Optimal Pilot based Frequency-dependent I/Q Imbalance Compensation for Wideband Direct-Conversion Transceivers

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Abstract: Current trends in low-cost and low power transceivers in state-of-the-art wireless systems use the direct-conversion principle. Such transceivers, however, suffer severely from the I/Q imbalance effect which introduces mirror-frequency interference and degrades the data detection. This paper proposes a new method for frequency-dependent I/Q imbalance estimation and compensation. The I/Q imbalance is estimated jointly in frequency domain with extremely low complexity and lowest error variance, relying on a special pilot and its optimization. A new time domain I/Q imbalance compensator structure is also developed to achieve the ideal compensation performance. The algorithm is implemented and its operation is verified through laboratory measurements showing excellent results in improving image rejection in an imbalanced modulator.

1. Introduction.

Due to the low cost, small-size yet flexible feature of direct-conversion transmitter (DCT), it is currently seen as the most promising candidate for the analogue front-end of currently existing and emerging wireless communication systems. However, the non-ideality of analogue components causes mismatch between the in-phase (I) and quadrature (Q) branches. This mismatch mainly stems from two sources. First, the phase shifter at the local oscillator (LO) introduces the frequency-independent gain and phase mismatches. Second, the frequency response mismatch between the baseband digital-to-analogue converters (DACs) and low pass filters (LPFs) of the I and Q branches introduces the frequency-dependent I/Q mismatch [1] [2]. The I/Q imbalance can result in mirror-frequency interference which greatly degrades the data detection and will be increasingly problematic when future higher-order modulated or more wideband multi-channel signal is used.

There has been some related work in the literature recently focusing on the frequency-dependent I/Q imbalance compensation. [1] - [4] has successfully derived the method for modelling the receiver/transceiver-side or joint frequency-dependent I/Q imbalance. Based on the baseband modelling, work in [2] and [4] proposed three alternative approaches for time domain estimation and compensation of the I/Q imbalance, showing good performance. Time domain estimation, however, loses the low complexity benefit of the frequency domain processing. In order to avoid the inconvenience of the time domain estimation, [3] [5] [6] introduced three alternative frequency domain estimation and compensation algorithms for OFDM systems. In [3], the joint maximum likelihood (ML) channel estimation scheme which was widely adopted in the literature is reduced to separate ML estimation of the two channel impulse responses and the estimation error variance is minimized thanks to a special training sequence and its optimization. Moreover, a frequency domain low complexity I/Q imbalance compensation structure is also developed which evidenced good performance on OFDM systems.

However, the algorithm introduced in [3] is limited to OFDM systems, especially the frequency domain compensation scheme works only for OFDM systems. It will be very useful to extend the ideas to any types of DCT. Moreover, the estimation algorithm introduced in [3] is suboptimal in terms of complexity. In this paper, a new channel estimation algorithm is introduced to with the key advantage of halving the complexity (relative to [3]) whilst still obeying the optimal pilot sequence criterion. Furthermore, this paper proposes a new three complex filters transmitter compensation structure that results in improved stability (relative to [2]) since the single filter time domain compensator structure of [2] suffers from instability problem which becomes more severe for large channel length.

2. I/Q Imbalance Baseband Equivalent Model.

As widely introduced in the literature, the I/Q imbalance can be effectively modelled by its baseband equivalent model, which is given by [1] - [3] as

$$z(t) = g_1(t) \circledast x(t) + g_2(t) \circledast x^*(t) \tag{1}$$

where $\circledast$ denotes convolution and $(.)^*$ stands for complex conjugation. x(t) and z(t), respectively denote the complex baseband input and ideally-received signals. The two complex imbalance filters $g_1(t)$ and $g_2(t)$ modelling the I/Q imbalance are functions of the gain and phase mismatches due to the LOs and the baseband DACs and LPFs. Since the Fourier transform of (1) is

$$Z(f) = G_1(f) \cdot X(f) + G_2(f) \cdot X^*(-f) \tag{2}$$

the conjugate part due to the I/Q imbalance results in mirror-frequency interference. The image-rejection-ratio (IRR) can now be defined as: $\mathrm{IRR} = 10\log(|G_1(f)|^2/|G_2(f)|^2)$.

3. I/Q Imbalance Estimation and Compensation.

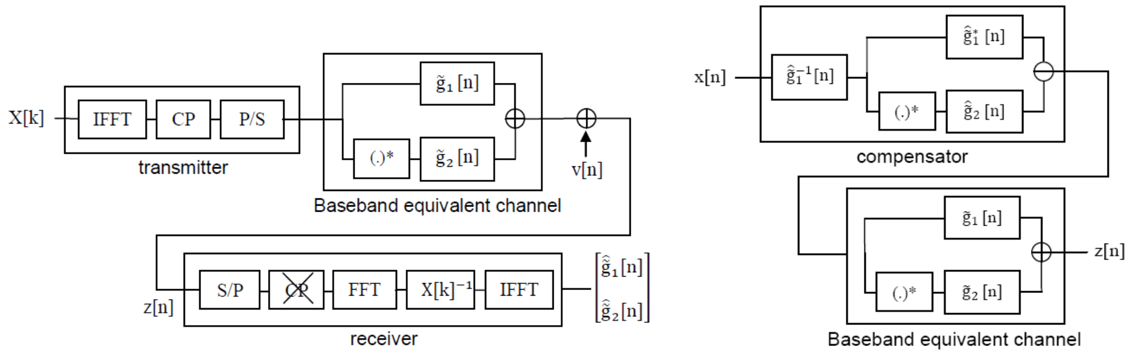

Fig.1. I/Q imbalance channel estimation (left) and compensation (right) schemes

Figure 1 (left) illustrates the I/Q imbalance channel estimation scheme. At the transmitter, a training sequence of size N is generated in the frequency domain and an IFFT is then performed to move the signal back to the time domain. After cyclic prefix (CP) insertion and parallel-to-series conversion (P/S), the training sequence then modulates an RF carrier and sent by the transmitter. The receiver captures the signal and estimates the imbalance filter responses with very low complexity and optimal estimation error variance thanks to a special pilot sequence and its optimization. Based on the above imbalance model (2) and switching to discrete notations, the captured signal in frequency domain can be formulated as

$$Z[k] = X[k] \cdot \widetilde{G}_1[k] + X^*[-k]_N \cdot \widetilde{G}_2[k] + V[k] \tag{3}$$

where $[\,]_N$ denotes the modulus operator and V[k] denotes the noise vector in the frequency domain. The notation $\widetilde{G}$ takes the receiver frequency response into consideration. The two imbalance filters responses may be estimated by multiplying the captured signal Z[k] by the inverse of X[k] and following an IFFT, gives

$$\hat{\tilde{g}}[n] = \tilde{g}_1[n] + \frac{1}{N}\sum_{k=0}^{N-1} D[k]\cdot \widetilde{G}_2[k]\cdot e^{j\frac{2\pi}{N}nk} + \dot{v}[n] \tag{4}$$

where $D[k] = X^*[-k]_N * X^{-1}[k]$ and $\dot{v}[n]$ denotes the noise vector resulting from the inversion and Fourier transform. Due to $\widetilde{G}_2[k]$ being the Fourier transform of $\tilde{g}_2[n]$, given by $\widetilde{G}_2[k] = \sum_{m=0}^{N-1}\tilde{g}_2[m]\cdot \exp(-j2\pi mk/N)$, equation (4) can be further rewritten as

$$\begin{aligned}\hat{\tilde{g}}[n] &= \tilde{g}_1[n] + \frac{1}{N}\sum_{k=0}^{N-1} D[k]\cdot e^{j\frac{2\pi}{N}nk}\left(\sum_{m=0}^{N-1}\tilde{g}_2[m]\cdot e^{-j\frac{2\pi}{N}mk}\right) + \dot{v}[n]\\ &= \tilde{g}_1[n] + \sum_{m=0}^{N-1}\tilde{g}_2[m]\cdot\left(\frac{1}{N}\sum_{k=0}^{N-1} D[k]\cdot e^{j\frac{2\pi}{N}(n-m)k}\right) + \dot{v}[n]\\ &= \tilde{g}_1[n] + \sum_{m=0}^{N-1}\tilde{g}_2[m]\cdot d[n-m]_N + \dot{v}[n]\\ &= \tilde{g}_1[n] + \tilde{g}_2[n]\odot d[n] + \dot{v}[n]\end{aligned} \tag{5}$$

where $\odot$ denotes the circular convolution operation. Observing (5), and taking $d[n]$ as

$$d[n] = [\underbrace{0\;0\;\ldots\;0}_{N/2}\,\vdots\,\underbrace{1\;0\;0\;\ldots\;0}_{N/2}] \tag{6}$$

and the channel length $L \le N/2$, the two channel impulse responses will be obtained jointly since in this case,

$$\tilde{g}_2[n]\odot d[n] = [\underbrace{0\;0\;\ldots\;0}_{N/2}\,\vdots\,\underbrace{\tilde{g}_2[0]\;\tilde{g}_2[1]\;\ldots\;\tilde{g}_2[L-1]\;0\;0\;\ldots\;0}_{N/2}] \tag{7}$$

and

$$\hat{\tilde{g}}[n] = \tilde{g}_1[n] + \tilde{g}_2[n]\odot d[n] + \dot{v}[n] = \begin{bmatrix}\tilde{g}_1\\ \tilde{g}_2\end{bmatrix} + \dot{v}[n] \tag{8}$$

According to the definition of d[n], it can be proved mathematically that d[n] satisfies (6) if and only if the magnitude and phase of the frequency domain pilot sequence satisfy $|X[k]| = |X[-k]_N|$ and $\varphi_{X[k]} + \varphi_{X[-k]_N} = \pi k$, respectively. Moreover, as indicated in [3] and [5], for equi-powered non-zero pilot tones, i. e. $|X[k]| = |X[-k]_N| = 1$ for all k, the channel estimation error is minimized. Therefore, the pilot sequence designed for this work is optimised following such rules. Furthermore the initial phases of X[k] should be set randomly to minimise peak to average power ratio (PAPR) and thereby reduce non-linear effects.

After the imbalance filter responses are estimated, the I/Q imbalance can be compensated at the transmitter by developing the inverse filter system of the I/Q imbalance baseband equivalent channel. Figure 1(right) illustrates a practical compensator structure, where the widely linear combination of $\hat{\tilde{g}}_1^*[n]$ and $\hat{\tilde{g}}_2[n]$ is used to compensate the I/Q mismatch and the inverse filter of $\tilde{g}_1[n]$ is used to cancel out the non-ideal frequency response of the receiver. Since the parameters of this compensator come directly from the estimated channel impulse responses, this new compensator structure will not suffer from filter stability problem as that proposed in [2], where performance is severely degraded by the truncation of unstable filter response.

4. Laboratory Measurement.

A laboratory test system is set up for verifying the proposed algorithm. The Aeroflex PXI 3025C digital RF signal generator with available bandwidth of 90MHz is used as the I/Q modulator. A PXI 3030C digitizer is used to implement the feedback down-conversion, filtering and sampling. Before introducing the I/Q imbalance compensation algorithm, the IRR of PXI 3025C is around 35dB. Then the pilot sequence as defined above with 64 carriers is loaded to the signal generator for channel estimation. The estimated channel impulse responses are ensemble-averaged over 30 independent runs. After I/Q imbalance compensation, the IRR is greatly improved to 50dB. A comparison of the spectrums between the before and after compensation cases is illustrated in figure 2.

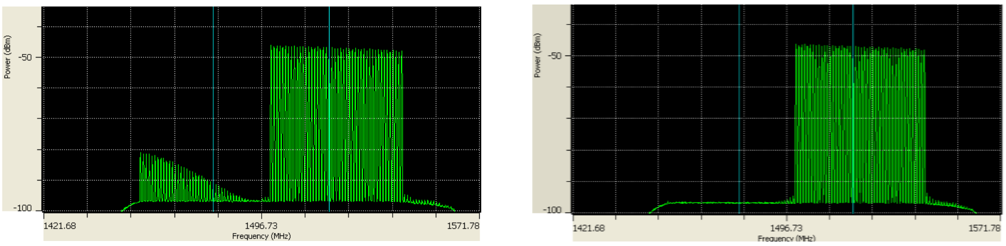

Fig.2. Spectrum average before (left) and after (right) I/Q imbalance compensation

5. Conclusions.

In this paper, a new frequency-dependent I/Q imbalance estimation algorithm has been proposed. Joint channel estimation and an optimised pilot sequence result in a receiver channel estimator design with very low complexity and lowest estimation error. Furthermore, a high performance time-domain compensation structure has been developed to compensate for transmitter frequency-dependent I/Q imbalance as well as cancellation of non-ideal receiver frequency response. The performance of the algorithm was evaluated through laboratory measurements and clearly indicates very good compensation performance.

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