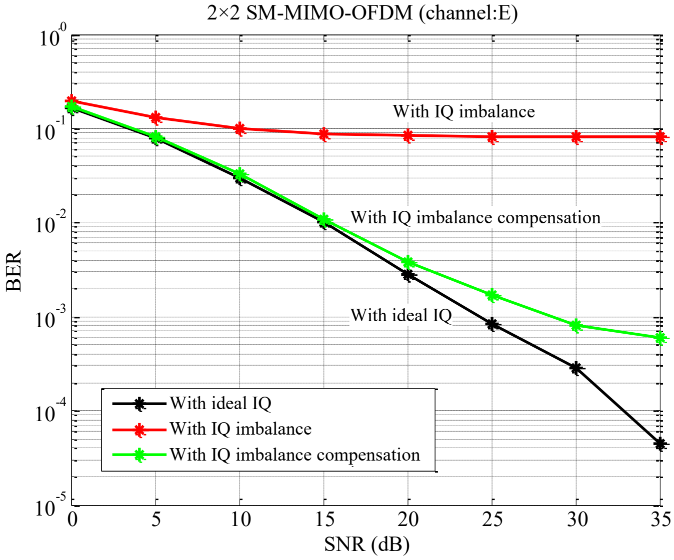

Figure 6. BER plot for channel: E with $(\varepsilon_1 = 0.1, \theta_1 = 10^{o})$, $(\varepsilon_2 = 0.1, \theta_2 = 10^{o})$.

the least square estimated channel vectors under ideal IQ condition. The red plots represent the least square estimated channel vectors under the effect of IQ imbalance. From IQ imbalance affected channel vectors; the imbalance parameters $(\hat{\alpha}_1, \hat{\beta}_1, \hat{\alpha}_2, \hat{\beta}_2)$ are calculated using Eq. (7), and corrected channel vectors are obtained using Eq. (8) [8–11]. The blue plots show the corrected channel vectors which closely match with the ideal channel vectors (black plots) and almost, entire effect of IQ imbalance has been removed from the least square estimated channel vectors (red plots).

Figure 6 shows the BER plot with same channel model E. The black plot shows the BER performance under perfect IQ condition. The red plot shows the BER without compensating IQ imbalance. Which shows that the BER cannot be reduced just by increasing signal power, when IQ imbalance is present. The green plot is obtained with our scheme of compensating IQ imbalance and equalizing data symbols with corrected channel coefficients. Our method results into considerable reduction in BER as shown in green plot as compared to uncompensated scenario in red plot and reduces BER below 10^{-3} even with channels having large delay spread.

CONCLUSION

In this study, we investigated the impact of IQ imbalance on channel estimation and Bit Error Rate (BER) in a 2×2 spatially multiplexed MIMO-OFDM system. Utilizing a preamble-based estimation approach, our method leverages the standardized pilot symbols embedded in the OFDM preamble frame across all subcarriers for channel estimation. This approach estimates both IQ imbalance and the channel without necessitating additional pilot symbols, thereby preserving throughput. Our proposed method significantly reduces the BER from 10^{-1} to 10^{-3}. Moreover, this technique is versatile and can be extended to any N×M spatially multiplexed MIMO-OFDM system, offering a scalable solution for improving performance in various configurations.

REFERENCES

1. Liu CL. Impacts of i/q imbalance on QPSK-OFDM-QAM detection. IEEE Trans Consum Electron. 1998 Aug; 44(3): 984–9.
2. Kolomvakis N, Matthaiou M, Coldrey M. IQ imbalance in multiuser systems: Channel estimation and compensation. IEEE Trans Commun. 2016 Apr 25; 64(7): 3039–51.
3. Le LD, Nguyen HH. Compensation of phase noise and IQ imbalance in multi-carrier systems. IEEE Access. 2020 Oct 20; 8: 191263–77.
4. Marey M, Samir M, Ahmed MH. Joint estimation of transmitter and receiver IQ imbalance with ML detection for Alamouti OFDM systems. IEEE Trans Veh Technol. 2013 Jan 23; 62(6): 2847–53.
5. Argyriou A. Joint estimation of the number of antennas and AoA of a wireless communication transmitter. 2022 IEEE International Symposium on Phased Array Systems & Technology (PAST), Waltham, MA, USA. 2022 Oct 11–14. 2022. p. 1–4. doi:10.1109/PAST49659.2022.9975054.
6. Chung YH, Phoong SM. Joint estimation of transmitter and receiver I/Q imbalances, CFO, and channel response for OFDM systems. The 2010 International Conference on Green Circuits and Systems, Shanghai, China. 2010 Jun 21–23. 2010. p. 247–252. doi:10.1109/ICGCS.2010.5543060.
7. Jnawali S, Beygi S, Bahrami HR. RF impairments compensation and channel estimation in MIMO-OFDM systems. In 2011 IEEE Vehicular Technology Conference (VTC Fall). 2011 Sep 5; 1–5.
8. Perahia E, Stacey R. Next Generation Wireless LANs: Media access control; 8. MAC throughput enhancements; 9. Advanced channel access techniques; 10. Interoperability and coexistence; 11. MAC frame formats; Part III. Transmit beamforming: 12. Transmit beamforming; Acronyms; Index. Cambridge: Cambridge University Press; 2008.
9. Cheng X, Yang Y, Li S. Joint compensation of transmitter and receiver I/Q imbalances for SC-FDE systems. IEEE Trans Veh Technol. 2020 May 19; 69(8): 8483–98.
10. Li Y, Li Y. The IQ Imbalance Model. In-Phase and Quadrature Imbalance: Modeling, Estimation, and Compensation. New York, NY: Springer; 2014; 3–27.
11. Sanoopkumar PS, Muneer P, Sameer SM. A low complexity iterative equalization technique for OFDMA and SC-FDMA uplink systems with Tx-Rx IQ imbalance and CFO under doubly selective channels. Phys Commun. 2020 Oct 1; 42: 101170.