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Self-interference cancellation in full-duplex wireless with IQ imbalance

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ABSTRACT

To achieve full-duplex wireless communication, the most essential issue is to eliminate in-band self-interference caused by simultaneous transmission and reception. In this paper, we investigate the impact of transmitter IQ imbalance on digital signal processing (DSP)-assisted analog self-interference cancellation, where two transmitters are used for transmission and cancellation, respectively. Our result implies that the transmitter IQ imbalance results in residual self-interference after conventional DSP-assisted analog cancellation, which still has a much higher power compared to the desired signal. Then, a baseband cancellation signal generated by widely linear (WL) filtering is proposed to effectively handle the transmitter IQ imbalance, and the optimal WL filter and the adaptive algorithm to obtain them can be derived. The impact of receiver IQ imbalance on the proposed adaptive algorithm is analyzed, and we show that the algorithm is capable of obtaining the same optimal WL filter despite receiver IQ imbalance. In addition, for practical implementation, we propose an adaptive algorithm based on the augmented complex least mean squares (ACLMS) method to obtain the WL filter, where no information about the transmitter and receiver IQ imbalances is needed. The steady state behaviors of the proposed adaptive algorithms are analyzed and the performance bounds are derived. Numerical simulation results confirm the validity and superior performance of the proposed ACLMS algorithm in various practical scenarios of transmitter and receiver IQ imbalances. Also, the tolerance of the proposed algorithm to other transceiver impairments was investigated using simulations.

1. Introduction

For a long time, wireless communication was recognized to be half-duplex only, due to severe self-interference arisen from simultaneous transmission and reception. Time-division duplex and frequency-division duplex are two popular half-duplex schemes in current wireless communications systems. Owing to its ability to double the throughput, full-duplex wireless communication has recently attracted great attention. The fundamental issue in full-duplex wireless communication is the mitigation of self-interference [1,2]. Self-interference is basically the loopback of a transmitted signal at the receiver, whose power is usually about 110 dB stronger than that of the desired signal sent by a far-end transmitter. Therefore, self-interference mitigation prior to the low noise amplifier (LNA) is necessary to avoid receiver circuit saturation [3]. Self-interference is caused by circuit leakage, impedance mismatch, and reflection of the transmitted signal. While the former two can be eliminated with careful circuit design, the latter is inherently unavoidable.

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Many self-interference elimination methods have been proposed in the literature. These can generally be categorized into two types: suppression and cancellation. Self-interference suppression, sometimes also called passive cancellation, aims to attenuate the power of the self-interference signal arriving at the receiving antenna. The antenna separation was proposed in [2,4], where the transmitting and receiving antennas were separated as far as possible. However, limited by the available physical space, the suppression performance of these methods is only up to 40 dB, which is not sufficient. On the other hand, spatial suppression approaches using multiple antennas were proposed in [1,5–7]. The method in [1] is based on antenna placement, where the receiving antenna is intentionally located at the destructive interference point of two transmitting antennas. The beamforming-based approaches in [5,6] depend greatly on the loopback channel matrix. Therefore, they risk not only creating an undesired null-point at the far-end receiver, but also sacrificing the capacity contributed by multiple antennas. A detailed investigation of suppression methods can be found in [4].

In addition to suppression, self-interference cancellation is still necessary for sufficient elimination. Different from suppression, cancellation generates a replica of the self-interference, and then cancels it out at the receiver. Depending on the generated replica, the cancellation can be performed in the analog or digital domain. In [8], analog cancellation using a Balun circuit, variable delay lines, and RF attenuators was proposed. This was later extended to fixed delay lines in [9,10]. The distillate of these methods is to use RF components (RFCs) to simulate the loopback channel. On the other hand, in DSP-assisted analog cancellation [2,11–14], the cancellation signal is first generated digitally in the baseband, and then upconverted using an extra transmitter to form the analog cancellation signal. These two kinds of analog cancellation approaches have their own advantages and disadvantages. The RFCs are relatively expensive, and it is not easy to tune them to precisely match the loopback channel. Usually, the RFC-based analog cancellation aims to merely cancel a major part of self-interference, for example, that caused by the main path of the loopback channel. Afterwards, the desired signal mixed with the residual interference is down-converted, and then digital cancellation is subsequently applied to the output of the analog-to-digital converter (ADC) to eliminate the residual interference [8,9]. At the price of complexity and cost, the combination of the RFC-based analog cancellation and digital cancellation can achieve high total cancellation performance [8,9]. In contrast, the reconfiguration of the cancellation signal according to the loopback channel is simple in the DSP-assisted approach. Moreover, since it can be easily implemented by adding a conventional transmit chain, it results in a smaller circuit area and a lower cost. A possible drawback of the DSP-assisted approach is that although it has the potential to improve the performance, a better analog cancellation does not necessarily lead to a better total cancellation when considering together with digital cancellation [11]. Nevertheless, the self-interference cancellation is naturally analog, and if we have a perfect analog cancellation before the LNA, digital cancellation can be omitted and an ordinary receiver can work fine. In practice, a compromise among complexity, cost and performance is necessary to choose a suitable cancellation scheme.

It is known that circuit impairments at the transceiver can severely limit the performance of full-duplex wireless systems [7,15]. Therefore, this should be considered in a practical design. Major circuit impairments include non-linearity, phase noise, and IQ imbalance. The non-linearity is largely caused by power amplifiers (PA) and limited ADC dynamic range, while phase noise and IQ imbalance are mainly induced by imperfect local oscillators (LO). The impact of non-linear distortion in full-duplex wireless communication has been investigated and reported in [16–19], while the effect of phase noise was analyzed in [10,20–22]. It is shown that the non-linearity and the phase noise can degrade the performance of self-interference cancellation, and the corresponding solutions can be found in [16,18,23,24]. Since the IQ imbalance is essentially the mismatch between in-phase and quadrature signals, it results in an image interference with the original signal [25]. Taking this additional image interference into account, self-interference cancellation in the presence of transmitter (Tx) IQ imbalance is studied in [26,27]. In [26], the cancellation signal is based on the down-conversion of the immediate Tx output, while a WL digital cancellation signal is proposed in [27]. However, these two methods are in effect digital cancellation, which requires effective analog cancellation in advance. On the other hand, although the receiver (Rx) IQ imbalance is considered in [10], the proposed cancellation scheme is costly to implement, due to the requirement of multiple down-converters for each tap of the loopback channel.

Because of its high flexibility, in this paper, we focus on the DSP-assisted analog cancellation scheme previously proposed in [2,11–14]. Special attention should be paid in this scheme, since there are two Txs for transmission and cancellation, respectively, and the impact of circuit impairments may be significant. In this paper, we focus on the signal distortion caused by transceiver IQ imbalance in this DSP-assisted analog cancellation. Note that although we neglect other circuit impairments for the sake of analysis, their influence will be investigated later using simulations. In our previous work [28], we have shown that Tx IQ imbalance-induced residual self-interference has considerably larger power when the two Txs share a common LO and experience the same IQ imbalance. However, even for this shared LO design, the mismatch of the circuit path may still cause differently biased LO signals. Therefore, in this paper, the more general case of two Txs having different IQ imbalance is considered. Since the Txs signals become improper due to IQ imbalance, like [28], the WL filtering method [29] which can effectively handle the improper signal, is employed to generate the baseband representation of the analog cancellation signal. Then, the optimal WL filter are derived in closed-form and the corresponding adaptive algorithm is given. The impact of Rx IQ imbalance on the adaptive algorithm is studied, and we will show that the adaptive algorithm can obtain the same optimal WL filter, even in the presence of Rx IQ imbalance. This adaptive algorithm is developed with known IQ imbalances, which however, is difficult to obtain when both Tx and Rx imbalances are present. Therefore, for practical implementation, an algorithm based on the ACLMS method