A Comparative Study of In-phase and Quadrature (IQ) Imbalance Estimation and Compensation Algorithms for OFDM Receivers

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***Abstract*— Systems based on orthogonal frequency division multiplexing (OFDM) are subject to limitations caused by the radio front end. These deficiencies are the result of imbalances between the In-phase (I) and Quadrature phase (Q) branches. For zero-IF receiver design which is commonly used in practice, IQ imbalance has been identified as one of the most critical issues. The signal to noise ratio (SNR) at the receiver, data rates and the supported constellation are some key metrices severely impacted by this imbalance. In this paper, the impact of IQ imbalance on OFDM receivers and digital techniques for mitigating the effect of IQ imbalance are explored and studied. We analyse IQ imbalance models and estimation techniques based on a low-complexity feed-forward and a standard-independent IQ imbalance compensation algorithms. The outcome of the constellation method may suggest that the proposed techniques increase performance appropriately.**

Keywords—OFDM receiver; IQ imbalance; IQ estimation; training samples

I. INTRODUCTION

Orthogonal frequency division multiplex (OFDM) based systems are subject to limitations caused by the radio front end. These deficiencies are the imbalances result of the In-phase (I) and Quadrature-phase (Q) branches. IQ imbalances are a concern for the Superheterodyne and zero-IF systems in the analogue realm. Due to the analogue circuit's sensitivity to component change, inevitable mistakes in IQ branches occurred because of temperature variations and process incompatibilities. As a result, achieving orthogonal sinusoidal waveforms as high as 5.2GHz at radio frequencies is a difficult task for silicon implementations (IEEE 802.11a). To mitigate these incompatibilities, certain approaches in the analogue domain have been devised. Voltage controlled oscillator (VCO) and tunable Polyphase are employed in analogue circuits because they are regarded the least prone to component mismatches [1]. However, these approaches suffer from measurement inaccuracies, variable offsets, and a lengthy calibration procedure [1].

Without digital correction, analogue domain approaches cannot match the criteria necessary for systems like as IEEE 802.11a [2]. The analogue domain's trade- offs, such as area for accuracy, power, and speed, do not exist with the same vigor in the digital domain. These trade-offs make it challenging to develop analogue circuits that are both power and area efficient. Consequently, digital processing power enables the analogue domain's imperfections to be improved. To maintain orthogonality between subcarriers, ideal conditions must be met. As an example, the channel must be time-invariant during the OFDM block period, without IQ imbalance or carrier frequency offset.

For a direct conversion or zero intermediate frequency (Zero-IF) reception, IQ imbalance leads to a distortion of the IQ signals themselves within the respective wanted channel. For both frequency down conversion concepts, the IQ imbalance is a serious issue degrading the reception performance. This spurious effect occurs mainly due to amplitude- and phase-impairments between the local oscillator paths as well as due to mismatches between the respective IQ branches after the analog down conversion. Unfortunately, for OFDM schemes, using higher order modulation is very sensitive to the nonidealities at the receiver front-end. Thus, employing a very low complexity scheme is desirable to estimate and correct IQ imbalance [3,4]. Meantime, for non-orthogonal multiple access (NOMA) systems which has also attracted much attention from researchers, IQ imbalance can also seriously affect the communication link's performance [5, 6].

Unlike previous papers, our work gives a comparative study and analysis of the IQ imbalance models, and some IQ estimation and compensation algorithms which is imperative in simulation work and design. Our simulation work also proves that with higher modulated signals like 64-QAM the selected method works well and can compensate the corrupted signals. This work can also easily extended to other types of communication networks like NOMA.

In Section II, IQ imbalance models are presented. Methods to estimate and compensate IQ imbalances are explained in Section III followed by the MATLAB simulation results in Section IV. Finally, Section V concludes this manuscript.

II. IQ ESTIMATION AND COMPENSATION

The negative impact of IQ imbalance on demodulation performance is a traditional problem. IQ imbalance results from a nonideal front-end component due to the power imbalance or the non-orthogonality between in-phase (I) and quadrature (Q) branches. Particularly for increasingly popular zero-IF or direct conversion receiver architectures, analog IQ separation is performed, and IQ imbalance is almost unavoidable. Due to higher-order modulation in the OFDM wireless local area network (WLAN) receiver, even manufacturing inaccuracies of analog front-end components will cause severe degradation of demodulation accuracy. Therefore, to avoid expensive devices for front-end requirements, digital algorithms and implementations must be introduced to compensate IQ imbalance and to improve demodulation accuracy.

For modulation type, 64-QAM modulation is used to compare the result. 64- QAM is a digital modulation technology that serves as the fundamental building element of OFDM The OFDM waveform is utilized in Long Term Evolution (LTE) and 5G cellular telephony networks. 64-QAM is a higher order modulation method that enables a single radio wave to represent six bits of data by modulating the radio wave's amplitude and phase to one of 64 discrete and measurable states. Each symbol is represented by six bits in 64-QAM. While the QAM approach gets more bandwidth efficient as the level rises, it needs very strong algorithms to decode complicated symbols to bits at the receiver.

Figure 4.1 above illustrated how the constellation of transmitted signal for 64- QAM modulation. The transmitted signal is consisted of the baseband and RF signal. This constellation represents for all transmitted signal from Radio 1 to Radio 4 and can be called as ideal and perfect. All of the points in the constellation are organized in a square grid with equal vertical and horizontal spacing.

Figure 4.2 below depicts the impacts of generic gain, phase, and phase-gain imbalances on signal constellations in the case under examination before going into detail about the influence of IQ imbalance on signal constellations [7]. As you can see in Figure 4.2, the image signal created during IQ imbalance distorts the signal constellation by spinning due to phase imbalance and shifting due to gain imbalance, resulting in the displacing constellations away from their optimal places.

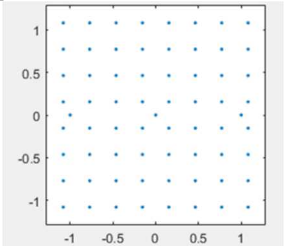


Figure 0.1: Perfect constellation of transmitted signal for 64-QAM modulation

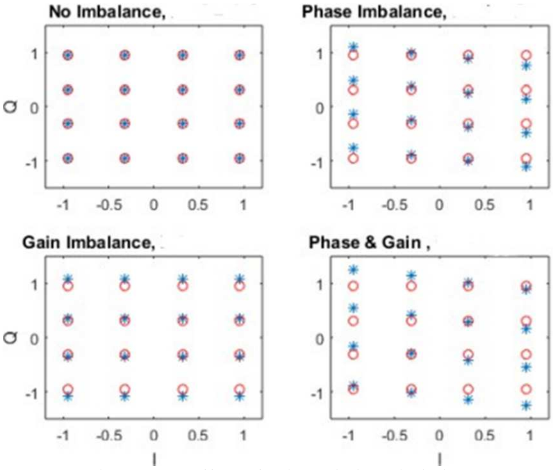


Figure 0.2: Effect of gain and phase imbalances

A. IQ Imbalance Model

IQ imbalance problem arises when there are mismatches in analog components thus resulting in imbalance in the gain and phase responses of the branches. There are 2 primary models which can be used to emulate the IQ imbalance in wireless communication networks. Both assume the IQ imbalance as frequency independent.

1) IQ Model (1)

In the first model [8], the parameter g corresponds to the gain mismatches between the branches of the receiver and φ describes the phase mismatches of the local oscillator (LO). There are 2 types of baseband signals in a scheme with an IQ imbalance. The perfectly balance complex baseband signal $z(k) = z_I(k) + jz_Q(k)$ and the complex baseband signal with an IQ imbalance $s(k) = s_I(k) + js_Q(k)$ where small k is the time index. The latter is the baseband seen by the digital baseband processor and the former is the baseband-equivalent seen at the antenna. Nonetheless, both equations are related through the g and φ model parameters as shown below:

$s(k) = K_1 z(k) + K_2 z^*(k)$ where * denotes complex conjugation. We also define

$$K_1 = \frac{1+ge^{-j\varphi}}{2}, \; K_2 = \frac{1-ge^{j\varphi}}{2} \quad (1)$$

As the complex baseband coefficients. A perfectly balanced baseband receiver $g = 1$ and $\varphi = 0^\circ$ resulting in $K_1 = 1$ and $K_2 = 0$. From above, $s(k) = z(k)$ which means that the baseband-equivalent signal at the antenna equals the received baseband signal in the digital baseband processor.

2) IQ Model (2)

In [9], IQ imbalance can be represented by 2 parameters: K as the amplitude imbalance which shows a power mismatch between I and Q branches, and φ the phase imbalance which gives an orthogonality mismatch between I and Q branches. For an impaired complex signal $s = s_I + js_Q$, it can be shown by the following relation that

$$\begin{bmatrix} s_I(k) \\ s_Q(k) \end{bmatrix} = \begin{bmatrix} K_I & 0 \\ -K_Q\sin(\varphi) & K_Q\cos(\varphi) \end{bmatrix} \begin{bmatrix} s_I'(k) \\ s_Q'(k) \end{bmatrix} \quad (2)$$

where s_I' and s_Q' denote the component of the unimpaired signal. The amplitude K is represented by 2 symmetrical factors K_I and K_Q while the phase imbalance is shown as φ which is the mismatch between I and Q branches.

B. Methods for Imbalance Estimation and Compensation

Estimation and compensation of unwanted imbalances have been presented in many articles in the literature. Four methods have been investigated and simulated in MATLAB. Here, the methods are introduced briefly and for interested readers, you may find derivations and further details in the references as stated in the end of this manuscript.

1) Method (1)

This method is presented by Held et al. [9]. The authors use the IQ imbalance model (2). Estimate of the amplitude imbalance is proposed as follows:

$$K_{est} = \sqrt{\frac{\sum_{l=1}^{L}\left|s_Q^2(k)\right|}{\sum_{l=1}^{L}\left|s_I^2(k)\right|}} \quad (3)$$

L denotes the size of the training samples e.g. preambles to compute the estimation. The estimation of phase imbalance coefficient is shown as follows

$$P_{est} = \frac{\sum_{l=1}^{L} s_I(k)s_Q(k)}{\sum_{l=1}^{L} s_I^2(k)} \quad (4)$$

Once these 2 coefficients are computed, correction of imbalances can be done. Thus, the corrected signal is shown as

$$\begin{aligned} \hat{s}_I(k) &= \frac{1}{K_{est}} s_I(k) \\ \hat{s}_Q(k) &= \frac{1}{\sqrt{1-P_{est}^2}}\left[s_Q(k) - P_{est}s_I(k)\right] \end{aligned} \quad (5)$$

2) Method (2)

This method in [10] uses IQ imbalance model 1. In this method, the receiver is assumed to have a set of corrupted symbols $z_m(k),\ z_{-m}(k)$ originating from one or multiple pairs of symmetric subcarriers m and $-m$. Based on this collected data, 2-step estimation is implemented. 1-step is shown as

$$\hat{K}_1\hat{K}_2 = \frac{\sum_{m\in\mathrm{M}}\sum_{k\in\kappa} z_m(k),\ z_{-m}(k)}{\sum_{m\in\mathrm{M}}\sum_{k\in\kappa}\left|z_m(k) + z_{-m}^*(k)\right|^2} \quad (6)$$

where m and k as the subcarrier and time index respectively.
In the 2-step, the estimation is split into the following parameters

$$\begin{aligned} \hat{K}_1 &= \frac{1+\hat{\alpha}-j\hat{\beta}}{2} \\ \hat{K}_2 &= \frac{1-\hat{\alpha}-j\hat{\beta}}{2} \end{aligned} \quad (7)$$

where

$$\begin{aligned} \hat{\beta} &= -2\Im m\left\{\hat{K}_1\hat{K}_2\right\}, \\ \hat{\alpha} &= \sqrt{1-\hat{\beta}^2 - 4\Re e\left\{\hat{K}_1\hat{K}_2\right\}} \end{aligned} \quad (8)$$

Where $\Im m\{\cdot\}$ and $\Re e\{\cdot\}$ denote the real and the imaginary part respectively.

3) Method (3)

The authors in [11] consider a multiplicative mixing method, the relationship between $s_I(k), s_Q(k)$ and $s_I'(k), s_Q'(k)$ are shown as follows which is slightly in different form IQ imbalance Model (2) above

$$\begin{pmatrix} s_I(k) \\ s_Q(k) \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -g\sin(\varphi) & g\cos(\varphi) \end{pmatrix} \begin{pmatrix} s_I'(k) \\ s_Q'(k) \end{pmatrix} \quad (9)$$

where g and φ are the relative mismatch in gain and phase respectively. s_I and s_Q are the actual received samples and s_I' and s_Q' are the samples before IQ distortion.

Of course, ideally the gain is 1 and phase is equal to 0. But, it is not the case, and it is assumed that the values are different for each frequency. To compensate this mismatch, one has to apply the reverse matrix, such as the overall chain (distortion + compensation) is equal to the identity matrix. The reverse matrix is:

$$R = \frac{1}{\cos(\varphi)} \begin{pmatrix} \cos(\varphi) & 0 \\ \sin(\varphi) & 1/g \end{pmatrix} \quad (10)$$

On the reception side, the IQ imbalance occurs after analog RF and analog-digital converter (ADC).

The I output branch at the receiver is represented as $cos(w_c k)$ where w_c is the baseband frequency assuming that the noise is negligible. Moreover, the output signal in the Q branch is equal to $g\, sin(w_c k - \varphi)$.

The relative mismatch in gain is simply calculated with the amplitude of the 2 branches. The signal Q is then multiplied by ratio in the processing. Concerning the phase, we have the following equation:

$$I*Q = g/2 * (sin\,(2w_c\, k + \varphi) + sin\,(\varphi)) \qquad (11)$$

If we apply a low-pass filtering, we get the value of $\sin(\varphi)$ and then φ. At this point, we simply apply the reverse matrix with

$$\begin{pmatrix} \hat{s}_I(k) \\ \hat{s}_Q(k) \end{pmatrix} = \frac{1}{\cos(\varphi)} \begin{pmatrix} \cos(\varphi) & 0 \\ \sin(\varphi) & 1/g \end{pmatrix} \begin{pmatrix} s_I(k) \\ s_Q(k) \end{pmatrix} \qquad (12)$$

4) Method (4)

This model uses the IQ imbalance model (1) and is proposed by [11]. The compensation block diagram is shown in the following Fig. 1.

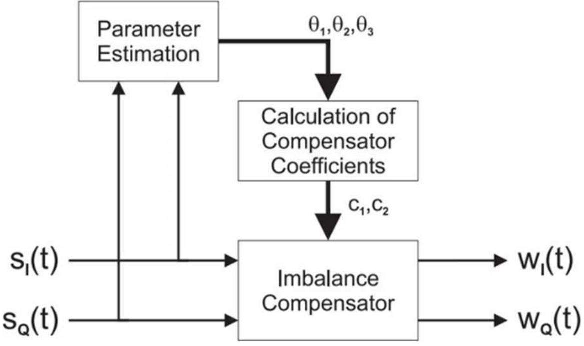


Fig. 1: The compensation block diagram.

From Fig.1, we have to compute the compensation coefficients/parameters c_1 and c_2 where they are defined as

$$c_1 = \frac{\theta_1}{\theta_2},\ c_2 = \sqrt{\frac{\theta_3^2 - \theta_1^2}{\theta_2^2}} \qquad (13)$$

Since we assume blind compensation scheme, all $\theta -$ parameters above are estimated from the samples of the signal.

$$\begin{aligned} \hat{\theta}_1 &= -\frac{1}{L}\sum_{l=1}^{L} sign(s_I(k))s_Q(k) \\ \hat{\theta}_2 &= -\frac{1}{L}\sum_{l=1}^{L} sign(s_I(k))s_I(k) \qquad (14) \\ \hat{\theta}_3 &= -\frac{1}{L}\sum_{l=1}^{L} sign(s_Q(k))s_Q(k) \end{aligned}$$

Table 1: Summary of the methods

Method	Strength	Weakness
1	It is simplest in computational complexity. It has been long used in IEEE 802.11a baseband receiver. It has been widely popular in many OFDM WLAN receivers.	It only works in error model (1) and time domain only (TD). It is suitable if we can only find exact contributor of impairments.
2	It works in frequency domain (FD). It works perfectly in OFDM schemes as initially proposed. It is also used in IEEE 802.11a WLAN standard.	The computational complexity is relatively high. To compute the compensation coefficients, one has to generate mirror subcarriers' values.
3	The computational complexity is fair. It is used in TD only.	It only works in error model (1) and time domain only (TD).
4	This method is the most robust. It can be used in TD or FD and suits in both error model (1) and (2). It requires only at least 20% symbols from the total symbols in a packet. It is a blind feed-forward compensator. The benefit of this algorithm is that it does not have the stability problems associated with feedback systems [13].	It needs smoothing filters (LPF) for faster convergence and better performance.

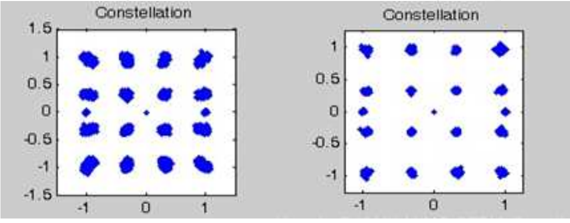
III. MATLAB SIMULATION

For this paper, 4x4 Multiple Input Multiple Output (MIMO) OFDM under multipath fading channel is used for the simulated scheme. To achieve both greater data rates and range performance, OFDM combined with MIMO is used, which is based on the IEEE 802.11n standard. This might be prevented if OFDM technology is used. Thus, MIMO in combination with OFDM is expected to play a prominent role in the upcoming networks. 4x4 MIMO, also known as 4T4R, utilizes four antennas to create up to four data streams with the receiving device. In comparison to conventional single-antenna (SISO) networks, 4x4 networks provide up to a 400% improvement in throughput. In contrast to 2x2 MIMO, when it was possible to employ just two polarizations, the usage of four distinct polarizations is uncommon. Nowadays, 4x4 MIMO equipment is readily accessible and compatible with the majority of smartphones and modems. Under strong signal circumstances, 4x4 outperforms 2x2 MIMO by around 90%, and outperforms 2x2 by up to 160 percent under poor signal conditions.

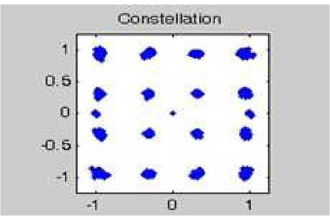
Table 2: Parameters used in the simulated scheme

Parameters	Value
Modulation Type	16-QAM/ 64-QAM
Number of bits per subcarrier	6
Number of OFDM data symbol	50
Number of OFDM subcarrier per symbol	52
Signal to Noise	25 dB
Over-sampling factor	1
Number of Samples	4240

Table 2 shows the simulation parameters used in this paper using MATLAB. Here, we use constellation diagrams for our performance comparison which provide a basic information about IQ imbalance in the system. First, we analyze the required training samples L required for the IQ estimation and compensation. We test a few values of training samples, L from the total transmitted packets using 16QAM. We test all methods using the IQ models with various combination to achieve the desired results. From the simulation results, we find only method (4) successfully estimating and compensating the corrupted signals. The result for method (4) is shown below in Figure 2 under different training samples.



$L = 500$ $L = 800$

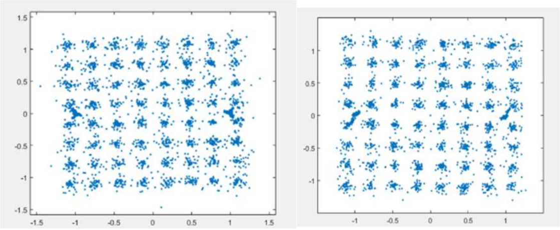


$L = 4240$

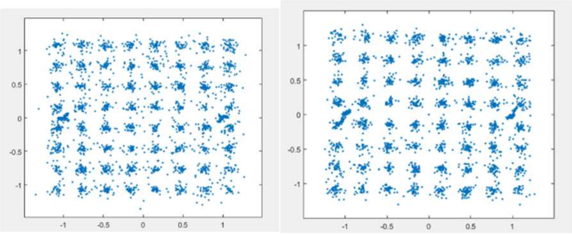
Fig. 2: IQ diagram under different training samples

Fig. 2 shows that inadequate samples do not effectively reduce the effect of the IQ imbalance at the receiver. User 1 is shown by the red arrow. It is clear that the scheme needs only around 20% training samples of the total packets to estimate the compensation coefficients and thus, quick convergence is achieved.

Next, we investigate the methods which can mitigate the IQ imbalance in our scheme. The results of transmitted signal for Radio 1, 2,3 and 4 will be achieved as shown in the Figure 3 below. Figure 3 shows the constellation method as the IQ imbalance is introduced in the simulated scheme. As we can observed, the constellation method is obviously different with the ideal constellation for 64-QAM modulation. The constellation method is distorted for Radio 1, Radio 2, Radio 3, and Radio 4 due to the presence of IQ imbalance in the simulated scheme.



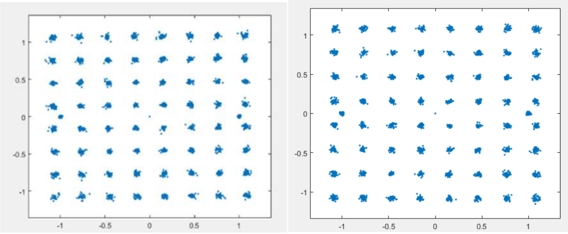
Radio 1 Radio 2



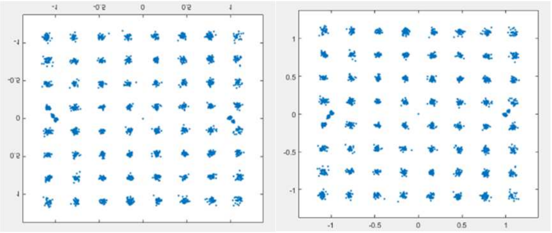
Radio 3 Radio 4

Figure 3: Constellation of transmitted signal with IQ imbalance

Figure 4 below shows the constellation of the transmitted signal after being compensated with method (4). From Radio 1 to Radio 4. As we can observe, the constellation method is almost identical to the ideal constellation for 64- QAM modulation. For comparison, Figure 5 shows the result for other methods which is noisy and much worse. In fact, from our observation, method (1)-(3) only work for IQ model (1) only and fail to perform in IQ model (2). Method (4) is not only robust but also flexible while maintaining good error rate performance in many channel setups. More importantly, method (4) works for both IQ imbalance models as explained in Sec. II.



Radio 1 Radio 2



Radio 3 Radio 4

Figure 4: Constellation of transmitted signal at Radio 4 after compensated with Method (4)

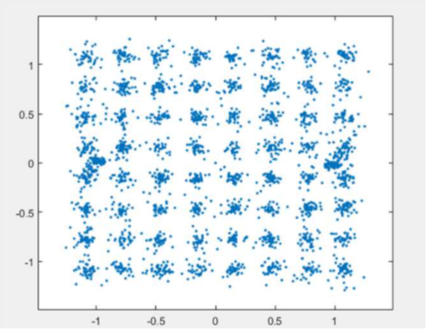


Figure 5: Constellation of transmitted signal at Radio 1 after compensated with Method (1),(2) and (3)

Next, we investigate the relation between the error rate performance against the number of required training samples used to compute the compensation coefficients. The minimum required samples to obtain error-less transmission performance in our scheme can be as low as 100 symbols (2% from total samples) only.

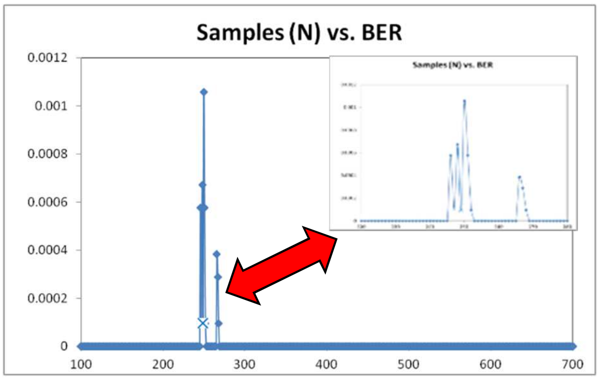


Figure 6: The relation between the error rate performance, BER against the number of samples of the compensation algorithm.

It is interesting to note that there is a transient around 200-300 samples. This phenomenon is due to the structure of the transmitted packet. In our scheme, we attach short training field (STF) and long training filed (LTF) sequences as the header. We insert '0' between the training sequences and the actual data to avoid ISI. Therefore, this transient is expected in the simulation above.

IV. CONCLUSION

We present a comparative study and analysis of the IQ imbalance models, and select an effective and efficient IQ estimation and compensation algorithm which is imperative in simulation work and design. Our simulation work also proves that with higher modulated signals like 64-QAM, the selected method works well and can compensate the corrupted signals. Four methods of IQ estimation and compensation algorithms and two IQ imbalance models have been studied. It is proven that method (4) not only works nicely theoretically but also simple in implementation. Currently, the method has been implemented into FPGA-based digital hardware platform and tested. Future works include finding the optimal number of training samples and the joint frequency offset and IQ imbalance methods under different networks like NOMA which are said to be more effective and efficient.

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