Adaptive Estimation/Compensation Scheme of IQ Imbalance with Frequency Offset in Communication Receivers

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Abstract: - IQ signal processing is widely utilized in today's communication system. However, it usually faces a common problem of front-end distortion such as IQ imbalance and frequency offset. Effective algorithms exist for estimating and compensating for IQ imbalance as well as frequency offset, when the two problems are treated separately. With both effects present, such algorithms do not lead to useful estimates of the related parameters. In this paper, we propose a robust technique to estimate and compensate for the IQ imbalance in the presence of carry frequency offset (CFO) by using a known preamble of repeated training sequence. In addition, to solve the problem of performance degradation when CFO is small we developed an adaptive scheme with small residual degradations. The performance of such a scheme has been validated by computer simulations on IEEE 802.11a signals. And it is shown that the proposed method is more robust and renders better performance than existing algorithm.

Key words: - IQ imbalance, carrier frequency offset (CFO), IEEE 802.11a

1 Introduction

The quadrature mixer is widely used in modern communication systems. The well-known direct-conversion architecture [1] as well as a more recent low intermediate-frequency (IF) architecture [2]-[3] both employ quadrature mixing, which in principle provides infinite image rejection ratio at the operating frequency band and eliminates the need for bulky analog image rejection filters. In practice, however, there is always some amplitude and/or phase mismatch in the analog front-end between in-phase (I) and quadrature (Q) branches, commonly known as IQ imbalance [4]. Amplitude mismatch between I and Q channels results from the non-uniformity of mixer, filters, or analog to digital converters (ADC) between the channels. Phase mismatch occurs when the phase difference between local oscillator signals for I and Q channels is not exactly 90 degrees. Such a mismatch will cause significant performance degradation to complex modulation techniques such as 64-QAM [5] and higher-order modulations typically used for high data rate transmission. To deal with this problem, a stringent front-end specification is often imposed and that usually calls for an expensive device. On the other hand, carrier frequency offsets (CFO), which occur quite often in practice because of the inaccuracy and instability of oscillators and moving terminals, can have additional adverse effect on system's performance, especially for Orthogonal Frequency Division Multiplexing (OFDM) signals that has been adopted by many broadband wireless standards due to its low hardware complexity, ease of implementation and higher spectral efficiency [6]-[7].

A good summary of the IQ imbalance problem for OFDM signals can be found in Buchholz's work [8] which proposed an AGC tuner to compensate IQ imbalance. Shafiee [9] discussed briefly the transmitter calibration and proposed an estimation technique for calculating the imbalance parameters. Schuchert [10] proposed a technique for OFDM DVB-T (Digital Video Broadcasting-Terrestrial) systems to cancel the image frequency interference at the receiver although the convergence can be slow. Most schemes compensate for the IQ imbalance without considering CFO [11]. However, the presence of CFO will certainly affect the accuracy of IQ imbalance compensation and the latter will affect the estimation of CFO. Two schemes which took into account the coupled effects of IQ imbalance and CFO were introduced in [12] and [13]. However, the method proposed in [12] requires extra FFT calculations and that in [13] needs to accurately estimate the frequency offset first by a Nonlinear Least Squares (NLS) frequency estimator. For the IEEE 802.11a OFDM standard, Tubbax [14] observed that channel estimation and correction could affect the IQ correction circuits and proposed a smoothing procedure to compensate for it. The authors of [15] proposed a scheme to jointly combat the IQ imbalance and phase noise at basedband, but the proposed procedure is not effective when the CFO is too small.

In this paper, we present a robust algorithm that uses a simple least-square (LS) algorithm to compensate for the IQ imbalance in the presence of CFO. First, it uses a known periodic training sequence to estimate the IQ imbalance parameters and then compensates accordingly the IQ imbalance. The CFO is estimated by examining the phases of the received time-domain samples in the successive training blocks [16]. We also propose an adaptive scheme to solve the problem of performance degradation when CFO is small. By system simulations on IEEE 802.11a signals, it is shown that the proposed algorithm is more robust and renders better performance than existing algorithms [12], and its implementation is computationally simple.

This paper is organized as follows. Section II presents the model employed to characterize IQ imbalance. In Section III, we propose a low-complexity estimation and compensation scheme for the IQ imbalance with coexisting CFO. Its performance is examined by simulations on the IEEE 802.11a signals. A modified scheme is presented in Section IV to solve the problem of performance degradation when CFO is small. Section V concludes this paper.

2 IQ Imbalance and CFO Model

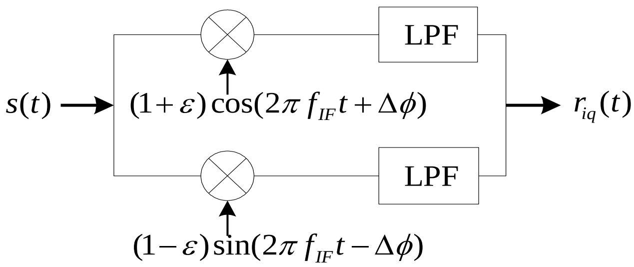

Fig. 1 IQ signal processing in the receiver.

IQ imbalance arises when a front-end component does not achieve power balance or orthogonality between *I* and *Q* signals. Fig.1 shows the architecture of in-phase (*I*) and quadrature-phase (*Q*) components in the receiver. IQ imbalance can be characterized by two elements: the amplitude imbalance ε between *I* and *Q* branches, and the phase orthogonality mismatch $\Delta\phi$. Ideally, with perfect matching, ε and $\Delta\phi$ are both zero. However, in a practical system, the RF implementation cannot achieve this ideal goal ($\varepsilon = 0,\ \Delta\phi = 0$).

The receiver signal $s(t)$, which suffers from a CFO, is represented as [17]

$$s(t) = 2\,\mathrm{Re}\left\{ r(t)e^{-j2\pi(f_{IF}+\Delta f)t} \right\} \tag{1}$$

where $\mathrm{Re}\{x\}$ refers to the real part of *x*, $r(t)$ is the equivalent baseband signal and Δf is the CFO. In (1), the scaling factor of 2 is introduced for analytical convenience. In the model depicted in Fig. 1, we multiply $s(t)$ by the in-phase factor $(1+\varepsilon)\cos(2\pi f_{IF}t+\Delta\phi)$ and the quadrature-phase factor $(1-\varepsilon)\sin(2\pi f_{IF}t-\Delta\phi)$. The equation for the complex baseband signal with imbalance effects after the IQ processing is given in [14], [15] by

$$\begin{aligned} r_{iq}(t) &= LPF\{s(t)[(1+\varepsilon)\cos(2\pi f_{IF}t+\Delta\phi) \\ &\qquad + j(1-\varepsilon)\sin(2\pi f_{IF}t-\Delta\phi)]\} \\ &= \alpha\left[r(t)e^{-j2\pi\Delta ft}\right] + \beta\left[r(t)e^{-j2\pi\Delta ft}\right]^* \end{aligned} \tag{2}$$

where

$$\begin{cases} \alpha = \cos\Delta\phi + j\cdot\varepsilon\cdot\sin\Delta\phi \\ \beta = \varepsilon\cdot\cos\Delta\phi - j\cdot\sin\Delta\phi \end{cases} \tag{3}$$

In (2), LPF denotes the low-pass filtering operation, while * indicates complex conjugate.

3 Proposed Solution for the IQ Imbalance

Most of the IQ imbalance compensation methods presented in the literature are sensitive to the presence of CFO [18]. Thus implementation of those methods requires the removal of CFO prior to the correction of IQ imbalance. On the other hand, estimation of CFO is sensitive to IQ imbalance particularly for those correlation-based methods. Hence, most papers [18], [19] adopted some kind of jointed estimation/compensation schemes with quite high complexity to deal with both impairments at the same process. In this paper, we propose a low complexity receiver structure those as shown in Fig. 2 in which the effects of the IQ imbalance and CFO are treated separately. First, it adopts a robust algorithm that uses a known training sequence and a simple adaptive least-square (LS) algorithm to estimate the IQ imbalance parameters α and β (or equivalently ε and $\Delta\phi$) in the presence of CFO, and the IQ imbalance can be compensated accordingly. Then, the estimation of the CFO can be performed by examining the phases of the received time-domain samples in the successive training blocks.

Based on this idea, the purpose of the first processor (IQ block) of the proposed scheme is to recover the equivalent baseband signal which suffers from the CFO, i.e., to recover $e^{-j2\pi\Delta ft}r(t)$. By (2), we have

$$r_{iq}(t) = \alpha e^{-j2\pi\Delta ft}r(t) + \beta e^{j2\pi\Delta ft}r^*(t) \quad (4)$$

and $$r_{iq}^{\ *}(t) = \alpha^* e^{j2\pi\Delta ft}r^*(t) + \beta^* e^{-j2\pi\Delta ft}r(t) \quad (5)$$

Solving for $e^{-j2\pi\Delta ft}r(t)$ from (4) and (5) yields

$$e^{-j2\pi\Delta ft}r(t) = \frac{\alpha^* r_{iq}(t) - \beta r_{iq}^*(t)}{|\alpha|^2 - |\beta|^2} \quad (6)$$

If α and β are known, we can determine the term $e^{-j2\pi\Delta ft}r(t)$. Hence, α and β are the key parameters to be estimated throughout the rest of this paper.

Assume that the training sequence structure is composed of N identical symbols and each symbol consists of δ samples. If necessary, a guard interval or cyclic prefix can be inserted between symbols to avoid inter-symbol interference as in OFDM. Dividing the term in (6) for the present sampling instant by the corresponding term for the prior instant at $t-\delta T_s$, we obtain

$$\frac{e^{-j2\pi\Delta f(t)}r(t)}{e^{-j2\pi\Delta f(t-\delta T_s)}r(t-\delta T_s)} = \frac{\alpha^* r_{iq}(t) - \beta r_{iq}^{\ *}(t)}{\alpha^* r_{iq}(t-\delta T_s) - \beta r_{iq}^{\ *}(t-\delta T_s)}, \quad (7)$$

where T_s is the sampling period. If the noise effects and time variations of the channel are neglected, the following approximation holds: $r(t-\delta T_s) \approx r(t)$. Equation (7) can thus be simplified to

$$e^{-j2\pi\Delta f(\delta T_s)} = \frac{\alpha^* r_{iq}(t) - \beta r_{iq}^*(t)}{\alpha^* r_{iq}(t-\delta T_s) - \beta r_{iq}^*(t-\delta T_s)} \quad (8)$$

Since the length of the whole training sequence is $L = N\cdot\delta$ samples, we can have $L-\delta$ values of $e^{-j2\pi\Delta f(\delta T_s)}|_l$ by (8), where suffix l indicates the sampling instant $l\,T_s$ and $l=\delta,\ \delta+1,\ \cdots, L$. If the consecutive samples are close to each other, then the mean square error (MSE) between the consecutive sampling intervals is approximately zero, namely,

$$MSE = \sum_{l=\delta}^{L-1}\left|(e^{-j2\pi\Delta f(\delta T_s)}|_{l+1}) - (e^{-j2\pi\Delta f(\delta T_s)}|_l)\right|^2 \approx 0. \quad (9)$$

To solve the IQ imbalance parameters α and β from (9), we make two assumptions that $\alpha \approx 1$ and $\beta^2 \approx 0$. For example, if $\Delta\phi = 3^\circ, \varepsilon = 40\%$, then $\alpha = 0.9986 + 0.018j \approx 1$ and $\beta = 0.399 - 0.052j$. Then, an estimate of the $\hat{\beta}$ value can be determined by (9) as

$$MSE = \sum_{l=\delta}^{L-1}\left|\left(\frac{r_{iq}(t)-\hat{\beta}r_{iq}^{\ *}(t)}{r_{iq}(t-\delta T_s)-\hat{\beta}r_{iq}^{\ *}(t-\delta T_s)}\bigg|_{l+1}\right) - \left(\frac{r_{iq}(t)-\hat{\beta}r_{iq}^{\ *}(t)}{r_{iq}(t-\delta T_s)-\hat{\beta}r_{iq}^{\ *}(t-\delta T_s)}\bigg|_{l}\right)\right|^2 \approx 0. \quad (10)$$

To satisfy (10), each term in the simulation should be zero. Hence, we have

$$\begin{aligned}&\left(\frac{r_{iq}(t)-\hat{\beta}r_{iq}^{\ *}(t)}{r_{iq}(t-\delta T_s)-\hat{\beta}r_{iq}^{\ *}(t-\delta T_s)}\bigg|_{l+1}\right) - \left(\frac{r_{iq}(t)-\hat{\beta}r_{iq}^{\ *}(t_s)}{r_{iq}(t-\delta T_s)-\hat{\beta}r_{iq}^{\ *}(t-\delta T)}\bigg|_{l}\right) = 0\\ &\Rightarrow \frac{r_{iq}(l+1)T_s - \hat{\beta}r_{iq}^{\ *}(l+1)T_s}{r_{iq}(l+1-\delta)T_s - \hat{\beta}r_{iq}^{\ *}(l+1-\delta)T_s} = \frac{r_{iq}(lT_s)-\hat{\beta}r_{iq}^{\ *}(lT_s)}{r_{iq}(l-\delta)T_s - \hat{\beta}r_{iq}^{\ *}(l-\delta)T_s},\\ &\text{for } l=\delta, \delta+1, \cdots, L\text{-}1\end{aligned} \quad (11)$$

We can simplify (11) to $a_l \cdot \hat{\beta} = b_l$ with the assumption $\hat{\beta}^2 \approx 0$, (12)

where

$$\begin{cases} a_l = r_{iq}(l-\delta)T_s \times r_{iq}^*(l+1)T_s + r_{iq}^*(l-\delta)T_s \times r_{iq}(l+1)T_s \\ \quad -\left(r_{iq}^*(l+1-\delta)T_s \times r_{iq}(lT_s) + r_{iq}(l+1-\delta)T_s \times r_{iq}^*(lT_s)\right) \\ b_l = r_{iq}(l-\delta)T_s \times r_{iq}(l+1)T_s - r_{iq}(l+1-\delta)T_s \times r_{iq}(lT_s) \end{cases}$$

Considering all the terms for $l=\delta \sim L-1$, (12) can be put into a matrix form as

$$\mathbf{A}\cdot\hat{\beta} = \mathbf{B}, \tag{13}$$

where $\mathbf{A} = [a_\delta, a_{\delta+1}, .., a_{L-1}]^H$ and $\mathbf{B} = [b_\delta, b_{\delta+1}, .., b_{L-1}]^H$.

Then, we can solve (13) for $\hat{\beta}$ with the method of Least Squares (LS), i.e.,

$$\hat{\beta} = \frac{\mathbf{A}^H \cdot \mathbf{B}}{\|\mathbf{A}\|^2} = \frac{\sum_{l=\delta}^{L-1} a_l^* \cdot b_l}{\sum_{l=\delta}^{L-1} |a_l|^2}. \tag{14}$$

After we get $\hat{\beta}$, we can obtain $\hat{\alpha}$ from (3).

$$(\mathrm{Real}\{\hat{\alpha}\})^2 + (\mathrm{I\,mag}\{\hat{\beta}\})^2 = 1$$
$$\Rightarrow \mathrm{Real}\{\hat{\alpha}\} = \sqrt{1-(\mathrm{I\,mag}\{\hat{\beta}\})^2}.$$

$$\mathrm{Real}\{\hat{\alpha}\}\bullet\mathrm{I\,mag}\{\hat{\alpha}\} = -\mathrm{Real}\{\hat{\beta}\}\bullet\mathrm{I\,mag}\{\hat{\beta}\}$$
$$\Rightarrow \mathrm{I\,mag}\{\hat{\alpha}\} = -\frac{\mathrm{Real}\{\hat{\beta}\}\bullet\mathrm{I\,mag}\{\hat{\beta}\}}{\mathrm{Real}\{\hat{\alpha}\}}.$$

$$\hat{\alpha} = \mathrm{Real}\{\hat{\alpha}\} + j\bullet\mathrm{Imag}\{\hat{\alpha}\}$$
$$= \sqrt{1-(\mathrm{I\,mag}\{\hat{\beta}\})^2} - j\cdot\frac{\mathrm{Real}\{\hat{\beta}\}\cdot\mathrm{Imag}\{\hat{\beta}\}}{\sqrt{1-(\mathrm{I\,mag}\{\hat{\beta}\})^2}}, \tag{15}$$

Real{. } is the real part and Imag{. } is the imaginary part.

Finally, after $\hat{\alpha}$ and $\hat{\beta}$ have been obtained by (14) and (15), the IQ imbalance can be compensated by (6) as

$$r_{compensated}(t) = \frac{\hat{\alpha}^* r_{iq}(t) - \hat{\beta} r_{iq}^*(t)}{|\hat{\alpha}|^2 - |\hat{\beta}|^2} \tag{16}$$
$$= e^{-j2\pi\Delta ft} r(t).$$

In summary, the algorithm that we propose here estimates and compensates the IQ imbalance in the presence of CFO with a known periodic training sequence. The entire process is executed in the time domain and the computational complexity is lower compared with other schemes. However, a problem arises when the CFO is too small. The reason is that a small value of CFO will cause $r_{iq}(lT_s) \approx r_{iq}((l+1)T_s)$ and $r_{iq}((l-\delta)T_s) \approx r_{iq}((l+1-\delta)T_s)$, and it makes a_l in (12) and (14) close to zero. And this may result in a large fluctuation value on $\hat{\beta}$ estimate in practical process when noise effect is not ignorable and it also leads to much degraded performance. A slightly modified algorithm that solves this problem will be presented in next section.

3.1 Simulation

To examine the performance of the proposed IQ-CFO compensation approach, an OFDM system was considered and computer simulations were carried out. The system parameters were set based on the specification of IEEE 802.11a Standard for Wireless LANs [20]. The training sequence consists of 10 identical short preamble symbols (each contains 16 samples) and two identical long preamble symbols (each contains 64 samples) as depicted in Fig. 3. Between the short and long preamble symbols, there is a guard interval of length 32 that constitutes the cyclic prefix of the long symbols. We ran simulations for coded 64QAM with coherent demodulation over an AWGN channel and an AWGN channel with multipath fading channel separately. The multi-path channel was modeled by a seven-ray channel model with exponentially decaying power profile and an rms channel delay spread equal to $T_{rms} = 50ns$. The ISI effect is ignored in this system since the length of the cyclic prefix is greater than that of the channel spread. In the simulations, the CFO is compensated by a conventional correlation scheme using the training sequence after IQ compensation for the proposed scheme. Two sets of IQ mismatch parameters, ($\varepsilon = 20\%$, $\Delta\phi = 1.5^\circ$) and ($\varepsilon = 40\%$, $\Delta\phi = 3^\circ$), were tested. Fig. 4 shows the effect of IQ imbalance on BER at various values of CFO in AWGN and multi-path channels. It can be seen that the impact of severe IQ imbalance is quite dramatic; it renders the system dysfunctional, exhibiting a performance floor. Hence, IQ estimation/compensation is clearly needed in a communication system where CFO is present.

Next we employ the proposed method to estimate and to compensate for IQ imbalance under the same sets of IQ imbalance parameter values. The simulation results in Fig. 5 show that when the CFO value exceeds 5KHz, the proposed scheme performs quite well. Hence, the proposed method can effectively estimate and compensate for IQ imbalances taking into account the effects of CFO.

However, its performance degrades significantly when the CFO value falls below 5KHz.

4 An Adaptive Scheme

Using the proposed method provided in the above section, we make two assumptions that $\alpha \approx 1$ and $\beta^2 \approx 0$. In practice, the transmitted signal is contaminated with additive white Gaussian noise (AWGN) and the receiver signal is subject to channel fading. The performance of the proposed method will be sensitive to low CFO values. On the other hand, a problem arises when the CFO is too small which make a_l close to zero. According to equation (12), the results in a very large value of $\hat{\beta}$, contradicting our assumption that $\beta^2 \approx 0$, and leading to much degraded performance. In this section, we proposed to add an adaptive scheme in order to resolve degraded performance when CFO is too small. The adaptive scheme include changing the original duplicated sampling interval that can avoid a_l close to zero and modifying average several sampling intervals that can eliminate the AWGN influence.

An efficient adaptive filtering in the proposed method, which takes into consideration both requirements including to change the original duplicated sampling interval and to modify average several sampling intervals in equation (7), has been introduced to resolve large fluctuation when CFO is too small. Specifically, denoting the number of iterations by *k*, we define H_k as follows,

$$H_k = \frac{\sum_{m=0}^{\left\lfloor \frac{k+1}{2} \right\rfloor - 1} e^{-j2\pi\Delta f(t-m\delta T_s)} r(t-m\delta T_s)}{\sum_{m=\left\lfloor \frac{k}{2} \right\rfloor + 1}^{\left\lfloor \frac{k+1}{2} \right\rfloor + \left\lfloor \frac{k}{2} \right\rfloor} e^{-j2\pi\Delta f(t-m\delta T_s)} r(t-m\delta T_s)} \approx e^{-j2\pi\Delta f(\left\lfloor \frac{k}{2} \right\rfloor + 1)\delta T_s} \quad (k = 1, 2, \cdots) \tag{17}$$

Note that H_k is the ratio obtained by the present sampling interval to the new duplicated sampling interval at $(\left\lfloor \frac{k}{2} \right\rfloor + 1)\delta T_s$ over the same average several sampling intervals. According to equation (17), the results of *k*=1 is the same as equation (7). An estimate of $\hat{\beta}_1$ value can be determined by the proposed method. On the other hand, Algorithm initialization is the same as the proposed method. Then, we can change the original duplicated sampling interval in H_k (k is even value ,for example, assuming *k*=2) to obtain the suitable value of $\hat{\beta}_k$. In addition, we modify average several sampling intervals in H_k (k is odd value ,for example, assuming *k*=3) to obtain the suitable value of $\hat{\beta}_k$ in order to eliminate the AWGN influence. With increased *k*, the value of the new duplicated sampling interval or the number of the new average sampling intervals will be increased. Consequently, the value of a_l is not likely to be close to zero, thereby resolving the algorithm's sensitivity to small values of CFO. The value of *k* can be progressively increased until convergence of the system is achieved. This proposed modification can achieve better performance when CFO is small and will also mitigate the effects of AWGN influence. Adaptive scheme is now specified by

$$\hat{\beta}_{k+1} = \hat{\beta}_k + \Delta\beta_k \tag{18}$$

The squared error $\Delta\beta_k = \left|\hat{\beta}_k - \hat{\beta}_{k-1}\right|^2$ can be used to select the best hypothesis as $\tilde{k} = \arg \min_{k=1,2,\cdots} \Delta\beta_k$. The corresponding $\hat{\beta}$ value decision is $\hat{\beta}_{\tilde{k}}$.

4.1. Performance

Our simulation results have shown that the performance with adaptive scheme is always better than without. The adaptive scheme provides significant performance improvement at low CFO. When the CFO is large, it shows that the adaptive algorithm can give a satisfactory performance. The average residual amplitudes and phases resulting from using the adaptive scheme method are depicted in Fig. 6 and Fig. 7 for a multi-path channels. Fig. 8 shows the performance of the adaptive IQ compensation for a coded 64QAM including IQ estimation and adaptive scheme. The adaptive method provides satisfactory performance for CFO > 1kHz and justifies taking into account the influence of CFO in dealing with IQ imbalance estimation/compensation.

5 Conclusions

In this paper, we introduce a robust adaptive IQ estimation/compensation scheme that takes into account the effects of CFO. The IQ imbalance of the RF front-end not only produces image interference but also degrades the accuracy of CFO estimation. When the IQ imbalance and CFO are considered jointly, the problem of estimation becomes quite complicated. With the proposed method, by employing a repetitive training sequence, we can estimate the IQ imbalance without knowing CFO exactly. Specifically, the proposed method can estimate/compensate the IQ imbalance in the first step, and estimate/compensate CFO in the next step. Both processes are independent and fulfilled in time domain. Because this method involves simply taking the ratio of a function of current symbols to that of the preceding symbols, it is robust with respect to channel variation and transmitter IQ imbalance. Furthermore, an adaptive scheme is proposed to improve the performance when CFO is small.

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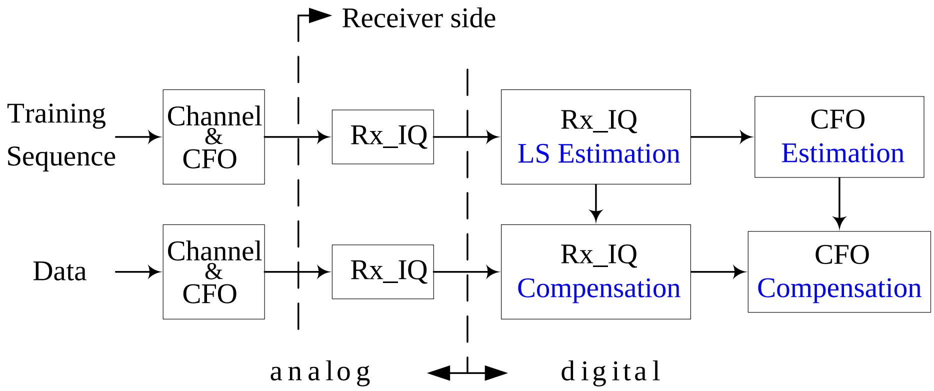


Fig. 2 Block diagram of the receiver structure for the proposed scheme.

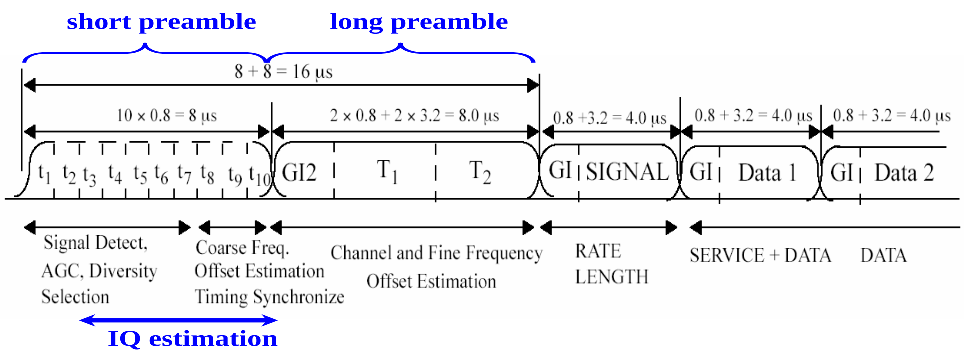


Fig. 3 Structure of the IEEE 802.11a training sequence

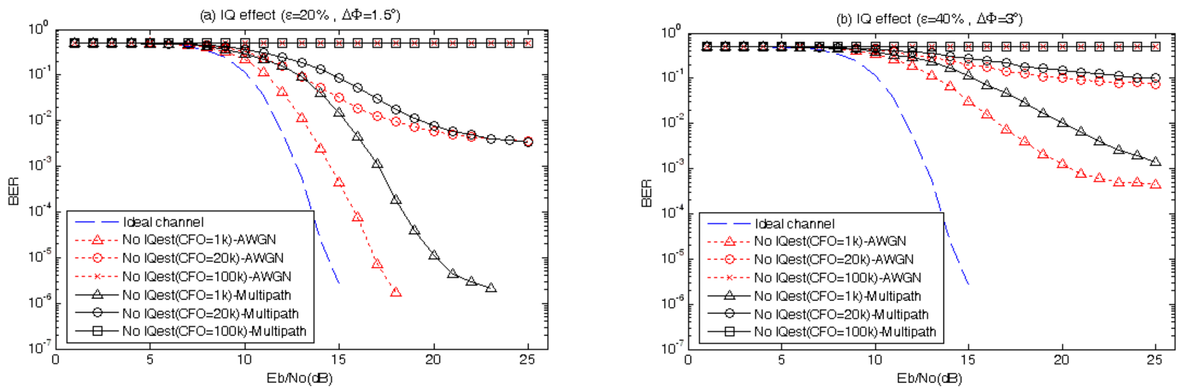


Fig. 4 The effects of IQ imbalance on BER at various values of CFO in AWGN and multi-path channels.

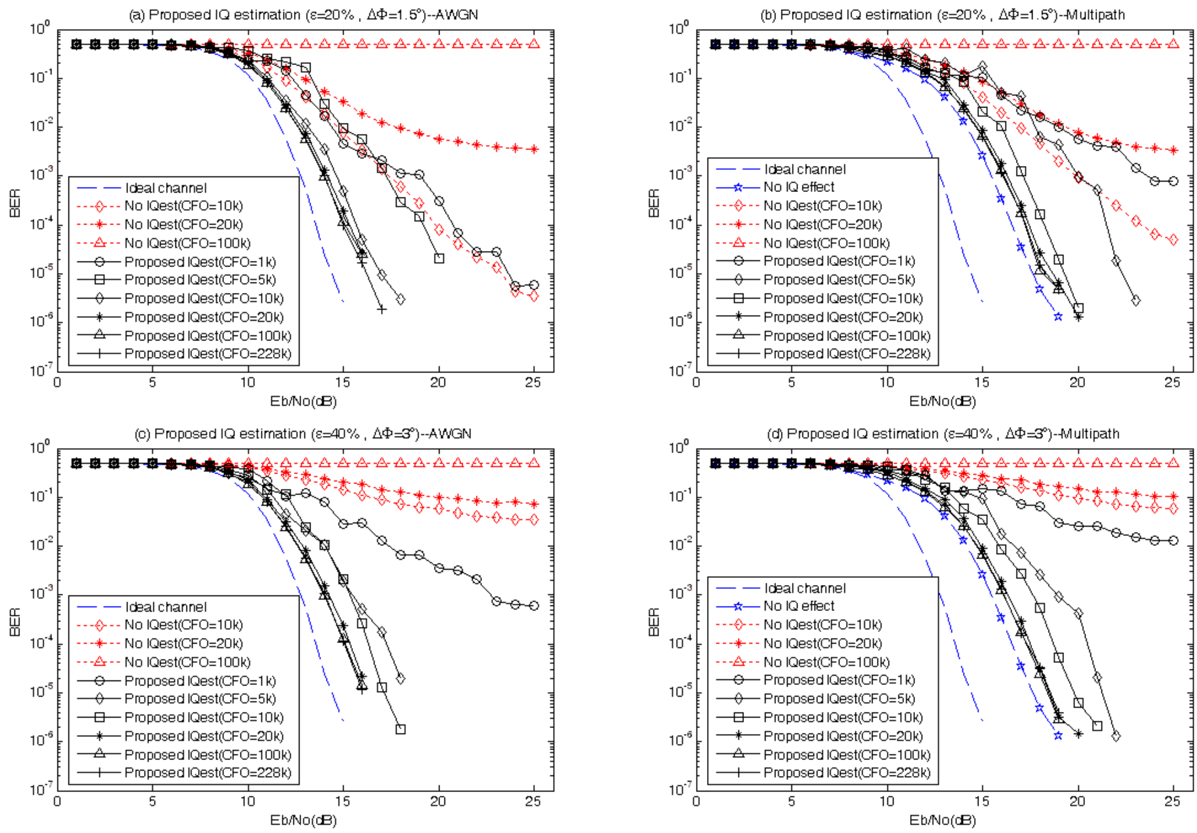


Fig. 5 IQ compensation with the proposed scheme under various CFO and IQ imbalance values.

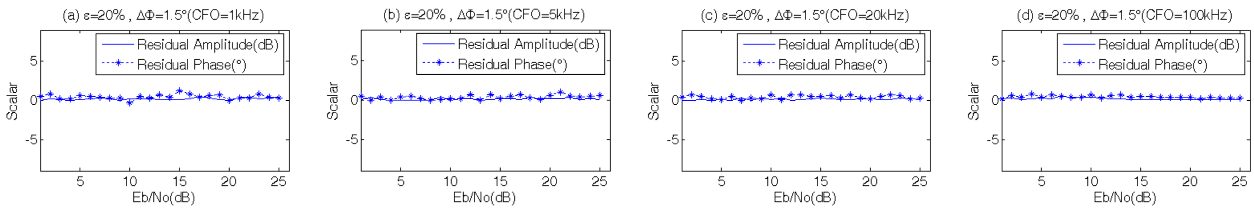


Fig. 6 Average residual amplitude and phase with the adaptive IQ correction for multi-path channel at with $\varepsilon = 20\%$ and $\Delta\phi = 1.5^{\circ}$

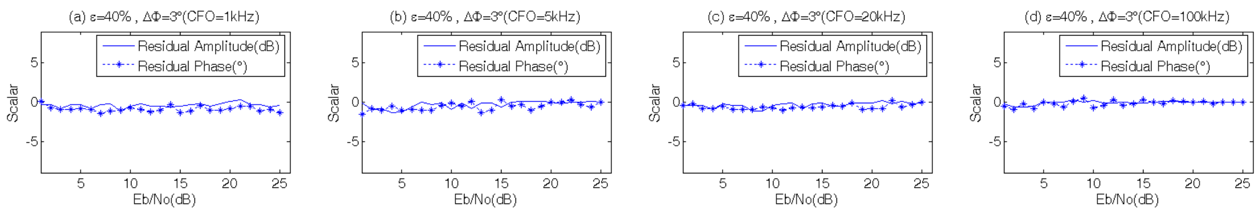
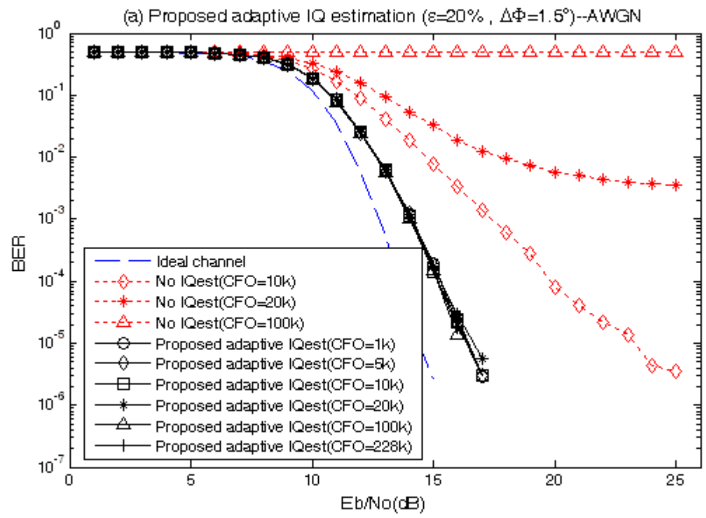
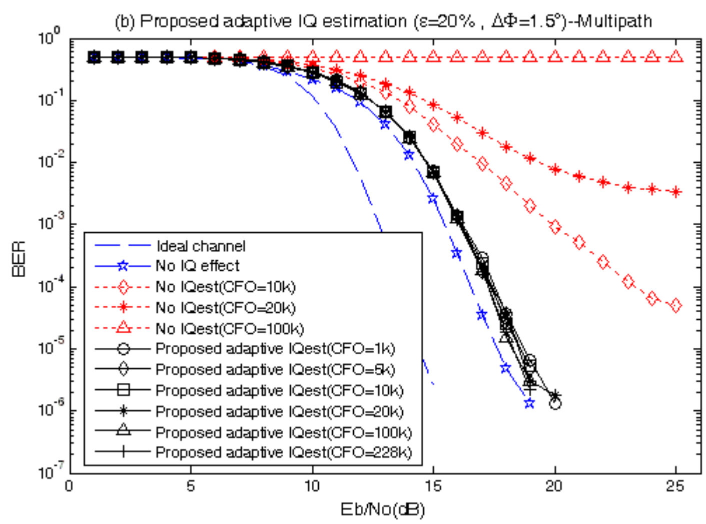


Fig. 7 Average residual amplitude and phase with the adaptive IQ correction for multi-path channel at with $\varepsilon = 40\%$ and $\Delta\phi = 3^{\circ}$


(a) Proposed adaptive IQ estimation (ε=20% , ΔΦ=1.5°)--AWGN
BER
Eb/No(dB)
Ideal channel
No IQest(CFO=10k)
No IQest(CFO=20k)
No IQest(CFO=100k)
Proposed adaptive IQest(CFO=1k)
Proposed adaptive IQest(CFO=5k)
Proposed adaptive IQest(CFO=10k)
Proposed adaptive IQest(CFO=20k)
Proposed adaptive IQest(CFO=100k)
Proposed adaptive IQest(CFO=228k)


(b) Proposed adaptive IQ estimation (ε=20% , ΔΦ=1.5°)--Multipath
BER
Eb/No(dB)
Ideal channel
No IQ effect
No IQest(CFO=10k)
No IQest(CFO=20k)
No IQest(CFO=100k)
Proposed adaptive IQest(CFO=1k)
Proposed adaptive IQest(CFO=5k)
Proposed adaptive IQest(CFO=10k)
Proposed adaptive IQest(CFO=20k)
Proposed adaptive IQest(CFO=100k)
Proposed adaptive IQest(CFO=228k)

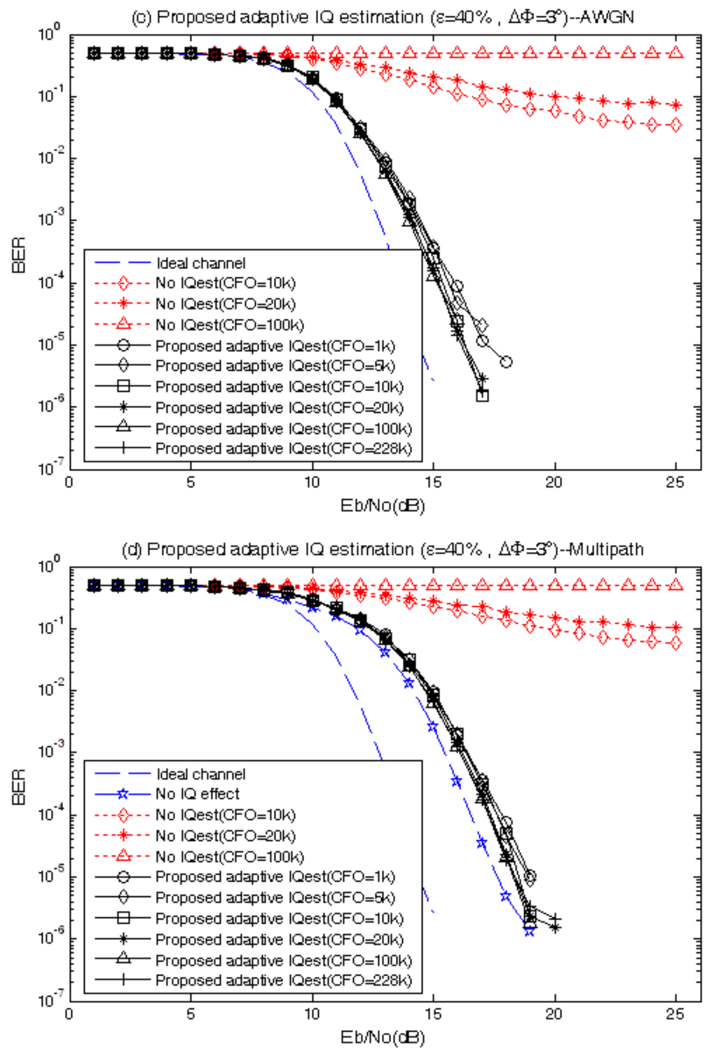


Fig. 8 IQ compensation with the proposed adaptive method under various CFO and $\Delta\phi$, ε