High I/Q Imbalance Receiver Compensation and Decision Directed Frequency Selective Channel Estimation in an OFDM Receiver Employing Neural Network

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Abstract

The disparity introduced between In-phase and Quadrature components in a digital communication system receiver known as I/Q imbalance is a prime objective within the employment of direct conversion architectures. It reduces the performance of channel estimation and causes to receive the data symbol with errors. This imbalance phenomenon, at its lowest still can result very serious signal distortions at the reception of an OFDM multi-carrier system. In this manuscript, an algorithm based on neural network scenario, is proposed that deploys both Long Training Symbols (LTS) as well as data symbols, to jointly estimate the channel and to compensate parameters that are damaged by I/Q imbalanced receiver. In this algorithm, we have a tradeoff between these parameters. I.e. when the minimum CG mean value is required, the minimum CG mean value could be chosen without others noticing it, but in usual case we have to take into account other parameters too, the limited values for the aimed parameters must be known. It uses the first iterations to train the system to reach the suitable value of GC without error floor. In this present article, it is assumed that the correlation between subcarriers is low and a few numbers of training and data symbols are used. The simulation results show that the proposed algorithm can compensate the high I/Q imbalance values and estimate channel frequency response more accurately compared with to date existing methods.

Keywords: I/Q Imbalance; OFDM; Zero-IF; Direct Conversion; Neural Network; Channel Estimation, Frequency Selective Channel.

1. Introduction

Fig. 1 depicts a direct conversion receiver, normally called zero-IF architecture that is usually employed over an Orthogonal Frequency Division Multiplexing (OFDM) based wireless communication system.

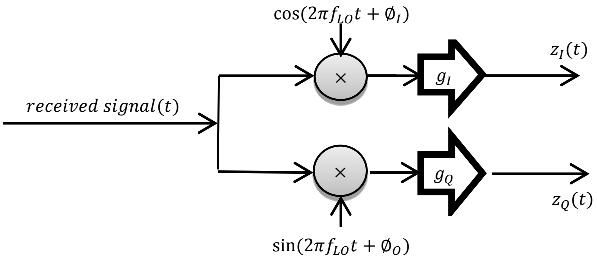

Fig.1. Generic model of an I/Q imbalance receiver

The direct conversion is a suitable approach that is deployed to decrease the complexity of an OFDM receiver. The receiver I/Q imbalance are observed by imperfect matching of the employed analog components in the In-phase (I) and the Quadrature (Q) branches which normally extinguishes the performance of the OFDM system (Fig. 1). Hence, the estimation of such ambiguous parameters becomes an imperative necessity to digitally compensate I/Q imbalance behaviors for the design of a high performance receiver. Two sets of techniques are introduced in the previous published papers to estimate the I/Q imbalance process. The first technique is based upon the received training symbols [1-4]. Their method of deploying the received training symbols are not affected by mutual interference between the pairs of symmetric subcarriers. Indeed, within such approach, the single OFDM training symbols must be somehow modified. The second method proposed by [5] uses the uncorrelated transmitted subcarriers to provide a blind estimation. Since the adopted estimation technique is based on statistical analysis, a large number of received data symbols are required otherwise an error floor arises even at high SNRs.

In [6], Traverso *et al*. introduced an algorithm that compensated I/Q-imbalance feature of the OFDM receivers and estimated the channel frequency response jointly. Their method deployed both training symbols and pilot symbols for the OFDM receiver to reach the system strongly against the high I/Q-imbalance feature and their proposed system require the two different LTS to estimate

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imbalance parameters (K_1, K_2) at the OFDM-receiver, but by employing the neural network the receiver could compensate the imbalance parameters deploying only one LTS to train the neural network.

In this present article, it is assumed that the correlation between subcarriers is low and a few number of training and data symbols are used. The proposed system employs a neural network scheme to compensate the parameters of the high I/Q imbalance receiver with a high-order modulation and it is sensitive to I/Q imbalance characteristics. The proposed system employs uniform distribution function to estimate initial value of training phase of neural network and then using multilayer perceptron to parallel-process distribution to achieve suitable values of I/Q imbalance receiver. It deploys decision-directed scheme too, similar to the existing methods, to improve the performance of an OFDM receiver.

2. I/Q Imbalance Receiver Model of an OFDM System

Fig. 1 depicts an I/Q imbalance receiver due to a gain mismatch g and a phase mismatch $\emptyset$. The gain mismatch is produced by unequal gain in I and Q receiver branches. The phase mismatch is occurred by asynchronous oscillators that are employed in the receiver architecture. The I/Q imbalance parameters [1] can be written as:

$$\mathrm{K}_1 = \left[\mathrm{e}^{-j\emptyset_\mathrm{I}}\mathrm{g}_\mathrm{I} + \mathrm{e}^{-j\emptyset_\mathrm{Q}}\mathrm{g}_\mathrm{Q}\right]/2 \tag{1}$$

$$\mathrm{K}_2 = \left[\mathrm{e}^{+j\emptyset_\mathrm{I}}\mathrm{g}_\mathrm{I} - \mathrm{e}^{+j\emptyset_\mathrm{Q}}\mathrm{g}_\mathrm{Q}\right]/2 \tag{2}$$

where $\emptyset_I$ and g_I show the mismatch phase and gain parameters of RF in-phase branch respectively and $\emptyset_Q$ and g_Q show the mismatch phase and gain parameters of RF quadrature-phase branch. In the proposed system, the received signal [12] is given as follows:

$$\mathrm{R}_\mathrm{k}(\mathrm{n}) = \mathrm{T}_\mathrm{k}(\mathrm{n})\mathrm{H}_\mathrm{k}\mathrm{K}_1 + \mathrm{T}^*_{-\mathrm{k}}(\mathrm{n})\mathrm{H}^*_{-\mathrm{k}}\mathrm{K}_2 = \mathrm{T}_\mathrm{k}(\mathrm{n})\alpha_\mathrm{k} + \mathrm{T}^*_{-\mathrm{k}}\beta_\mathrm{k}$$
$$\text{for} \quad \mathrm{k} \in \pm\left[1; \mathrm{N}_{\frac{\mathrm{DFT}}{2}} - 1\right] \tag{3}$$

where $\mathrm{R}_\mathrm{k}(\mathrm{n})$is the received signal of k^{th} subcarrier at the n^{th} symbol and $\alpha_\mathrm{k} \triangleq \mathrm{H}_\mathrm{k}\mathrm{K}_1$ and $\beta_\mathrm{k} \triangleq \mathrm{H}^*_{-\mathrm{k}}\mathrm{K}_2$. $\mathrm{T}_\mathrm{k}(\mathrm{n})$, $\mathrm{N}_{\mathrm{DFT}}$ and H_k show the sender transmitted symbols, the Discrete Fourier Transform block size and the frequency response of transmission channel that are not damaged by imbalance receiver respectively. By using (3), the received symbols are formulated [6] as follows:

$$\mathrm{R} = \mathrm{A1} \times \mathrm{H} \times \mathrm{T} \tag{4}$$

Where

$$\mathrm{R} = \begin{bmatrix} \mathrm{R}_\mathrm{k}(\mathrm{n}) \\ \mathrm{R}^*_{-\mathrm{k}}(\mathrm{n}) \end{bmatrix}, \ \mathrm{A1} = \begin{bmatrix} \mathrm{K}_1 & \mathrm{K}_2 \\ \mathrm{K}_2^* & \mathrm{K}_1^* \end{bmatrix}$$
$$\mathrm{H} = \begin{bmatrix} \mathrm{H}_\mathrm{k} & 0 \\ 0 & \mathrm{H}^*_{-\mathrm{k}} \end{bmatrix}, \ \mathrm{T} = \begin{bmatrix} \mathrm{T}_\mathrm{k}(\mathrm{n}) \\ \mathrm{T}^*_{-\mathrm{k}}(\mathrm{n}) \end{bmatrix} \tag{5}$$

Note that, $\mathrm{K}_1^*$and K_1^* are the conjugate of K_1 and K_2 respectively. In this case, the frequency offset between local oscillators is not studied and it is assumed that its value is Negligible. Algorithms that are employed in [15], [5] can be used to cancel the effect of frequency offset in I/Q imbalance receivers.

In this section, it is explained that when sender transmits two different Long length Training Symbols (LTS), to compensate the parameters of I/Q imbalance receiver and to estimate the frequency response of transmission channel together, are not impossible objectives. By dividing the received LTS $(\mathrm{P}_{\mathrm{rk}})$ by the corresponding LTS $(\mathrm{P}_{\mathrm{tk}})$ that is transmitted by sender, the estimate value of channel C_k can be calculated. Note that the received LTS $(\mathrm{P}_{\mathrm{rk}})$ and transmitted LTS $(\mathrm{P}_{\mathrm{tk}})$, both are known at the OFDM receiver. In this case, P_{rk} and P_{tk} represent the powers of $\mathrm{R}_\mathrm{k}$and $\mathrm{T}_\mathrm{k}$respectively. By using (1), when sender transmits two LTSs that are different, two channel estimations $\mathrm{C}_\mathrm{k}(1)$ and $\mathrm{C}_\mathrm{k}(2)$ have to be available at the destination that are damaged by imbalance receiver. These channel estimations have linear relations [6] as follows:

$$\mathrm{C}_\mathrm{k}(1) = \frac{\mathrm{P}_{\mathrm{r}_\mathrm{k}}(1)}{\mathrm{P}_{\mathrm{t}_\mathrm{k}}(1)} = \alpha_\mathrm{k} + \mathrm{L}_\mathrm{k}(1)\beta_\mathrm{k}$$
$$\mathrm{C}_\mathrm{k}(2) = \frac{\mathrm{P}_{\mathrm{r}_\mathrm{k}}(2)}{\mathrm{P}_{\mathrm{t}_\mathrm{k}}(2)} = \alpha_\mathrm{k} + \mathrm{L}_\mathrm{k}(2)\beta_\mathrm{k} \tag{6}$$

where $\mathrm{L}_\mathrm{k}(1) = \mathrm{P}^*_{\mathrm{t}_{-\mathrm{k}}}(1)/\mathrm{P}_{\mathrm{t}_\mathrm{k}}(1)$ and $\mathrm{L}_\mathrm{k}(2) = \frac{\mathrm{P}^*_{\mathrm{t}_{-\mathrm{k}}}(2)}{\mathrm{P}_{\mathrm{t}_\mathrm{k}}(2)}$ are parameters that the receiver has the knowledge of [17]. If the condition C defined by [6] is satisfied, by using the condition $\mathrm{K}_1 + \mathrm{K}_2^* = 1$ and known parameters α_k and β_k, the frequency response of transmission channel [17] is calculated as follows:

$$\mathrm{H}_\mathrm{k} = \alpha_\mathrm{k} + \beta^*_{-\mathrm{k}} \tag{7}$$

By using (7) and $\alpha_\mathrm{k} = \mathrm{H}_\mathrm{k}\mathrm{K}_1$, the I/Q imbalance parameters is obtainable [6] as follows:

$$\mathrm{K}_1 = \frac{\alpha_\mathrm{k}}{\alpha_\mathrm{k} + \beta^*_{-\mathrm{k}}}, \tag{8}$$

$$\mathrm{K}_2 = 1 - \mathrm{K}_1^*. \tag{9}$$

At first, the estimation value of channel response and parameters of imbalance receiver are calculated and then by employing the matrix A_1 in (4), the transmitted data symbols are obtained.

3. OFDM Standard Employ a Single LTS

In many OFDM receivers, the LTSs are equal [6] and thus, the condition C[6] is not satisfied and previously adapted approaches are not suitable. In this part, a new algorithm is proposed to compensate the I/Q imbalance parameters by using the neural network with a single LTS as well as channel response and data symbols.

In the proposed iterative algorithm, primarily, the $\widehat{\mathrm{K}_1}$ parameter is estimated by using the neural network and the single LTS and then the $\widehat{\mathrm{K}_1}$ to estimate the channel frequency response and data symbols.

3.1 Algorithm with neural network

The four following steps are performed to establish the neural network algorithm:

1) Direct-decisions on data symbols: using the channel estimation $\mathrm{C_k}$ to estimate the sending data symbols $\mathrm{T_k(n)}$ even in the absence of I/Q imbalance receiver.

2) Estimation of the I/Q imbalance parameters K_1 *and* K_2: it is known that, the best case is when the $\mathrm{K_1}$ is unity and $\mathrm{K_2}$ is zero. Considering neural network scenario, α_k and β^*_{-k} are as inputs to the network and $\mathrm{K_1}$ is defined as network output.

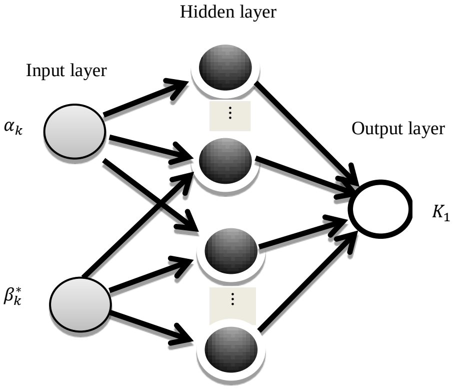

Fig.2. The neural network schematic to compensate the $\mathrm{K_1}$ parameter

$$\widehat{K_1} = \frac{\widehat{\alpha_k}}{\widehat{\alpha_k}+\widehat{\beta^*_{-k}}} \tag{10}$$

where $\widehat{K_2}$ is the imbalance parameter that is calculated by $\widehat{K_2} = 1 - \widehat{K^*_1}$.

3) Compensate the data symbols of the proposed OFDM system: By using $\mathrm{K_1}$ and $\mathrm{K_2}$ that are estimated in step 2 and the invert form of the matrix $\mathrm{A_1}$ given in (4), the data symbols are obtained as follows:

$$\widehat{D_k}(n) = \frac{\widehat{K^*_1}R_k(n) - \widehat{K_2}R^*_{-k}(n)}{\left|\widehat{K_1}\right|^2 - \left|\widehat{K_2}\right|^2} \tag{11}$$

4) Compensation of the channel estimation response: To estimate coefficients of channel response, the proposed algorithm employs independent LTS for each transmitted packet. To achieve this matter, in different bits and at different times the transmitted data and the received data are considered approximately independent. The estimate values $\widehat{H_k}$ resulted from $\widehat{H_k} = \widehat{\alpha_k} + \widehat{\beta^*_{-k}}$ are not good approximation for the following reasons; $\widehat{H_k}$ is severely damaged by errors that occur in step 1 since there is no averaging over the frequency range. But, because the estimation values of I/Q imbalance parameters with neural network are reliable, the I/Q imbalance compensation of the rough channel estimation Ck provides a good estimation of $\mathrm{H_k}$ employing step 3:

$$H_k = \frac{\widehat{K^*_1}C_k - L_k\widehat{K_2}C^*_{-k}}{\left|\widehat{K_1}\right|^2 - \left|\widehat{K_2}\right|^2}. \tag{12}$$

After four steps are performed, (4) can be written as follows:

$$\begin{bmatrix} \widehat{D_{1k}}(n) \\ \widehat{D^*_{1-k}}(n) \end{bmatrix} = \widehat{A_1}^{-1} A_1 \begin{bmatrix} H_k & 0 \\ 0 & H^*_{-k} \end{bmatrix} \begin{bmatrix} T_k(n) \\ T^*_{-k}(n) \end{bmatrix} \tag{13}$$

where $\widehat{A_1}$ is the estimation compensation matrix of the I/Q imbalance receiver. If the estimation compensation of the I/Q imbalance parameters is perfect, then $A_2 = \widehat{A_1}^{-1}A_1$ would be the identity matrix. Therefore, the data symbol and I/Q imbalance matrix are perfectly compensated. However, in most cases, the hard decision is erroneous, so the algorithm estimates I/Q imbalance parameters imperfectly. From $K_1 + K^*_2 = 1$ and $\widehat{K_1} + \widehat{K^*_2} = 1$, it follows that after using the neural network by some hidden layers. And, using the α_k and β^*_{-k} as inputs to the network as well as $\mathrm{K_1}$ is defined as network output, the value of $\widehat{K_1}$ would be compensated and $\widehat{D_{1k}}(n) = H_k T_k(n)$ can be used as the compensated data symbol at the receiver.

4. Simulation Results

In this section, the performance of the proposed algorithm is assessed in terms of compensation and the performance enhancement of the I/Q imbalance receiver and channel estimation. The data subcarriers of the system are modulated by a 64-QAM (Quadrature Amplitude Modulation). For each transmitted packet an independent channel realization of the Channel C [14], is assumed. The curves are the result of averaging over 100 received packets by I/Q imbalance receiver in the direct conversion OFDM system.

The algorithms have three parameters: the number of iterations i, the number of data symbols N and the Conversion Gain (CG) mean value. In this algorithm, we have a tradeoff between these parameters. I.e. when the minimum CG mean value is required and the other parameters are not important, the minimum CG mean value could be chosen without others noticing it, but in usual case we have to take into account other parameters too, the limited values for the aimed parameters must be known.

A good criterion to choose these parameters is minimize the number of iterations i with suitable value of the conversion gain defined as the power of the undesired complex down-conversion divided by the power of the desired complex down-conversion [12].The conversion gain of the compensated signal after the $\mathrm{i^{th}}$ iteration [6] is defined by:

$$GC_{comp} = \left|\frac{\widehat{K_{2i}}}{\widehat{K_{1i}}}\right|^2 \tag{14}$$

where $\widehat{K_1}_i$ and $\widehat{K_2}_i$ are the remaining I/Q imbalance parameters after using neural network in the $\mathrm{i^{th}}$ iteration. This system is used under condition that the packet error rate does not exceed 10%,

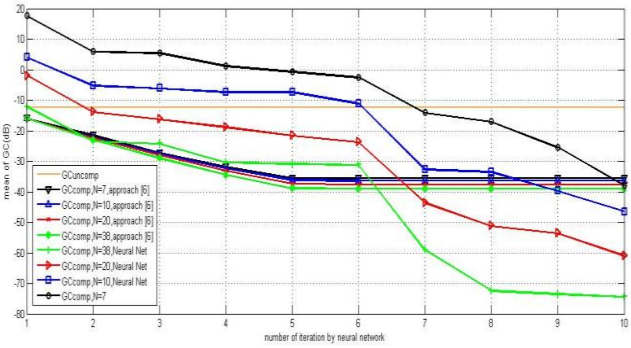

Fig.3. The conversion gain means versus the number of iterations for different values of N using the neural network

In the case that the energy per bit to noise ratio (E_b/N_0) is 25 dB, for the system without I/Q imbalance, the uncoded BER is 2×10^{-4} (Fig. 5). Hence, we have to define the optimal number of data symbols N, iterations i and the conversion gain for the compensated signal at $E_b/N_0 = 25$ dB.

4.1 System performance

The parameters that are chosen to perform I/Q imbalance conversion are $\emptyset_I = 0$, $g_I = 1$, $g_Q = 1.5$ and $\emptyset_Q = 15^\circ$. Fig. 3 shows the mean of GC_{comp} versus the number of iterations for different values of N where $g_Q = 1.5$ and $\emptyset_Q = 15^\circ$ with $E_b/N_0 = 25$ dB deploying neural network. The GC_{uncomp} is defined as the conversion gain of the uncompensated data symbols. Fig. 3 shows both approaches, the Traverso et al. [6] approach and the approach employed here, to decrease the GC. As Fig. 3 shows the curves for the approach where the system uses data from the fifth iteration to train the network and then uses the trained network to decrease the GC, to reach to a suitable GC without limitation. The best tradeoff between complexity and performance is also obtained for $i = 6$ and $N = 10$. Fig. 4 shows the mean of GC_{comp} versus the number of iterations for $N = 38$ and for different values of I/Q imbalance parameters. All curves show that as I/Q imbalance parameter values are increased, the absolute value of GC is decreased.

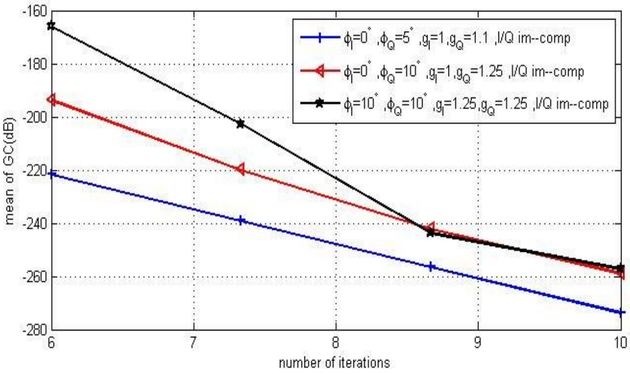

Fig.4. The conversion gain mean versus the number of iterations for different values of I/Q imbalance parameters with neural network.

Fig. 5 compares the performance of the mentioned algorithm with the performance of a system with no I/Q imbalance as well as the performance of a system with I/Q imbalance but without any compensation mechanism with the uncoded BER curves versus E_b/N_0 for $N = 64$, $\emptyset_I = 0$, $g_I = 1$, $g_Q = 1.5$ and $\emptyset_Q = 15^\circ$.

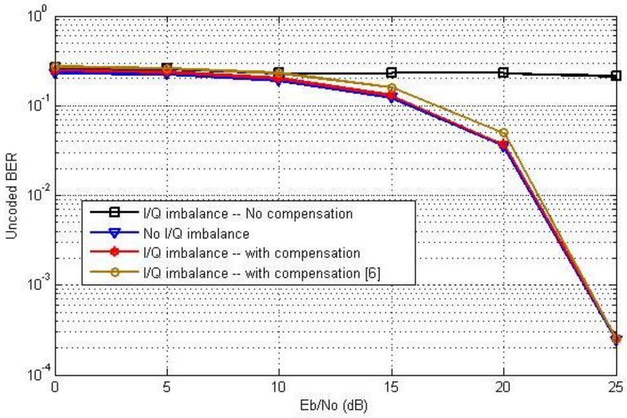

Fig.5. The uncoded BER performance for the receiver with no compensation, for the receiver using the proposed algorithm and for the receiver with no I/Q imbalance, as well as the receiver employed by [6] for comparison

As Fig. 5 shows, the BER of the proposed algorithm is very close to the BER curve of a system without I/Q imbalance even for high I/Q imbalance.

5. Conclusions

As it is known, it is impossible to match I and Q branches at the OFDM receiver in the analog domain perfectly. The I/Q imbalance affects the receiver performance. It reduces the performance of channel estimation and causes to receive the data symbol with errors. We propose an algorithm with neural network for joint channel estimation and I/Q imbalance compensation in OFDM receivers. The proposed algorithm uses the training and data received OFDM symbols in a decision-directed scheme. It provides a good improvement in the performance of I/Q imbalance receiver. It uses the first iterations to train the system to reach the suitable value of GC without error floor.

Furthermore, to employ the proposed system over a time-varying multipath channel, a memory device of about 100Mbytes which are commonly available in today's systems, is required to save few number of received data bits for such a neural network evaluations.

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