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The Effects of I/Q Imbalance on Wireless Communications: A Survey

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Abstract—**Radio frequency front-ends constitute a core part of both conventional and emerging communication systems. Yet, although hardware realizations practically suffer from several types of impairments that degrade the overall system performance, the corresponding effects are often neglected and transceivers are assumed ideal. This typically refers to effects that are typically related to amplier nonlinearities, phase noise and in phase and quadrature imbalance (IQI), with the latter being among the most critical ones. In this context, this work provides a thorough survey on the effects of IQI, aiming to highlight their important manifestations which depending on the considered scenario can result to destructive and occasionally constructive effects.**

I. INTRODUCTION

The rapid growth of wireless applications has led to the development of flexible and software-configurable transceivers that are capable of meeting the increasingly demanding quality of service requirements. In this context, the concept of direct-conversion for frequency translation is an effective approach since it does not require external intermediate frequency and image rejection filters. Instead, the image rejection is provided by means of signal processing in the in-phase (I) and quadrature (Q) component. As a result, this architecture is more suitable for monolithic integration of the analogue front-end as well as for low-cost overall hardware implementations.

It is recalled that in ideal scenarios, the I and Q branches of a mixer should have equal amplitude and a phase shift of 90°; however, in practice, the direct-conversion transceivers are sensitive to certain analog front-end related impairments. A critical example is the I/Q imbalance (IQI), which refers to the amplitude and phase mismatch between the I and Q branches of a transceiver and leads to imperfect image rejection which results to considerable performance degradation of conventional and emerging communication systems [1] - and the references therein.

II. I/Q IMBALANCE SIGNAL MODEL

A. Single-carrier systems impaired by IQI

In this subsection, we present the mathematical formulation of a signal model for a single-carrier system, in which the transmitter (TX) and/or the receiver (RX) suffers from IQI. To this end, the baseband representation of the IQI impaired signal is given by [2]

$$g_{\text{IQI}} = \mu_{T/R} g_{\text{ideal}} + \nu_{T/R} g^*_{\text{ideal}} \tag{1}$$

where g_{ideal} is the baseband IQI-free signal and g^*_{ideal} stands for the involved IQI effects. Also, the superscripts t/r denote the up/down-conversion process, respectively. Whereas the IQI coefficients $\mu_{T/R}$ and $\nu_{T/R}$ are expressed as follows [3]:

$$\mu_T = \cos(\phi_T) + j\epsilon_T \sin(\phi_T), \tag{2}$$
$$\nu_T = \epsilon_T \cos(\phi_T) + j \sin(\phi_T), \tag{3}$$
$$\mu_R = \cos(\phi_R) - j\epsilon_R \sin(\phi_R) \tag{4}$$

$$\nu_R = \epsilon_R \cos(\phi_R) + j \sin(\phi_R) \tag{5}$$

where $\epsilon^{T/R}$ and $\phi^{T/R}$ account for the TX/RX amplitude and phase mismatch, respectively.

1) TX impaired by IQI: In this scenario, it is assumed that the RX front-end is ideal, while the TX suffers from IQI. From (1), the baseband equivalent transmitted signal is given by

$$s_{\text{IQI}} = \mu_T s + \nu_T s^* \tag{6}$$

where $s(k)$ is the transmitted signal at the k-th carrier. The baseband equivalent received signal is expressed as

$$hs_{IQI} + n = \mu_T hs + \nu_T hs^* + n \tag{7}$$

where $h(k)$ and $n(k)$ are the corresponding channel coefficient and the circular symmetric complex AWGN, respectively.

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2) RX impaired by IQI: In this scenario, it is assumed that the RF front-end of the TX is ideal, while the RX suffers from IQI. From (1), the baseband equivalent received signal is given by

$$r = \mu_R h s + \nu_R h^* s^* + \mu_R n + \nu_R n^*. \tag{8}$$

It is observed from (7) and (8) that, for single carrier transmission, TX IQI impacts the desired signal only causing self-interference from the conjugate of the transmitted signal, whereas RX IQI impacts both the desired signal and the noise.

3) Joint TX/RX impaired by IQI: Unlike the above two cases, in this scenario, it is assumed that both the TX and RX suffer from IQI. Based on (1), it follows that the baseband equivalent received signal is represented as follows [3]:

$$r = \left(\xi_{11} h + \xi_{22} h^*\right) s + \left(\xi_{12} h + \xi_{21} h^*\right) s^* + \mu_R n + \nu_R n^* \tag{9}$$

where

$$\xi_{11} = \mu_R \mu_T, \tag{10}$$

$$\xi_{22} = \nu_R \nu_T^*, \tag{11}$$

$$\xi_{12} = \mu_R \nu_T \tag{12}$$

and

$$\xi_{21} = \nu_R \mu_T^*. \tag{13}$$

It is noted here that according to (6), in direct-conversion transceivers, the IQI effect can be practically viewed as the so-called self-image problem, where the baseband equivalent signal is interfered by its complex conjugate.

B. Multi-carrier systems impaired by IQI

In this subsection, it is assumed that multiple RF carriers are down-converted to the baseband based on the wideband direct-conversion principle, where the RF spectrum is translated to the baseband in a single down-conversion. Based on this, we denote the set of channels as $S_K = \{-K, \cdots, -1, 1, \cdots, K\}$ and the baseband equivalent IQI-free transmitted signal at the subcarrier k as $s(k)$. Furthermore, the parameter $\theta \in \{0, 1\}$ indicates the existence of a signal at channel $-k$. In what follows, we formulate the signal in each subcarrier for the above three realistic scenarios.

1) TX impaired by IQI: In this scenario, it is assumed that the RF front-end of the RX is ideal, while the TX suffers from IQI. Based on this and with the aid of (1), the baseband equivalent transmitted signal in the k^{th} subcarrier is given by [3]

$$s_{\text{IQI}}(k) = \mu_T s(k) + \nu_T s^*(-k) \tag{14}$$

whereas the equivalent received baseband is expressed as

$$r(k) = \mu_T h(k) s(k) + \nu_T h(k) s^*(-k) + n(k). \tag{15}$$

2) RX impaired by IQI: This scenario is opposite to the previous as it is assumed that the RF front-end of the TX is ideal, while the RX suffers from IQI. The baseband equivalent received signal in the k^{th} subcarrier is given by

$$\begin{aligned} r(k) =& \mu_R h(k) s(k) + \theta \nu_R h^*(-k) s^*(-k) \\ &+ \mu_R n(k) + \nu_R n^*(-k). \end{aligned} \tag{16}$$

3) Joint TX/RX impaired by IQI: Last, it is assumed that both the TX and RX suffer from IQI, which constitutes the most realistic scenario in wireless communications. The baseband equivalent received signal in this case is given by

$$\begin{aligned} r(k) =& \left(\xi_{11} h(k) + \xi_{22} h^*(-k)\right) s(k) + \mu_R n(k) + \nu_R n^*(-k) \\ &+ \left(\xi_{12} h(k) + \xi_{21} h^*(-k)\right) s^*(-k). \end{aligned} \tag{17}$$

Based on (17), it is observed that IQI causes the transmitted baseband equivalent signal at the k^{th} subcarrier, $s(k)$, to be distorted by its image signal at the subcarrier $-k$, namely $s^*(-k)$. Therefore, it becomes evident that in a multi-carrier system, IQI results to crosstalk between the mirror frequencies in the down-converted signal [4].

III. EFFECT OF I/Q IMBALANCE ON WIRELESS COMMUNICATIONS

In order to evaluate the performance of both conventional and emerging wireless systems, the effect of hardware impairments should be considered along with the signal distortion during wireless transmission. Due to the detrimental effects that can be caused by this impairment, considerable efforts have been devoted to the estimation and compensation of IQI effects. In [5], [6], a blind non-data-aided digital signal processing compensation algorithm is proposed for single carrier transmission with frequency-independent IQI and multi-carrier transmission with frequency-dependent IQI, respectively. The considered compensation method is effective and is based on the features of complex communication waveforms.

A. Orthogonal Frequency Division Multiplexing (OFDM)

It is recalled that OFDM was introduced to overcome inter-symbol interference (ISI) in multicarrier wireless transmission. This is achieved by converting a wideband, and often frequency selective, channel into multiple narrowband flat fading channels that are orthogonal to each-other. In addition to achieving data rates comparable to single carrier transmission, the orthogonality between the subcarriers in OFDM provides high spectral efficiency since the subcarriers are overlapping without resulting interference. Nevertheless, as mentioned above, in the presence of IQI, the downconverted signal is interfered by the signal at the image frequency, causing detrimental effects that can not be practically neglected particularly in emerging communication systems.

In [4] the authors considered the effects of IQI on the outage probability in N*Nakagami-m cascaded fading channels, which have been shown to provide accurate characterization of multipath fading in mobile scenarios, including the emerging technology of vehicular communications. The subcarrier signal-to-interference-plus-noise-ratio (SINR) expression in case of OFDM systems impaired by IQI is evaluated in [7] for the cases of TX-only IQI, RX-only IQI, and joint TX/RX IQI, with equal levels of IQI at TX and RX. In the same context, the effects of IQI on multi-carrier receivers was investigated in [8], [9]. Specifically, the authors in [8] analyzed the impact of the IQI in the quadrature down-converter on the bit error rate (BER) performance of a OFDM-QAM system, whereas in [9], the received OFDM signals, subject to an I/Q imbalanced transceiver, were derived and a compensation algorithm was proposed. In [10], frequency-dependent RX IQI compensation in OFDM based on the kurtosis criterion is proposed. The authors estimate the IQI parameters isolated from fading channel and use these parameters for time-domain compensation. This approach is motivated by the scenario where the training symbols used for IQI estimation are transmitted from different antenna ports than those used for data transmission.

B. Multiple Input Multiple Output (MIMO)

It is widely known that MIMO systems aim at improving the performance of wireless communication systems by considering multiple antennas at both the TX and the RX sites. These multiple antennas can be exploited in order to reduce the detrimental effects caused by the channel fading or in order to improve the data rate. In this context, the effects of IQI in MIMO systems was investigated in [11] - and references therein. Specifically, the authors in [12] analyzed the performance loss of both TX and RX IQI in a space division multiplexing based MIMO OFDM system where the corresponding symbol error rate were derived for the case of Rayleigh fading channels.

C. Cooperative Communications

In the context of cooperative communications, that are distinct for providing effective spatial diversity, the performance of amplify and forward dual hop relaying was investigated in [13]–[16]. Analytical expressions for the symbol error probability (SEP) over Rayleigh fading channels were derived in [13], [14]. In the former, IQI was assumed at the destination node only, while in the latter IQI was considered at the TX and RX nodes, which ultimately led to the derivation of upper and lower bounds. The authors in [15] considered independent but non-identically distributed Nakagami-m fading and an analytical expression for the OP was derived assuming IQI at the relay's RX and TX, when the source and destination are assumed ideal. Moreover, the case of dual hop opportunistic OFDM in the presence of IQI in all nodes was studied in [16] and the OP was derived considering independent, frequency-selective channels in all wireless links.

D. Cognitive Radio

Cognitive radio is a promising technology that can enhance the performance of wireless communications [17]. The basic concept underlying CR, is that secondary users (SUs) are allowed to access the spectrum, which is assigned to a licensed primary user (PU), opportunistically, for the time period that is not utilized. The CR users perform spectrum sensing, in order to identify idle spectrum. Energy detection (ED) is considered the most common sensing technique due to its low implementation complexity and no requirements for knowledge of the sensed signal. However, other sensing techniques can achieve better performance, which typically comes at a cost of increased complexity [18].

In [19], ED based spectrum sensing in both single channel and multi-channel direct-conversion receiver scenarios impaired by IQI is investigated. This showed that assuming complex Gaussian PU signal model, the single-channel receiver scenario is fairly robust to IQI while the wideband multi-channel sensing receiver is very sensitive to the image channel crosstalk induced by IQI. More precisely, the false alarm probability of multi-channel ED increases significantly, compared to ideal RF receiver case, depending on the image carrier power level and IQI values. Furthermore, the authors propose a waveform level interference cancellation method to mitigate the image channel crosstalk and hence, prevent the performance degradation caused by IQI. In [20], an effective algorithm is proposed based on crosscorrelation of the received signal at subcarrier k and $-k$ where, due to IQI, both contain signals from the desired spectrum and from the harmonic image. In order to allow correct spectrum sensing under conditions where harmonic images are present, a frequency offset is used in the analog front-end to frequency shift the harmonic images and the desired signal by different amounts. In [21] and [22], a three-level and four-level hypothesis blind detector is introduced, respectively. Moreover, the effect of IQI on the detection is studied and it is shown that this detector is less vulnerable to IQI than conventional two-level detectors. Finally, very interesting results have been reported in [3] where the authors derived the likelihood ratio test for OFDM-based CR networks in the presence of IQI at the analog front-ends of both the PU and the SUs. It is shown that TX IQI at the PU improves the likelihood ratio test detection probability at a fixed false alarm probability. In fact, correlation properties of the PU's signal induced by transmit IQI are signal features that can be exploited blindly at the SU to enhance the detection probability significantly compared to the conventional energy detector. Closed-form expressions for the probabilities of detection and false alarm for the ED are derived and compared to the likelihood ratio test where it is shown that the latter performs significantly better. It is noted however that the likelihood ratio test is an ideal detector that requires knowledge of all system parameters, which is not a realistic assumption for CR. Hence, the authors also derived the generalized likelihood ratio test's false alarm probability as a function of the received signal.

E. Full Duplex Radio Transceivers

Full-duplex wireless transceivers, which enable simultaneous transmission and reception of information are receiving increasing attention due to their potential to double the throughput of conventional half-duplex transceivers. However, the challenge with full-duplex radio is how to overcome the corresponding self-interference problem that can be even more powerful than the desired signal. In [23], it is shown that for two TX sharing the same local oscillator, the IQ imbalance-induced residual self-interference has considerably larger power when the two TXs share a common local oscillator and experience the same IQ imbalance as well as when they have different oscillators with distinct IQI, respectively. Moreover, a baseband cancellation signal, generated by the widely linear filtering method, was proposed. Digital cancellation was proposed in [24]–[26] where in [24], a digital widely linear self-interference cancellation scheme is developed while in [25] the cancellation signal is based on the down-conversion of the TX output. In [27], a multi-stage self-interference cancellation scheme consisting of two-stage passive reconstruction based analog cancellation and a final stage of digital cancellation is proposed. Finally, in [26], a measurement-based approach is adopted in order to experimentally identify and isolate these hardware imperfections, including IQI, leading to residual self-interference in full-duplex, while a theoretical model that can provide effective suppression of these effects was also proposed.

F. Diversity Gain via IQI

While most works on IQI have showed its detrimental effects and attempted to compensate it, TX IQI can be also treated as a source of transmit diversity which can be exploited using maximum likelihood (ML) detection. This contribution was recently reported in [28] and [29] where the authors show via simulations and analysis, respectively, that performance gain can be achieved with the diversity gain caused by the IQI combined with the frequency selective channels when ML and ordered successive interference cancellation are employed. Finally, in [30] the authors coordinate the self-interference caused by RX IQI in order to achieve frequency diversity. Specifically, the authors have managed to eliminate the self interference term caused by IQI and achieve a diversity order of two in the context of transmission over two consecutive time symbols or two frequency bands.

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