Recent Advances in Full-Duplex Relaying

Taneli Riihonen

Aalto University School of Electrical Engineering
Center of Excellence in Smart Radios and Wireless Research
P.O. Box 13000, FI-00076 Aalto, Finland
taneli.riihonen@aalto.fi

Abstract

This presentation provides an overview of essential aspects to be considered when introducing full-duplex operation into relaying systems. Firstly, the unavoidable self-interference is mitigated by passive isolation, active cancellation and beamforming-based suppression as well as transmit power adaptation. Secondly, the feasibility of full-duplex operation in the presence of residual self-interference is determined by comparing it to reference half-duplex systems.

1 Introduction

Full duplex is a hot emerging research topic and a progressive concept which may bring a paradigm shift to wireless communications, revolutionizing the way how the next-generation systems are designed and operated. In principle, full duplex facilitates frequency reuse by employing radios that can receive and transmit simultaneously on a single frequency band. Hence, full duplex is sometimes descriptively referred to as single-frequency "*simultaneous transmit and receive*" (STAR). Such operation was considered to be impossible until recently researchers have started to question their premises and genuine drive has arisen to make full duplex reality. All conventional communication systems apply *half duplex* in the form of time-division and/or frequency-division duplex (TDD and/or FDD) such that each radio transmits and receives always at different time slots and/or frequency bands. Herein, the main scope is on *relaying*, which can be regarded as the first candidate for adopting full duplex. The general concept itself is already well established and famous from the field of cooperative communications, but practical relay links have resorted to TDD or FDD until now. Other potential applications for full duplex are bidirectional communication between two full-duplex terminals and a full-duplex access point (or a base station) serving downlink user simultaneously with an uplink user, both of them operating in the half-duplex mode.

This presentation is an overview of the author's work on full-duplex relaying in 2008–2011. The results were originally published in multiple journal and conference papers [1–12]. In particular, this presentation provides a tutorial to essential aspects that need to be considered when introducing full-duplex operation into multihop relaying systems such as the one illustrated in Fig. 1. Special attention is also paid to merge full-duplex communication with orthogonal frequency-division multiplexing (OFDM) and multiple-input multiple-output (MIMO) techniques.

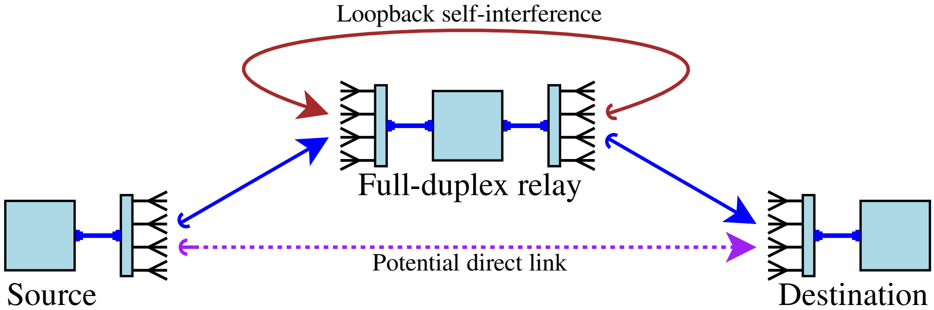

Fig. 1: Two-hop full-duplex multiantenna relay link.

2 Full-Duplex Relaying

The general purpose of any *relay* is to route signals from a source transmitter to a destination receiver as illustrated in Fig. 1; this three-node system is the baseline relaying scenario while other network topologies, e.g., those having multiple hops or parallel relays, are also possible. More specific *full-duplex relays* receive and transmit simultaneously such that source–relay and relay–destination transmissions share the same frequency band. In their simplest form, such devices can be just on-channel repeaters which are already used as gap-fillers in digital television broadcasting and as cellular signal boosters. Actually, some early works thus refer to full-duplex relaying as "*single-frequency relaying*" due to its origins in single-frequency networks (SFNs). However, it should be noted that general full-duplex relays can implement more sophisticated protocols than pure analog amplification, e.g., decode-and-forward (DF) signal regeneration is feasible.

The existence of a *direct link* between the source and the destination (see Fig. 1) draws a line between two different applications for relays: a) *coverage extension* where the relay is deployed because the direct link is weak; b) *diversity improvement* where transmission from both the relay and the source should be strong at the destination. The more potential application for full duplex is coverage extension since half-duplex relays can already offer the maximum available diversity gain while rate gain given by full-duplex relaying becomes marginal if the direct link is strong.

Ideally, full duplex can render up to double spectral efficiency when compared to conventional half-duplex operation. Obviously, the largest gains are attained when the two simultaneous communication directions use the channel for the same amount of time. Therefore, relay links are good candidates for adopting full duplex due to their inherent symmetry: a relay must receive and transmit the same amount of data (in the long run) to avoid overflow or underflow. This renders equal *requested* transmission rates in the two communication directions, but the relay link may still be subject to channel imbalance due to which the *achieved* transmission rates are not the same.

3 Mitigation of Loopback Self-interference

However, full-duplex operation is possible only after tackling a significant technical challenge: unavoidable *self-interference* due to relay's output looping back to its input as shown in Fig. 1. Due to the huge difference of power levels (interference vs. the signal of interest), full duplex is adopted first for fixed infrastructure-based nodes and later for small portable, or even handheld, radios. This makes the concept of full-duplex relaying essentially different from cooperative communication among mobile nodes where half-duplex (usually TDD) operation is the baseline assumption.

First of all, the self-interference needs to be mitigated by *passive isolation* which can be improved by deploying two separate antennas (or antenna arrays): one for receiving and the other for transmitting. Actually, also half-duplex relay links benefit from the use of two antenna arrays since typically the source and the destination are located at approximately opposite directions which facilitates separate optimization for antenna directionality and placement. Otherwise, the physical isolation is provided only by a circulator connecting receiver and transmitter circuitry to a single antenna, but their electrical design is not yet good enough for communication purposes.

Once receiver saturation is avoided with sufficient passive isolation, the relay may apply *active mitigation* schemes such as subtractive *cancellation* in analog or digital domain and beamforming-based *suppression*, e.g., antenna or eigenbeam selection, null-space projection and minimum mean square error (MMSE) filtering. In some cases, it is beneficial to combine time-domain cancellation and spatial suppression. Reasonable objective is the transparent minimization of the interference level such that the relay protocol can be implemented as if it operated in a half-duplex mode but at twice the symbol rate. Thereby, mitigation becomes separated from the protocol design and the developed schemes are applicable with all kinds of relaying protocols. In fact, the solutions are not even limited to relaying systems but they could be used in all full-duplex transceivers.

However, it is concluded that, in practice, there will always be *residual self-interference* after applying all means of mitigation, e.g., due to channel estimation errors and non-ideal transceiver components introducing unknown transmit-side noise. Fortunately, its effect can be still minimized by proper *transmit power adaptation*, i.e., gain control in the context of so-called amplify-and-forward (AF) relays. Transmit power adaptation exploits channel imbalance due to residual self-interference: in principle, the relay should appropriately lower its own transmit power, thus relieving the interference situation, if the first hop is the bottleneck of the system. Actually, this is often the practical case due to self-interference which means that relays may rarely use their maximum allowed transmit power. In fact, transmit power adaptation is a sort of win–win solution for the problem: energy savings can be achieved together with performance optimization.

4 Full Duplex vs. Half Duplex

The ultimate feasibility of full-duplex relaying in the presence of residual self-interference can be determined by comparing it to reference half-duplex systems. Such comparison reflects the fundamental *rate–interference trade-off* to choose whether to decrease the signal-to-interference and noise ratio or to avoid the self-interference completely at the cost of reducing the end-to-end symbol rate. It should be noted that transmit power adaptation changes the trade-off essentially, because it modifies the channel imbalance to the advantage of full duplex, and that the results summarized next are general since both common relaying protocols, AF as well as DF, are covered.

Achievable transmission rate is an obvious metric for the comparison since the main incentive for phasing out half duplex comes from improved spectral efficiency, but similar analysis can be done also in terms of outage probability. The comparison yields switching boundaries between the modes according to channel imbalance. They can be designed based on instantaneous channel states (fast fading) or long-term channel gains (path loss and slow shadow-fading). An important reference case is pure direct link transmission because the relay may not occasionally be needed after all. Finally, it is noted that, instead of adhering to any mode at early design stage, it is advantageous to implement *hybrid full-duplex/half-duplex relaying*, i.e., opportunistic switching between the modes, because the trade-off favors them alternately during operation.

5 Conclusions and Future Work

In the future, specific schemes for the *joint design of mitigation and relaying protocol* could be studied as they are expected to bring performance gain. Likewise, the possibility to exploit the *direct link as an additional diversity branch* deserves also further study; instead of just switching between direct transmission and relaying, the destination could apply signal processing techniques to separate and constructively combine the superimposed signals from the source and the relay.

The advances in full-duplex communication began from relaying but extensions to other communication scenarios are expected soon. The next candidates are *full-duplex two-way communication* and *full-duplex access points* for simultaneous downlink transmission and uplink reception. In a broader scope, it is noted that full duplex is so far exploited mainly at the physical layer for frequency reuse while its other uses are not yet completely understood. For example, enabling *simultaneous sensing and transmission* could be very useful for the medium access control (MAC) layer, e.g., to combat the *hidden terminal problem* or to facilitate *cognitive radio* applications.

Finally, it can be speculated that the main limitation for successful full-duplex operation is set by the *dynamic range* of the receiver due to finite resolution in its analog-to-digital (A/D) interface. In principle, receiver saturation would render any digital-domain interference mitigation technique useless. Thus, self-interference mitigation at analog domain requires further study. For example, transmit-side beamforming can be used to eliminate the interference “on-the-air” before it even reaches the receiver front-end. These issues are central for all kinds of full-duplex transceivers.

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