FREQUENCY DOMAIN QUADRATURE ERROR CORRECTION

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Abstract

Many new wireless comunication standards use complex modulation schemes with many subcarriers, which put high requirements on small Quadrature Errors. Linearization schemes such as digital predistortion also put high requirements on Quadrature Errors and in-band filter response.

This paper describes the development of an adaptive signal processing algorithm aiming to correct frequency dependent Quadrature Errors and to improve the in-band frequency response simultaneously. The correction is done in frequency domain using 4-by-4 matrix multiplication with different coefficients for different subcarrier groups.

Theory and simulation suggest that these algorithms substantially can improve the transceiver performance and/or relax the requirements on its analogue and mixed signal components.

Key Words: Quadrature error correction, I/Q-mismatch, equalization, design methodology.

1 Introduction

Multi-carrier systems require an in-band filter response with flat amplitude and linear phase, i.e. the amplitude and phase errors over the subcarriers must be small. Standards with higher order modulation schemes, e.g. 64-QAM, put high requirements on small Quadrature Errors (QEs) in the constellation diagram. Linearization schemes such as digital predistortion also put high requirements on QEs and in-band filter response.

QEs come from gain and phase imbalance in the mixer and the base band parts of the transceiver (TRx). The non-ideal filter response comes from filtering in components in the signal path of theTRx.

In order to fulfil the requirements on the in-band filter response equalization can be used and the most common method to lower the QEs is to use time-domain Quadrature Error Correction (QEC). The major drawback of current equalization schemes is their complexity and the major drawback of time-domain QEC is that they normally only correct frequency independent QEs.

This paper describes the development of an adaptive signal processing algorithm aiming to correct frequency dependent QEs and to improve the in-band filtering simultaneously. The correction is done in frequency domain using 4-by-4 matrix multiplication with different coefficients for different subcarrier groups. The groups can be as small as one subcarrier pair (subcarrier with the same absolute frequency) per group and as large as all the subcarriers in one group. This makes the method very flexible. The receiver (Rx) adaptation can be done using the actual signal and the Rx correction will correct for non-idealities in the Rx, the RF channel and the transmitter (Tx). The Tx adaptation uses training signals for each subcarrier pair (see equation 5). Since the subcarrier pairs can be grouped and the coefficients for one group can be used to speed up the adaptation of other groups the correction can be gradually improved from a fast initial adaptation. This is also true for the Rx.

2 Transmitter with Quadrature Errors

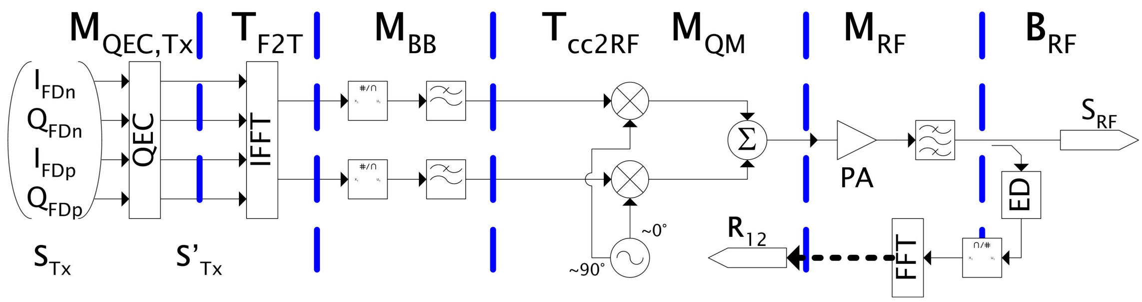

Figure 1. OFDM Tx with corresponding matrices.

The QEs in an Orthogonal Frequency Division Multiplexing (OFDM) based Tx, e.g. using the WLAN standard IEEE 802.11a, can be described using matrices according to figure 1and the following equation:

$$S_{RF} = \mathbf{B}_{RF} \cdot \mathbf{S}_{RF} = \mathbf{B}_{RF} \cdot \mathbf{M}_{Tx} \cdot \mathbf{S}_{Tx} \tag{1}$$

where

$$\mathbf{M}_{Tx} = \mathbf{M}_{RF} \cdot \mathbf{T}_{cc2RF} \cdot \mathbf{M}_{QM} \cdot \mathbf{M}_{BB} \cdot \mathbf{T}_{F2T} \qquad \mathbf{S}_{RF} = \begin{pmatrix} L_{RFc} \\ L_{RFs} \\ U_{RFc} \\ U_{RFs} \end{pmatrix} \qquad \mathbf{S}_{Tx} = \begin{pmatrix} I_{FDn,Tx} \\ Q_{FDn,Tx} \\ I_{FDp,Tx} \\ Q_{FDp,Tx} \end{pmatrix} \tag{2}$$

The input signal components I_{FDn} and Q_{FDn} correspond to negative frequency and I_{FDp} and Q_{FDp} to positive frequency. The output signal components L_{RFc} and L_{RFs} correspond to a frequency lower than the carrier frequency and U_{RFc} and U_{RFs} correspond to a higher frequency, i.e. lower and upper sideband respectively.

The 4-by-1 vector $\mathbf{B}_{RF}$ is an Ortho Normal (ON) base for the Radio Frequency (RF) signal representations. The 4-by-4 matrices $\mathbf{T}_{cc2RF}$ and $\mathbf{T}_{F2T}$ are used to convert between different ON bases and representations. The QEs in the Baseband (BB), Quadrature Modulator (QM) and RF parts are described by the 4-by-4 matrices $\mathbf{M}_{BB}$, $\mathbf{M}_{QM}$ and $\mathbf{M}_{RF}$ respectively.

An ideal Tx can be represented by the 4-by-4 matrix $\mathbf{M}_{Tx} = \mathbf{M}_{Tx,ideal}$.

3 Transmitter Quadrature Error Correction

QEC is done by calculating the (pre-) corrected frequency domain representation of the BB signal (see figure 1) according to the following equation:

$$\mathbf{S'}_{Tx} = \widehat{\mathbf{M}}_{QEC,Tx} \cdot \mathbf{S}_{Tx} \quad \text{where} \quad \mathbf{M}_{QEC,Tx} = \mathbf{M}_{Tx}^{-1} \cdot \mathbf{M}_{Tx,ideal} \tag{3}$$

On the Rx side, the transmitted symbols can be estimated using the following equation:

$$\widehat{\mathbf{S}}_{Tx} = \widehat{\mathbf{M}}_{QEC,Rx} \cdot \mathbf{S}_{Rx} \tag{4}$$

The correction matrices can be estimated according to the method described in the following section and the concept of Tx and Rx QEC is shown in figure 2

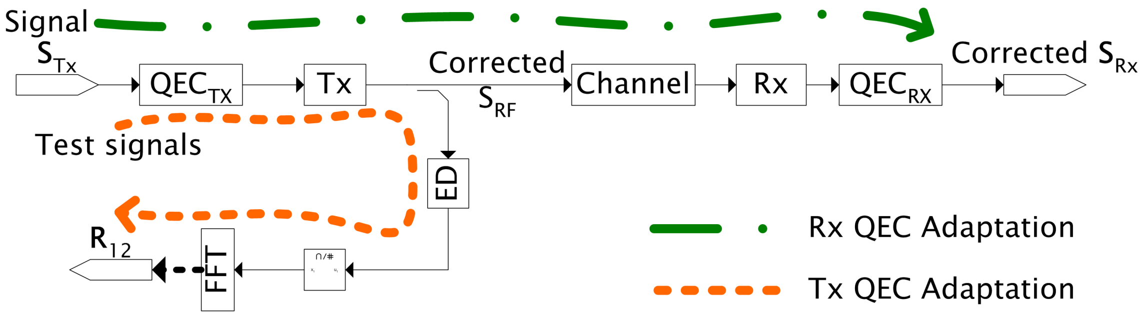

Figure 2. Tx and Rx QEC concept.

4 Adaptation of Quadrature Error Correction

4.1 Transmitter Specific Part

In the absence of an ideal Rx the Tx QEC adaptation has to use some other type of feedback. An Envelope Detector (ED) is a good choice since it does not have any QEs and the fact that it can be used as an Amplitude Modulation (AM) detector. However, it restricts the adaptation to one subcarrier pair at a time. If the Tx LO leakage has been minimized and the QEs in the DC-component are small enough two similar test streams can be used. They use the same subcarrier values, but have a DC-value on the the In phase (I)- and the Quadrature phase (Q)-part respectively. The streams are defined by:

$$TS_1 \equiv I_C + \mathbf{B}_{TD} \cdot \mathbf{T}_{F2T} \cdot \mathbf{S}_{Tx} \qquad TS_2 \equiv Q_C + \mathbf{B}_{TD} \cdot \mathbf{T}_{F2T} \cdot \mathbf{S}_{Tx} \tag{5}$$

The ED output, ED_i, for the test-signals can be approximated by

$$ED_1 \approx I_C + R_{II}\cos(\omega t) + R_{IQ}\sin(\omega t) \qquad ED_2 \approx Q_C + R_{QI}\cos(\omega t) + R_{QQ}\sin(\omega t) \tag{6}$$

R_{II} etc. can be found by performing an FFT on the ED output to find the values at the subcarrier frequency. The frequency domain representation, $\mathbf{S}_{Rx}$, corresponding to an ideal Rx can now be estimated by

$$\widehat{\mathbf{S}}_{Rx} = \mathbf{H}_{R2S} \cdot \mathbf{R}_{12} \quad \text{where} \quad \mathbf{R}_{12} = \begin{pmatrix} R_{II} & R_{IQ} & R_{QI} & R_{QQ} \end{pmatrix}^T \tag{7}$$

and $\mathbf{H}_{R2S}$ is a 4-by-4 convertion matrix.

Now, the Tx QEC adaptation can be done similar to the Rx QEC adaptation. However, each subcarrier pair must be corrected separately and special test signals must be used.

4.2 Receiver Parts (Common Parts)

The Rx QEC adaptation can use the actual signal, preferably using a mode with low Packet Error Rate (PER), to estimate the transmitted signal, $\mathbf{S}_{Tx}$. The correction matrices, $\mathbf{M}_{QEC,Tx}$

and $\mathbf{M}_{QEC,Rx}$, can now be estimated in a common way. They are estimated using the least square method. (The ideal $\mathbf{M}_{QEC,Tx}$ in equation 3 can be used to improve the estimate.)

$$E\left\{\mathbf{M}_{QEC}[n]\right\} = \widehat{\mathbf{M}}_{QEC}[n] = \mathbf{S}_{Tx,N}[n] \cdot \mathbf{S}^{T}_{Rx,N}[n] \cdot \left(\mathbf{S}_{Rx,N}[n] \cdot \mathbf{S}^{T}_{Rx,N}[n]\right)^{-1} \tag{8}$$

where $\mathbf{S}_{Tx,N}[n]$ and $\mathbf{S}_{Tx,N}[n]$ are streams of subcarrier pairs, at a certain subcarrier frequency, $nf_{\text{subcarrier spacing}}$.

Note that the Tx QEC only corrects the Tx whereas Rx QEC corrects the whole Tx-Rx chain (see figure 2).

5 Results

Simulations were done in Matlab using 10 symbols for adaptation, 1000 symbols for EVM calculation and a noise variance of 0.01. The noise is added to give a more realistic case.

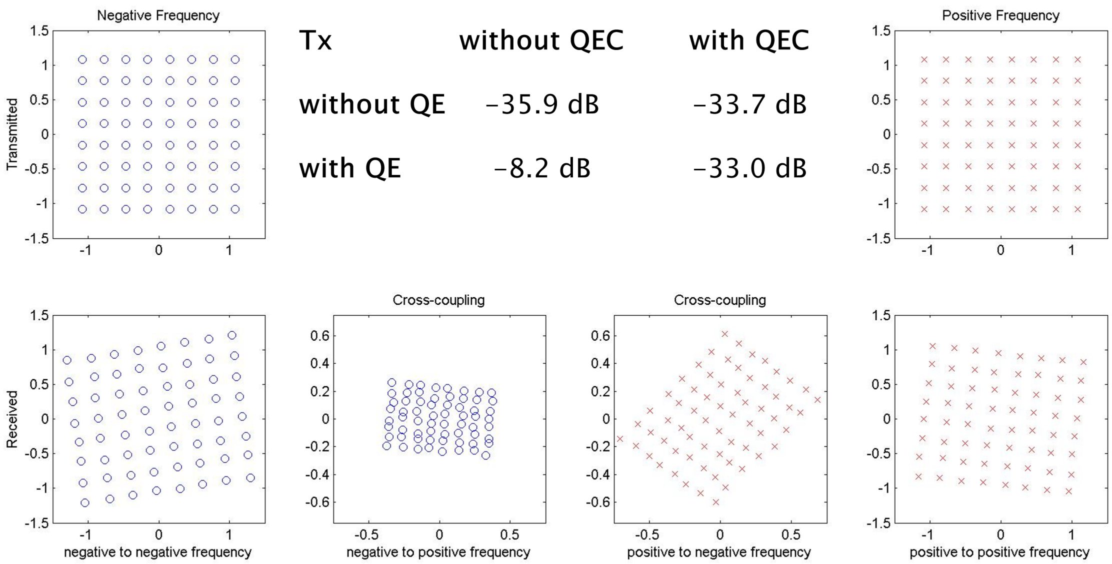

Figure 3. Impact of QE and QEC on constellation points and EVM.

The transmitted constellation points (for 64-QAM) for negative frequencies will be scewed and scaled by QEs (see lower left part of figure 3). They will also be cross-coupled to the corresponding positive frequency (see lower middle left part of figure 3). Vice versa is true for the positive frequencies. The performance enhancement, i.e. the lowered Error Vector Magnitude (EVM), due to Tx QEC for a Tx with QEs is great, as can be seen in figure 3.

As long as the correction matrix can be found and the DC QEs are small an EVM close to the ideal (in terms of QEs) can be achieved. This will relax the QE requirements on the analog components in the TRx.

6 Conclusion

Theory and simulation suggests that these algorithms substantially can improve the TRx performance and/or relax the requirements on its analogue and mixed signal components.