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Wideband full-duplex MIMO relays with blind adaptive self-interference cancellation

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ABSTRACT

We develop adaptive self-interference cancellation algorithms for both filter-and-forward and decode-and-forward multiple-input multiple-output relays. The algorithms are blind in the sense that they only exploit the spectral properties of the transmitted signal to identify the self-interference channel, while dealing with frequency-selective channels and arbitrary signal spectra. Our approach is non-intrusive in the sense that the algorithms can successfully identify, track, and cancel the self-interference distortion while the relay is operating in its normal mode. We study the stationary points of the algorithms and analyze under which conditions they achieve perfect cancellation of the self-interference. Simulation results show that the algorithms provide residual self-interference levels below the noise floor by using the time samples of only a few OFDM symbols.

1. Introduction

MIMO techniques, such as diversity schemes or spatial multiplexing, can provide high system throughput in a bandwidth-efficient manner [1]. However, extending network coverage while preserving consistent performance can be resource-demanding and, therefore, *in-band relaying* offers an attractive alternative for coverage extension due to the relaxed requirements for extra bandwidth usage [2,3]. This paper concerns MIMO relays, which, as part of a MIMO link, are equipped with antenna arrays at both the transmit and receive sides to support end-to-end multistream communication.

Based on the employed transmission protocol, relays are usually classified as either filter-and-forward (FF) relays, of which amplify-and-forward (AF) is particular case, or decode-and-forward (DF) relays [4]. While FF relays simply forward the message, after some basic processing [5,6], to the next network element without awareness of the data content, DF relays process the message and regenerate/re-encode the source data streams [7,8]. As a consequence, DF relays generally yield better performance than FF relays [9,10]. Relays can be further grouped into half-duplex (HD) or full-duplex (FD) relays. In particular, HD relays use orthogonal resources for transmission and reception, whereas FD relays share a common resource for both processes. For example, when in-band relaying is used, HD relays must designate two non-overlapping time slots: one for reception and one for transmission. On the other hand, FD relays can receive and transmit at the same time, thus achieving higher data rates (approximately double) or higher spectral efficiency than HD relays [11,12].

Full-duplex transmission introduces a new form of distortion caused by the relay itself, so-called *self-interference* (SI), wherein the transmitted signal loops back into the receive side. In particular, when both antenna arrays are closely located, the power imbalance between the transmitted signal and the signal received from the source can be high. As a consequence, we may end up with a scenario where the SI power at the relay input can be up to 100 dB higher than the information-bearing signal power, rendering the relay useless [13–16]. Therefore, to realize maximum performance of the FD relay network, efficient SI mitigation techniques must be employed at the relay.

1.1. Self-interference mitigation methods

The different SI mitigation techniques found in the literature can be classified into the following three categories [17]:

1. *Isolation methods* [13,18,19] reduce SI power by optimizing the

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radiation pattern and improving the passive electromagnetic isolation between antenna arrays. Although isolation can reduce the interference by tens of decibels, the remaining residual SI in the system is likely high enough to affect the performance. Therefore, isolation techniques are typically used together with active analog and/or digital signal processing techniques that further reduce the residual interference.
2. *Spatial-domain suppression methods* [17,20–23] exploit the degrees of freedom offered by multiple antennas to reduce the SI signal. For example, the signal may be transmitted in the nullspace of the SI channel, which ideally results in an interference-free signal at the receive side of the relay.
3. *Time-domain interference cancellation methods* [16,17,23–33] create a replica of the interference signal and subtract it from the relay input. Ideally, through an estimate of the SI channel, the residual SI will be negligible. Time-domain cancellation can be applied both in the analog domain to avoid glitches during analog-to-digital (A/D) conversion and in the digital domain to effectively cancel the remaining interference in the presence of multipath propagation.

The spatial suppression methods mentioned above [17,20–23] assume the explicit knowledge of the SI path. This is normally solved by means of an external estimation method or taking advantage of a pilot scheme embedded in the signal, which requires some processing in the frequency domain. Such approach only makes sense in a DF relay, where the signal is being regenerated. This not only intensify the computing requirements of the system, because each subcarrier should be treated independently, but also introduces an unavoidable delay due to the required demodulation/modulation process. Any additional delay can be harmful at the destination if the relative delay between the signal coming from the relay and the signal coming from the source exceeds the cyclic prefix length. Therefore, a shorter delay in the relay may result in better performance. In this work, we take a time-domain approach to reduce the processing delay by avoiding the demodulation/modulation to/from the frequency domain.

The time-domain cancellation methods presented in [25–28] are restricted to work in a single-stream transmission. In [26–28], an additional delay is introduced to perform the cancellation. As explained before, when the network uses OFDM any additional delay can be harmful. In [29,30], a training-based cancellation method is proposed that disrupts the relay transmission, with the consequent data rate loss. If the relay is used for coverage extension, interrupting the transmission to redesign the interference canceller is not feasible. The use of a training sequence of a pilot embedded scheme introduces another implementation problem: the relay needs to be synchronized with the network, which, specially in the FF case, might not be possible. The use of blind techniques is convenient and in some cases the viable only option. In this work, we propose mitigation blind algorithms that do not introduce delay and do not require the use of any training sequence.

The implementation of the mitigation scheme follows one of the following categories: on-line or adaptive solutions and off-line or closed-form solutions. Whereas in the DF case an off-line solution is feasible (we provide a recursive implementation of an off-line solution), the nature of the problem does not allow to use a closed-form expression in the FF case. This limits the possible FF solutions to iterative processes, from which an adaptive solution is a natural choice. An adaptive solution has some advantages when compared to its off-line counterpart, e.g., reduced computational load per sample, zero processing delay (the adaptation is performed as samples arrive with no buffering required), and the ability to track time variations of the environment.

Finally, the mitigation scheme should not affect the relay normal operation. The link design is significantly simpler when assuming no self-interference at the relay and, therefore, it is important that self-interference is removed before any further processing of the received signal [17]. Our mitigation techniques are transparent to the relay operation and delivers a below-noise-level interference signal within the relay.

1.2. Contributions of the paper

This paper focuses on *low latency adaptive SI mitigation solutions for multistream relay networks*.[1] For this purpose, blind time-domain adaptive cancellation algorithms are proposed that effectively cope with SI. Our algorithms can be classified into stochastic gradient descent based algorithms and recursive least-squares based algorithms, and they are tailored separately for both FF and DF relays. The proposed algorithms can deal with arbitrary signal spectra and frequency-selective channels by exploiting statistical information about the source signal.

When considering OFDM relays, the proposed algorithms serve as attractive alternatives to frequency-domain methods, e.g., [17,20–23], since the computational load is independent of the number of subcarriers. The algorithms also feature spectrally efficient implementation, since the estimation of the SI path requires only statistical information of the source signal. That is, no external estimation method or dedicated pilot scheme is required. This feature allows the algorithms to perform the interference mitigation without disrupting the relay's normal operation. Furthermore, the algorithms can efficiently cope with spatio-temporal inter-symbol interference (ISI), while previously mentioned methods only consider spatial ISI.

Preliminary results pertaining to stochastic gradient implementations have appeared in [32] (FF case) and [33] (DF case). The associated material for the current paper has been rewritten and significantly extended. In addition, we present and analyze the stationary points of two new recursive least-squares based algorithms that feature faster convergence and improved performance when compared to their stochastic gradient counterparts. The analysis presented herein is more thorough and the bias problem associated with MIMO FF relays is discussed in more detail.

1.3. Organization of the paper

The paper is organized as follows. Section 2 describes the system model of the considered relay network, discusses the impact of the SI in the system, and introduces the MIMO SI cancellation architecture. Section 3 addresses the problem of SI for a MIMO DF relay and derives gradient descent based and recursive least-squares based algorithms that effectively cancels the SI by using a power minimization approach. In this section we also provide details on algorithm convergence and stationary points. Section 4 describes the bias problem originating from using a power minimization approach in a MIMO FF relay. Bias-corrected adaptive algorithms for SI cancellation and channel compensation are presented and stationary points are analyzed. Section 5 illustrates the performance of the proposed algorithms for an OFDM relay system, whereas Section 6 draws the conclusions.

1.4. Notation

Let $\mathbf{H}[n] = \sum_{k=0}^{L_{\mathrm{H}}} \mathbf{H}(k)\delta[n-k]$ denote an L_{H}th-order linear time-invariant causal filter of size $M \times N$ and coefficients $\{\mathbf{H}(k)\}_{k=0}^{L_{\mathrm{H}}}$. Let $\mathbf{x}[n]$ denote a signal vector of size $N \times 1$. The result of filtering $\mathbf{x}[n]$

[1] By latency we mean any additional delay introduced by the self-interference mitigation scheme in the source–destination link.