I/Q Imbalance Compensation and Channel Equalization in OFDM Receivers

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Abstract: IQ imbalance that is prominent in Decision-directed architecture can cause significant degradation in the performance of wireless communication systems. In this paper, a discussion of a new algorithm that uses both training and data symbols in a decision-directed fashion to jointly estimate and compensate for the effects of the channel and high receiver I/Q imbalance is presented.

Key Words: -- Orthogonal Frequency Division Multiplexing, IQ imbalance, equalization, estimation, compensation

I. Introduction

Orthogonal frequency division multiplexing (OFDM) is a potential technique for transmitting high bit rate data over indoor and outdoor wireless communication systems, which can be seen from the facts that it has been widely accepted by most of standards for next generation communication systems, such as digital TV, wireless LAN and fixed point wireless communication. This is due to its simple implementation with high bandwidth efficiency and its robustness to multi-path delay and Inter symbol interference (ISI). An OFDM-based system divides a high-speed serial information signal into multiple lower-speed sub-signals that the system transmits simultaneously at different frequencies in parallel.

The two main factors that degrade the performance of OFDM systems are I/Q imbalance and the time varying and frequency selective nature of the channel. The performance of the OFDM system can be vastly increased with dynamic estimation and equalization of the channel and compensation for I/Q imbalance before the demodulation of OFDM signals.

Channel equalization is an important subsystem in a communication receiver. Equalization is a technique used to remove inter-symbol interference (ISI) produced due to the limited bandwidth of the transmission channel. When the channel is band limited, symbols transmitted through will be dispersed. This causes previous symbols to interfere with the next symbols, yielding the ISI. From the estimated values of channel impulse response and I/Q imbalance, equalization is performed by inverting the values of the same.

This paper is organized as follows. Section II and III deal with modeling the OFDM system and I/Q imbalance respectively. Section IV deals with the estimation and compensation of the channel and I/Q imbalance using the proposed algorithm.

2. OFDM System Model

An OFDM transmitter consists of five basic blocks which are as shown in Fig. 1.

![OFDM Transmitter block diagram](image)

The incoming serial bits of data are divided into N (Number of sub-carriers) parallel streams and are modulated by a suitable constellation mapping technique (M-ary QAM, PSK). These symbols are then fed into the IFFT block and after inserting a cyclic prefix, I/Q modulation is done and the data is transmitted over the channel. The Receiver implements the inverse of the operations performed at the transmitter side.
A basic OFDM receiver block diagram is shown in Fig. 2.

Fig. 2 OFDM Receiver block diagram

3. I/Q Imbalance Model:

OFDM signals are complex baseband signals and are converted into real passband signals using I/Q modulation. In this section, we briefly introduce the baseband and passband representations and introduce the model for I/Q imbalance. The baseband signal, \( s(t) \), is usually a complex function of time. Therefore, it can be written into rectangular form as

\[
S(t) = S_I(t) + jS_Q(t)
\]

(1)

Where,

\[
s_I(t) = \sum_{k=0}^{N-1} (\Re\{s_k\} \cos(2\pi f_c t) - \Im\{s_k\} \sin(2\pi f_c t))
\]

\[
s_Q(t) = \sum_{k=0}^{N-1} (\Im\{s_k\} \cos(2\pi f_c t) + \Re\{s_k\} \sin(2\pi f_c t))
\]

(2)

and \( \Re\{s_k\} \) and \( \Im\{s_k\} \) denote the real and imaginary parts of the complex symbol \( s_k \), respectively.

I/Q modulated signal can be expressed as:

\[
s_p(t) = \Re\{s_I(t)e^{2\pi j f_c t}\}
\]

\[
= s_I(t) \cos(2\pi f_c t) - s_Q(t) \sin(2\pi f_c t)
\]

(3)

where, \( f_c \) is the carrier frequency of the communication system.

The following diagram demonstrates I/Q modulation.

Fig. 3 Communication system depicting I/Q modulation (without I/Q imbalance)

Mismatches in analog components cause an imbalance in the gain and phase responses of the branches from the local oscillator to the I and Q branches of the receiver. This is termed as I/Q imbalance. The following diagram illustrates the problem of I/Q imbalance.

Fig. 4 Communication system depicting I/Q modulation (with I/Q imbalance at receiver)

The I/Q imbalance is caused by a gain mismatch \( g \) and a phase mismatch \( \phi \). The gain mismatch is due to a difference of the overall gain between the I and Q branches. The phase mismatch is due to a non-ideal layout, i.e., the fact that the lines between the mixer and the local oscillator of the I and Q branches are not exactly of the same length. Let \( K_1 = (1 + ge^{-j\phi})/2 \) and \( K_2 = (1 - ge^{j\phi})/2 \) be the I/Q imbalance parameters as defined in [6]. For an OFDM system impaired by the receiver I/Q imbalance, the received signal on the \( k \)th subcarrier during the \( n \)th symbol \( R_k(n) \) can be written as in [6]:

\[
R_k(n) = T_k(n) H_k K_1 + T^*_k(n) H^*_k K_2 = T_k(n) \alpha_k + T^*_k(n) \beta_k
\]

(4)

\( k \in [1; NDFT/2-1] \)

where \( \alpha_k = H_k K_1 \) and \( \beta_k = H^*_k K_2 \). \( T_k(n) \), \( H_k \) and \( NDFT \) denote respectively the transmitted symbols, the channel frequency response not affected by I/Q imbalance, and the block size of the Discrete Fourier Transform. The matrix form of the received symbols defined by equation (4) is:

\[
\begin{bmatrix}
R_k(n) \\
R^*_k(n)
\end{bmatrix} =
\begin{bmatrix}
K_1 & K_2 \\
K_1^* & K_2^*
\end{bmatrix}
\begin{bmatrix}
H_k & 0 \\
0 & H^*_k
\end{bmatrix}
\begin{bmatrix}
T_k(n) \\
T^*_k(n)
\end{bmatrix}
\]

(5)
Note that the above model does not take into account the unavoidable frequency offset between the transmitter/receiver local oscillators. The estimation of the frequency offset in the presence of I/Q imbalance can be performed using the method proposed in [7] for example. Thus we assume a pre-compensation at the transmitter or an analog pre-compensation of this effect at the receiver.

4. Estimation

For estimation, if two different LTS are transmitted consecutively, the two channel estimations $C_k(1)$ and $C_k(2)$ affected by I/Q imbalance form a system of linear equations in two variables:

$$
C_k(1) = \frac{P_r k(1)}{P_t k(1)} = \alpha_k + L_k(1)\beta_k
$$

$$
C_k(2) = \frac{P_r k(2)}{P_t k(2)} = \alpha_k + L_k(2)\beta_k
$$

Where, $P_r k$ is the received LTS and $P_t k$ is the transmitted LTS and,

$$
L_k(1) = Pr_{-k}(1)/Pr(1)
$$

$$
L_k(2) = Pr_{-k}(2)/Pr(2)
$$

In this case, estimation can be performed for $L_k(1)\neq L_k(2)$ which is referred to as condition $C$.

From the (4) it is seen that

$$
H_k = \alpha_k + \beta^*_k
$$

This yields the following relationship from which the IQ imbalance parameters can be found

$$
K_1 = \frac{\alpha_k}{\alpha_k + \beta^*_k}
$$

$$
K_2 = 1 - K_1^*
$$

(9)

Once the IQ parameters and the channel frequency response have been estimated, the data symbols are compensated for I/Q imbalance inverting matrix $A_1$ in equation (5), and the channel equalization can be performed.

However in many OFDM standards the same LTS is sent twice for reduced overheads. In that case the condition $C$ is not satisfied, and it is not possible to apply the method described in Section III. In this Section we propose a new method for joint compensation of the I/Q imbalance and estimation of the channel frequency response using only a single LTS and data symbols. Note that if known pilots subcarriers are inserted in the data symbols satisfying the criteria $C$, they can be used as a second LTS as defined in Section III. Since pilot subcarriers do not always satisfy the condition $C$ and with the aim of reducing the number of pilots in the sequel, we only consider data subcarriers.

The proposed algorithm is iterative. In first Subsection we present the algorithm with a single iteration, and in the second Subsection we give the general case of $i, i > 1, \text{iterations}$.

A. Algorithm with a single iteration

We now present the 3 steps of our algorithm.

4.1 Hard decisions on N received data symbols:

Even if the I/Q imbalance is pronounced, the $N$ received symbols $Rk(n)$ equalized by the channel estimation $C_k$ are good approximations of $T_k(n)$. We denote the hard decisions of these equalized symbols as $D[R_k(n)/C_k]$.

4.2 Estimation of the I/Q imbalance parameters $K_1$ and $K_2$:

If $T_k(n)$ and $T_{-k}(n)$ are replaced by the previous hard decisions in equation (4), we obtain an equation equivalent to the second received LTS, as described in Section III. Let $\zeta$ be a set of all subcarriers satisfying $D[R_k(n)/C_k]L_k \neq D[R_{-k}(n)/C_{-k}]$.

For each subcarrier $k$ in $\zeta$, the estimation of $\alpha_k$ and $\beta_k$ is possible. Since $K_1$ is the same for all the subcarriers, and since we use $N$ data symbols, it is possible to average the estimates over time and frequency:

$$
\hat{R}_1 = \frac{1}{\text{card}(\zeta)} \sum_{k \in \zeta} \hat{\alpha}_k + \hat{\beta}^*_k
$$

$R_2$ is obtained by $\hat{R}_2 = 1 - \hat{R}_1^*$.

4.3 I/Q Imbalance Compensation:

The estimates $\hat{H}_k$, deduced from $\hat{H}_k = \hat{\alpha}_k + \hat{\beta}^*$, $k$ are not reliable for two reasons. The first one is that for each received data symbol, $\hat{H}_k$ is not available when $k$ does not belong to $\zeta$. Secondly, $\hat{H}_k$ is severely corrupted by hard decision errors because there is no averaging over the frequency range. Since the estimations of the I/Q imbalance parameters are reliable, the I/Q imbalance compensation.
of the rough channel estimation $C_k$ gives a reliable estimation of $H_k$.

$$\hat{H}_k = \frac{\hat{K}_1^* C_k - L_k \hat{K}_2 C_k^*}{|\hat{K}_1|^2 - |\hat{K}_2|^2}$$

$I/Q$ imbalance compensation of data symbols:

Once $K_1$, $K_2$ and $H_k$ have been estimated, the data symbols are compensated for the $I/Q$ imbalance by inverting the matrix $A_1$ given in equation

B. The algorithm with $i$ iterations:

The matrix form of the data symbols compensated for $I/Q$ imbalance after the first iteration can be written as follows:

$$\begin{bmatrix} \hat{D}_{1k}(n) \\ \hat{D}_{-1k}(n) \end{bmatrix} = A_1^{-1} \begin{bmatrix} \hat{T}_k \\ T_{-k} \end{bmatrix}$$

where $A_1$ corresponds to the estimation compensation matrix of the $I/Q$ imbalance and channel response, and $A_2$ to the remaining $I/Q$ imbalance matrix and channel response after the first iteration. Simple algebra leads to $A_2$ in the following form:

$$A_2 = \begin{bmatrix} J_{11} & J_{21} \\ J_{21} & J_{11} \end{bmatrix}$$

If the estimation of the $I/Q$ imbalance parameters and channel response obtained after the first iteration was perfect, then $A_2$ would be the identity matrix. In this case $\hat{D}_{ik}(n) = H_k T_i(n)$, and the $I/Q$ imbalance and channel effects would be perfectly compensated. However, in the presence of hard decision errors, the algorithm estimates imperfect $I/Q$ imbalance parameters. From $K_1 + K_2 = 1$ and $\hat{K}_1 + \hat{K}_2 = 1$, it follows after simple algebra that $J_{11} + J_{21} = 1$, regardless of the values of $K_1$, $K_2$ and their estimates. Therefore equation (12) is similar to equation (5). It is possible to reiterate the estimation of the remaining $I/Q$ imbalance parameters returning to the step 1 of the core algorithm. The data symbols and the channel estimation necessary in step 1 at the iteration $i$ are those obtained in the iteration $i-1$. Thus, the matrix $A_{ni}$ after the $i^{th}$ iteration is:

$$A_{i+1} = A_i \cdot A_{i-1} \cdots A_2 \cdot A_1$$

The experimental results evidence that $A_{ni}$ tends to the identity matrix when there is no noise and $i$ go to infinity.

5. Conclusion

Presence of I/Q imbalance drastically degrades the performance of OFDM systems. In order to design a high performance receiver, it is necessary to estimate and compensate for the $I/Q$ imbalance. In this paper, an algorithm to jointly estimate and equalize the effects of channel and $I/Q$ imbalance has been presented.

References


