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EVALUATION OF THE IMPACT OF I/Q IMBALANCE COMPENSATION ON COMMUNICATION PERFORMANCE

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ABSTRACT. Quadrature mixing is widely used in wireless communication receivers since it provides a solution for image signal problem with low-cost implementations. Image signal is caused by phase and amplitude mismatches between in-phase (I) and quadrature (Q) paths of the receiver. This problem is known as I/Q imbalance and degrades the communication performance if not compensated. In this study, the impact of I/Q imbalance compensation on wireless communication performance is evaluated through experiments and simulations. Simulation results demonstrate that significant communication performance improvement can be achieved in terms of bit error rate (BER) and symbol error rate (SER) by compensating the I/Q imbalance properly. In the experiments, compensation is applied to the signals captured using a software defined radio with zero-IF architecture. Experimental results demonstrate that wireless transmission success rate for the zero-IF receiver is increased by compensating I/Q imbalance.

1. INTRODUCTION

Developments in communication and network technologies, especially with the studies carried out within the framework of 5G and the internet of things (IoT), have increased the widespread use of wireless networks. The growing use of wireless systems increases the demand for low-cost communication receivers. With this demand, architectures compatible with integrated circuits such as zero-IF (zero intermediate frequency) and low-IF (low intermediate frequency) receivers gain importance. These architectures have been developed to provide low-cost solutions for image signal problem which reduces communication performance in receivers.

Keywords. Zero-IF receiver, image signal problem, I/Q imbalance compensation.
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The main principle of rejecting the image signals in these receivers is to use quadrature mixing, also known as complex mixing [1]. For an ideal quadrature mixer, the image rejection ratio is infinite. However, this ratio is limited in practical systems due to imperfections in the mixers, which causes phase and amplitude imbalances between I and Q paths in the quadrature receiver. This problem leads to interference in both zero-IF and low-IF receivers, therefore increases the bit error rate. Without increasing the cost and complexity of the receiver, digital signal processing algorithms are employed to mitigate the effects of I/Q imbalance. Several techniques have been developed for this purpose. For example, I/Q imbalance compensation was performed digitally for low-IF [2] and zero-IF [3] receivers in order to simplify the analog front-end of the receiver.

Compensation methods for I/Q imbalance can be classified as blind and data-aided. In data-aided methods, compensation is carried out by using prior information of the transmission signals such as training symbols, whereas prior information is not required in blind methods. In most of the wireless communication protocols, training signals are used for synchronization and channel estimation tasks. These known signals have been employed to compensate the mismatches between I and Q channels in data-aided methods [4]. For example, a low complex compensation method was proposed for OFDM based wireless local area network (WLAN) signals in [5]. In this method, legacy long training field (L-LTF) of the WLAN preamble is used for compensation. Performance of the method has been evaluated for different modulation schemes used in IEEE 802.11a/g under AWGN and fading channel conditions. Data-aided methods can have high performance for I/Q imbalance compensation, however these methods require decoding of the transmitted signals. When I/Q imbalance level is high and detection performance is low accordingly, the success of these methods may be limited.

The blind methods are independent of the communication protocol since prior knowledge is not required. This allows these methods to be used in a heterogeneous network including different communication protocols. However, the converge of blind techniques may take a long time in some applications [6]. A blind approach is based on removing the correlation between I and Q signals. Correlation originated from I/Q imbalance makes the complex signals non-proper [7], even if the received communication signal has the properness condition which is a statistical property of quadrature signals. In this approach, the main principle is to make the observed signal proper again by using adaptive filtering, which mitigates the distortion effect of the I/Q imbalance [8]. Another blind technique using adaptive filtering is called interference cancellation. In this technique the image signal is modeled as an interference and estimated using an adaptive filter [8, 9]. In order to obtain an estimation for the desired signal, the estimated interference signal is subtracted from the imbalanced received signal. For the filter adaptation, least mean square (LMS) or recursive least squares (RLS) approaches can be employed [10]. In [8], this adaptive filtering approach has been performed for the case in which complex conjugate form of the observed signal is taken as reference signal for the filter.

In [11], along with the properness condition for communication signals, a second statistical property called equi-absolute variance condition is used for blind I/Q compensation. The authors have proposed two adaptive compensation methods based on RLS and LMS algorithms. It has been shown by simulations that the proposed method converges to the ideal solution. In [12], statistical characteristics resulted from the modulation and orthogonality of imbalanced quadrature signals for an OFDM system are used for I/Q imbalance compensation.

In this work, the impact of I/Q imbalance and its compensation on wireless communication performance in zero-IF receivers is investigated through simulations and experiments. In the simulations, performance of the method has been evaluated in terms of BER and SER curves. Experimental results have been obtained using a software defined radio. Both simulation and experimental results demonstrate that wireless transmission performance can be enhanced by compensating I/Q imbalance in zero-IF receivers.

2. I/Q Imbalance In Zero-If Receivers

In quadrature downconversion based receivers, gain values in I and Q channels are not equal due to imperfections of the components in analog front-end [7]. This phenomenon is called gain imbalance. Moreover, local oscillator signals generated for I and Q branches do not have ideal phase difference of 90°, which results in phase imbalance. I/Q imbalance is introduced to represent the overall of these distorting effects, which causes image signal problem in the downconversion process. The image signal distorts the desired signal and deteriorates the performance both in transmitter and receiver sides [7, 10].

In zero-IF receiver architecture, the local oscillator signal is generated such that its frequency is equal to the center of the desired RF spectrum in order to downconvert the desired RF signal to the baseband. In this case, negative frequency components of the desired signal occur as the image signal, which is called self-image.

Figure 1 visualizes the downconversion process with a quadrature mixer in the amplitude spectrum. When I/Q imbalance is not present (Fig. 1 left), which is called ideal case, the desired signal is mixed with an exponential at $-f_c$ whose spectrum is represented by blue impulse. In this case, the image problem does not occur since only the desired spectrum is downconverted to the baseband. When I/Q imbalance is present (Fig. 1 right), an unwanted complex exponential occurs at f_c whose spectrum is represented by red impulse. This exponential also downconverts the self-image signal depicted at $-f_c$. Self-image signal downconverted to the baseband is indicated by dashed red lines. Note that the resulting baseband spectrum is corrupted by the self-image signal and the amount of distortion depends on I/Q imbalance level. As the I/Q imbalance level increases, amplitude of the complex exponential at f_c also increases, which makes the image signal stronger.

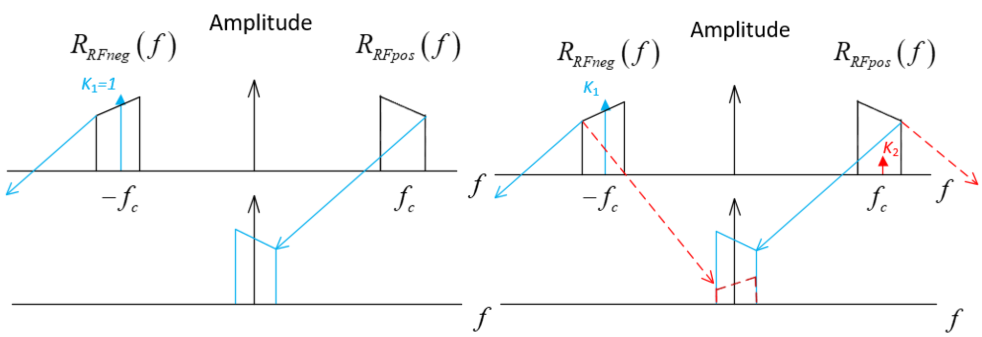

FIGURE 1. Downconversion in zero-IF receivers using quadrature mixer in the ideal case (left) and in the case of presence of I/Q imbalance (right).

Image rejection ratio is theoretically infinite, however due to imperfections of the analog components in the receivers, this ratio is 20-40 dB in practical implementations [9]. High image attenuation level is required especially for high order modulation schemes. Therefore, the distortions caused by image problem should be removed in order to obtain high communication performance in zero-IF receivers, especially for high data rate communication applications.

2.1. **Signal Model.** In zero-IF receiver architecture, quadrature mixing is used to directly downconvert the RF signal to the baseband as shown in Fig. 2. The baseband signal is then low pass filtered and digitized in I and Q branches.

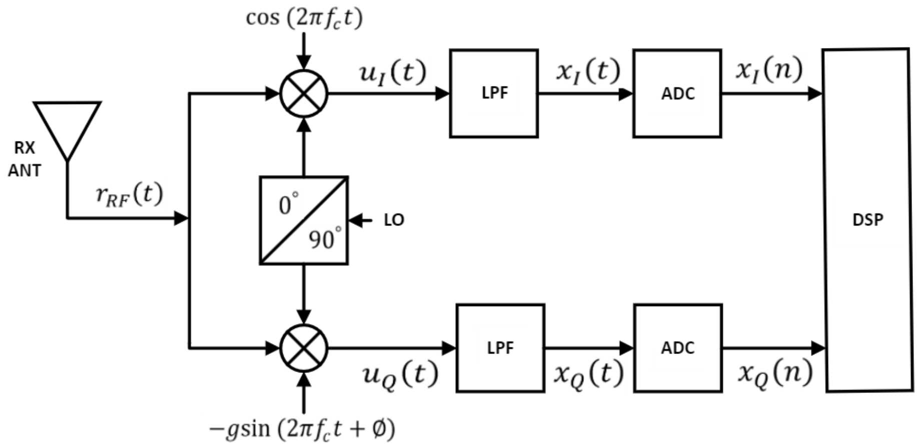

FIGURE 2. Quadrature mixing for zero-IF receivers with I/Q imbalance.

When I/Q imbalance is occurred, the local oscillator (LO) signal which is set to carrier frequency f_c can be modeled as [9]

$$a(t) = \cos(2\pi f_c t) - jg \sin(2\pi f_c t + \emptyset) \tag{1}$$

where $\emptyset$ is phase imbalance and g is gain imbalance (Fig. 2). LO signal can be rewritten by using Euler's equations as

$$a(t) = K_1 e^{-j\omega_c t} + K_2 e^{j\omega_c t} \tag{2}$$

where $K_1 = \frac{1+ge^{-j\emptyset}}{2}, K_2 = \frac{1-ge^{j\emptyset}}{2}$. The degree of I/Q imbalance can be quantified by defining the image rejection ratio (IRR) as follows [11]

$$IRR = 10log_{10} \frac{|K_1|^2}{|K_2|^2} \tag{3}$$

In the ideal case $g = 1$ and $\emptyset = 0$, and therefore $K_1 = 1$ and $K_2 = 0$, which results in infinite IRR.

The received RF signal can be represented as

$$r_{RF}(t) = r_{RFpos}(t) + r_{RFneg}(t) \tag{4}$$

where $r_{RFpos}(t)$ and $r_{RFneg}(t)$ represent time domain signals corresponding to the positive and negative frequency components, namely $R_{RFpos}(f)$ and $R_{RFneg}(f)$, of RF signal shown in Fig. 1. By multiplying LO signal in (2) with RF signal in (4), the signal at the mixer's output is obtained as follows

$$u(t) = K_1 e^{-j\omega_c t} r_{RFpos}(t) + K_2 e^{j\omega_c t} r_{RFneg}(t) + \underbrace{K_2 e^{j\omega_c t} r_{RFpos}(t) + K_1 e^{-j\omega_c t} r_{RFneg}(t)}_{high\ \ frequency\ terms} \quad (5)$$

After filtering high frequency terms in (5) using a low pass filter, the baseband I/Q imbalanced analog signal model is given as [13]

$$x(t) = K_1 e^{-j\omega_c t} r_{RFpos}(t) + K_2 e^{j\omega_c t} r_{RFneg}(t) \quad (6)$$

$x(t)$ can also be expressed as

$$x(t) = K_1 r(t) + K_2 r^*(t) \quad (7)$$

where $r(t)$ and $r^*(t)$ denote the ideal analog baseband signals when there is no I/Q imbalance and are defined as

$$r(t) = e^{-j\omega_c t} r_{RFpos}(t) \quad (8)$$

$$r^*(t) = e^{j\omega_c t} r_{RFneg}(t) \quad (9)$$

Note that these ideal baseband signals can only be obtained in the case that I/Q imbalance is not present, in which case $x(t) = r(t)$ since $K_1 = 1$ and $K_2 = 0$.

The digitized version of the imbalanced received baseband signal in (7) is defined as

$$x(n) = K_1 r(n) + K_2 r^*(n) \quad (10)$$

where n denotes the discrete time index.

3. I/Q Imbalance Compensation

Distortions due to I/Q imbalance increases as the level of receiver hardware imperfections increases. This may degrade the communication performance significantly. The effect of interference caused by the image signal in zero-IF receivers can be mitigated by compensating the I/Q imbalance. Statistical features of the signals or known characteristics of the transmitted signals can be employed for this purpose. Blind and data-aided approaches used in this paper are presented in the following subsections.

3.1. **Adaptive Filtering Based Blind I/Q Imbalance Compensation.** I/Q imbalance compensation can be performed by subtracting estimated interference signal from the observed imbalanced signal $x(n)$. This approach is known as interference cancellation. Interference signal can be estimated by using an adaptive filter [9], [10] as shown in Figure 3. In this approach the main issue is defining a reference signal $v(n)$ applied to adaptive filter. Adaptive filter coefficients $w(n)$ can be calculated by using LMS or RLS algorithms [10].

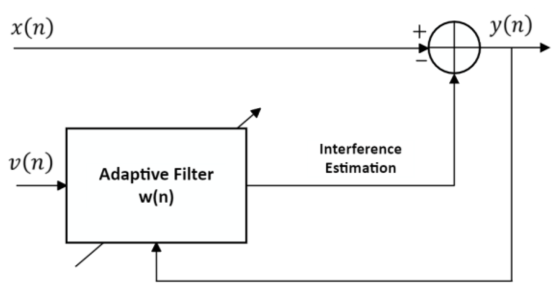

FIGURE 3. Interference cancellation approach using adaptive filtering [9].

In blind I/Q imbalance compensation methods, statistical properties of the signal can be employed. One of these statistical properties is the properness which is satisfied for many communications signals [14]. The distortions caused by wireless channels do not affect the properness condition for communications signals [15]. On the other hand, I/Q imbalance leads to improper signals at the receiver even if the transmitted signal is proper [14]. Considering these facts, compensation techniques based on ensuring that the received signal has the properness condition again have been proposed [8, 11]. For this purpose, adaptive filtering is employed in [8]. In this method, the reference signal for adaptive filter is taken as the complex conjugate of the I/Q imbalanced signal such that $v(n) = x^*(n)$. By using LMS algorithm filter adaptation is carrier out as follows [8]

$$y(n) = x(n) + w^T(n)x^*(n) \tag{11}$$
$$w(n+1) = w(n) - \mu y(n)y(n) \tag{12}$$

where $x(n)$ is I/Q imbalanced signal and $y(n)$ is compensated signal. The filter coefficients are represented by $w(n)$ and μ denotes step size. The step size should be determined by considering the characteristics of the application. An optimization approach for determining the step size for this method is proposed in [16].

In [11], a second statistical property called equi-absolute variance condition in addition to properness condition for communication signals is employed to compensate the I/Q imbalance. The compensated baseband signal $y(n) = y_I(n) + jy_Q(n)$ is obtained as follows [11]

$$y_I(n) = x_I(n) \tag{13}$$

$$y_Q(n) = \hat{\beta}\left(\hat{\alpha}x_I(n) + x_Q(n)\right) \tag{14}$$

where $x_I(n)$ and $x_Q(n)$ are defined as the I and Q components of the received imbalanced baseband signal which is given in the form of $x(n) = x_I(n) + jx_Q(n)$. $\hat{\alpha}$ and $\hat{\beta}$ denote the estimated compensation parameters which include gain and phase imbalances. In order to estimate these parameters, two different adaptive filtering approaches based on RLS and LMS algorithms were proposed in [11].

3.2. **Data-Aided Compensation Method for OFDM based WLAN.** WLAN signals contain known training signals and pilots for synchronization and channel estimation tasks. This prior information about the transmitted signals can be employed to compensate the I/Q imbalance. In [5], a low complex I/Q imbalance compensation method using legacy long training field (L-LTF) of the WLAN preamble was proposed for OFDM based WLAN systems. In this method, for a complex valued I/Q imbalanced L-LTF signal $z(n) = z_I(n) + jz_Q(n)$, I/Q imbalance correction factors are calculated as

$$\rho = \sqrt{\frac{\sum_n^L z_Q^2(n)}{\sum_n^L z_I^2(n)}} \tag{15}$$

$$\zeta = \frac{\sum_n^L (z_I(n) z_Q(n))}{\sum_n^L z_I^2(n)} \tag{16}$$

where L is the length of one OFDM symbol without cyclic prefix in L-LTF signal. I and Q components of the compensated signal is obtained as follows

$$y_I(n) = \frac{x_I(n)}{\rho} \tag{17}$$

$$y_Q(n) = \frac{1}{\sqrt{1-\zeta^2}}\left[x_Q(n) - \zeta x_I(n)\right] \tag{18}$$

4. Results

4.1. **Simulation Results.** The impact of I/Q imbalance and its compensation on the constellation diagram is visualized for 16 QAM symbols in Fig. 4. Blue circles indicate the symbols corrupted by additive white Gaussian noise such that SNR is 25 dB for the case that there is no I/Q imbalance. Red circles show the symbols observed when there is I/Q imbalance with $g = 1.2$ and $\emptyset = 10°$. When the I/Q imbalance is compensated, improved constellation diagram is represented with yellow circles. Note that the compensation mitigates the distortions due to I/Q imbalance and makes the symbols close to the reference ideal symbols observed in the absence of I/Q imbalance.

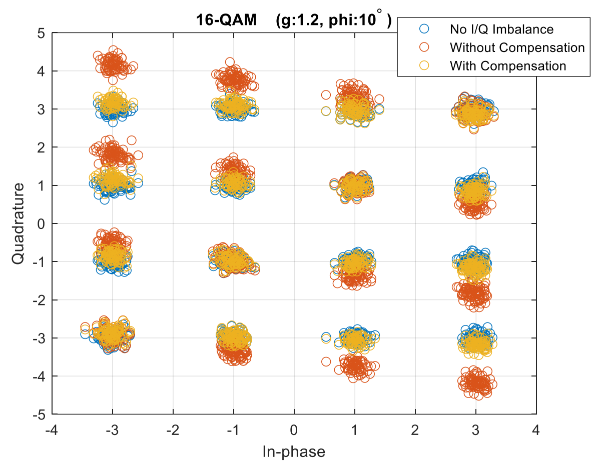

FIGURE 4. Constellation diagram for 16 QAM: No I/Q imbalance (blue), with I/Q imbalance (red), compensated (yellow).

Monte Carlo simulations were performed to evaluate the impact of I/Q imbalance compensation on wireless communication performance in terms of SER and BER curves. Three blind and a data-aided compensation methods were applied to the distorted signals with the same amplitude and phase imbalance values for a fair comparison. BER and SER performance for I/Q imbalanced and compensated cases by using different methods were evaluated for different SNR levels. In each SNR level, BER and SER values are calculated from the randomly generated data consisting of 100.000 bits. Average error rates are calculated over 100 Monte Carlo simulations with different realizations of additive white Gaussian noise.

In order to determine the imbalance values, four different cases in which gain and phase imbalances take different values were considered. Performance degradation for different imbalance values is given in terms of BER versus SNR in Fig. 5. This figure shows that BER performance degrades as the phase and gain imbalance values increase. For the simulations performed to observe the compensation effect, phase imbalance is set to 10° and gain imbalance is set to 1.2. For these imbalance values, image rejection ratio is found to be approximately 18 dB by using (3). This is close to the image rejection ratio encountered in practical implementations [9].

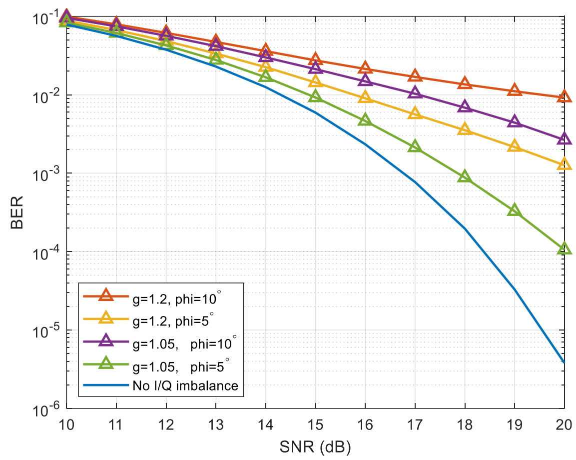

FIGURE 5. BER versus SNR curves for 16 QAM in the ideal case (no IQ imbalance) and in the cases where signals are distorted with different I/Q imbalance values.

The impact of I/Q imbalance compensation for two different modulation level of 16 and 64 QAM was evaluated. BER and SER curves are given in Fig. 6 for four different compensation methods. Note that BER and SER performances are lower for 64 QAM compared to those obtained for 16 QAM. The underlying reason is that as the QAM level increases, the distances between symbols get smaller, resulting in higher error rates. Therefore, I/Q imbalance compensation becomes more crucial when the level of QAM is high. These figures show that BER and SER performances significantly increase with I/Q imbalance compensation for both QAM levels. The performances of the data-aided [5] and RLS based blind adaptive [11] compensation methods are very close to the ideal performance that is obtained when there is no I/Q imbalance. Note that RLS based blind adaptive [11] compensation method achieves this performance without any prior information. Similar performances were obtained with complex conjugate [8] and LMS based [11] blind adaptive compensation methods. Performances of these methods are slightly lower than that of the ideal case as the SNR level increases.

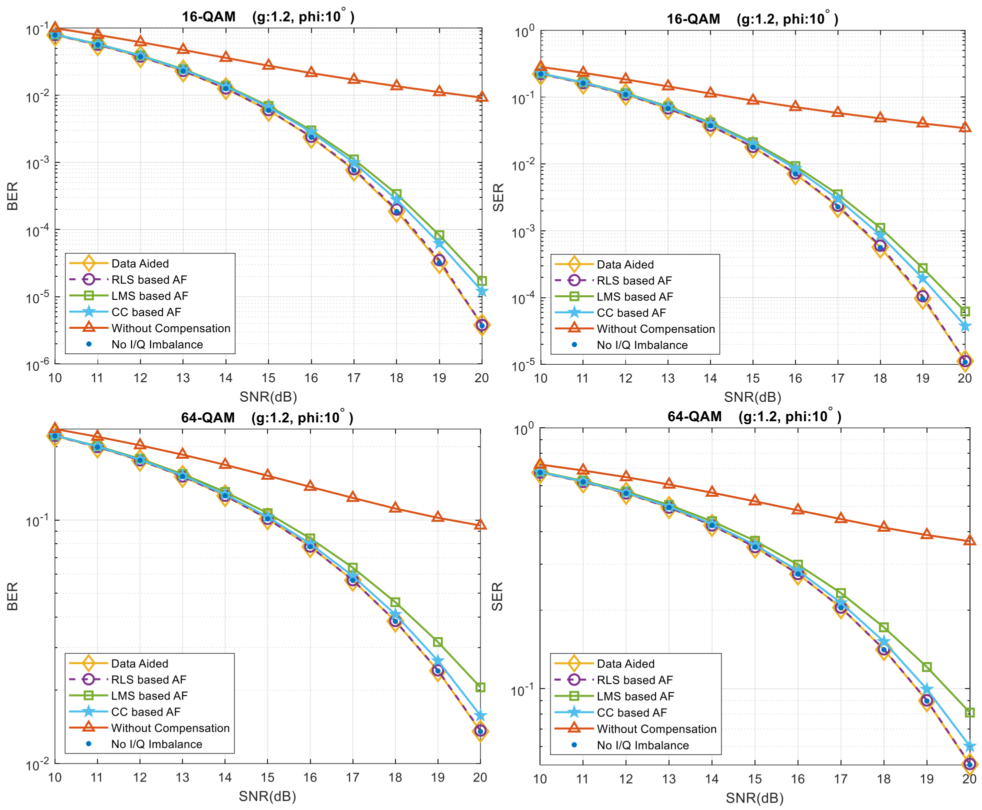

FIGURE 6. BER and SER performance improvement with I/Q imbalance compensation by using data-aided and adaptive filtering (AF) based methods for different SNR values.

4.2. **Experimental Results.** The performance improvement through I/Q imbalance compensation for a wireless communication system using software defined radio (SDR) was evaluated by experiments. The experimental setup consisting of a computer with MATLAB software and a SDR with zero-IF architecture is given in Fig. 7. The computer and SDR are connected with a USB cable. In the experiments, an image is transmitted through a wireless channel by using SDR. OFDM based data packets consisting of 64 QAM symbols are generated based on IEEE 802.11g protocol by using WLAN toolbox in MATLAB and transmitted over a wireless network [17]. The center frequencies of the transmitter and receiver were set to 2.427 GHz. At the receiver side of SDR, signals were downconverted to the baseband located at [-10, 10] MHz and digitized at a sampling rate of 30 MSamples/s. Data packets were decoded using WLAN toolbox after compensating I/Q imbalance with different methods.

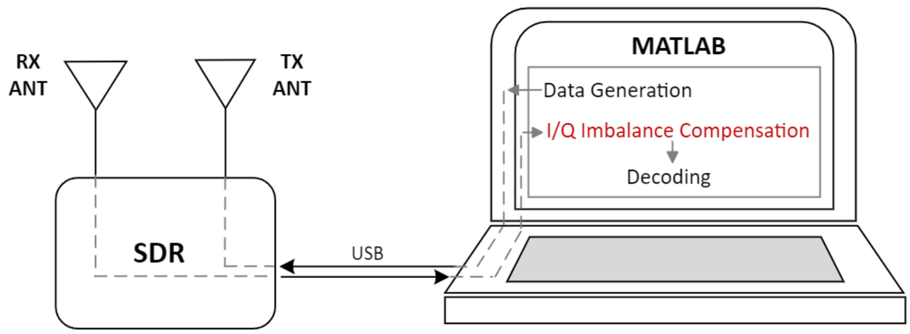

FIGURE 7. Experimental setup.

In the experiments, transmission success ratios were calculated over a hundred tests for the cases in which I/Q imbalance is not compensated and compensated with adaptive filtering (AF) based blind methods. The average results are given in Table 1. The data-aided method implemented in Section 4.1 cannot be used for the experiments since this method requires the preamble part of the WLAN signals, which is inaccessible in this experimental setup. Transmission success ratio was calculated as 55% when I/Q imbalance was not compensated. This ratio was improved about 20-30% via I/Q imbalance compensation using different blind adaptive filtering based methods. It should be noted that the experiments were not performed under ideal conditions. Therefore, the performance results of the methods may change for different experiments due to random nature of wireless channels, e.g. interference and multipath channel distortions. The main result of Table 1 is that all the adaptive filtering (AF) based methods implemented for I/Q imbalance compensation provide a considerable performance improvement in terms of transmission success ratio for the cases in which I/Q imbalance is not compensated and compensated.

TABLE 1. Transmission success ratio calculated over a hundred tests

Methods	**Success Ratio (%)**
Not compensated	55
RLS based AF	75
LMS based AF	78
Complex Conjugate AF	85

5. Conclusions

I/Q imbalance problem in zero-IF receivers and compensation approaches for this problem are examined. Performance improvement of different compensation techniques have been evaluated by using experimental and simulation data. It has been demonstrated by simulations that the distorting effect due to I/Q imbalance increases as the imbalance values increases. Simulation results also illustrate that SER and BER performances can be improved significantly by compensating the I/Q imbalance. In simulations, the performance of the RLS based adaptive filtering method is very close to that of the data-aided method. This is an important result showing that a performance improvement can be achieved using a blind method as high as obtained with a data-aided method.

Experimental results obtained from an OFDM based WLAN system by using a software defined radio illustrate that a considerable performance improvement via blind I/Q imbalance compensation in terms of transmission success ratio can be achieved for zero-IF architecture. Regarding the fact that protocol independent approaches gain importance for the heterogeneous networks including devices using different protocols, the experimental results showing that blind methods can be employed in these networks with a sufficient performance are considered to be important.

Author Contribution Statements The authors contributed equally to this work.

Declaration of Competing Interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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