Enabling Practical Full-Duplex Wireless: From Circuits to Software

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Abstract

Full-duplex (FD) wireless has the potential to double wireless capacity by enabling simultaneous transmission and reception on the same frequency channel. However, its practical implementation remains elusive due to two key challenges: the presence of extremely strong, time-varying self-interference (SI), and the logistical difficulties of integrating the requisite SI cancellation mechanisms into functional transceivers. My research addresses both challenges through the co-design of a hardware- and software-based cancellation and communication framework, resulting in a wideband adaptive FD radio that incorporates an analog RFIC canceller and its FPGA-based optimization algorithm into a software-defined radio (SDR) communication chain. The design considerations learned from this development lend themselves to a replicable conceptual framework for practical SDR-based FD transceivers, bridging the gap between custom IC-based analog hardware and software-defined experimentation.

CCS Concepts

• **Hardware → Wireless devices**; *Radio frequency and wireless circuits*; • **Networks → Network architectures**; **Network experimentation**; **Wireless access networks**.

Keywords

Full-duplex wireless, software-defined radios, self-interference cancellation, adaptive optimization, open-access experimentation

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1 Introduction

As wireless traffic grows exponentially and significantly more devices compete for network resources, the next generation of communications infrastructure requires a radical rethinking. A promising solution that has received focus in recent years is *full-duplex* (FD) wireless, a paradigm by which devices transmit and receive simultaneously on the same frequency channel, as shown in Figure 1. If implemented successfully, FD wireless promises to double wireless capacity compared to existing wireless networks [4].

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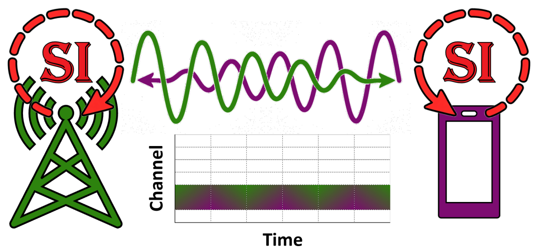

Figure 1: Under FD operation, two devices transmit and receive simultaneously on the same frequency channel, doubling wireless capacity at the cost of very strong SI.

Meaningful advances over the past decade have provided insight into critical components of FD wireless; nevertheless, the translation from academic works to practical implementations capable of operating in real-world conditions notably lags. Two main challenges prevent the adoption of FD into existing wireless standards: (i) the presence of extremely strong, time-varying *self-interference* (SI) from the radio's transmitter (Tx) to its receiver (Rx), requiring a multilayered adaptive *SI cancellation* (SIC) system to extract the desired signal; and (ii) the logistical challenges of integrating such SIC mechanisms into functional transceivers without impairing their ability to communicate over an actual FD link.

I aim to address both by co-designing a hardware- and software-based cancellation and communication framework to advance FD wireless from proof-of-concept to practical deployment. In this extended abstract, I present a wideband adaptive FD radio capable of achieving robust SIC across diverse electromagnetic environments [1, 2], the development of which yielded insight into the design considerations and implementation techniques necessary to integrate IC-based FD frontends with software-defined radio (SDR) platforms to operate within a functional communication link [3].

2 Adaptive Wideband SI Cancellation

Recent works have employed a multi-domain approach to achieving sufficient SIC, including passive antenna interface isolation, active analog cancellation through specialized frontend circuitry, and digital cancellation algorithms. The analog stages are crucial to prevent saturation at the Rx and, in turn, desensitization stemming from the extreme power disparity between the SI and the desired signal. Achieving sufficient analog SIC is difficult even at relatively narrow bandwidths, and performance degrades sharply as the bandwidth is increased. To address this, focus has shifted to increasingly complex RF integrated circuit (RFIC) architectures with large numbers of independent parameters to model the multipath SI channel. However, this complexity comes at a cost: precisely configuring these parameters is challenging due to the exponentially large configuration space and the timing constraints of the dynamic SI channel.

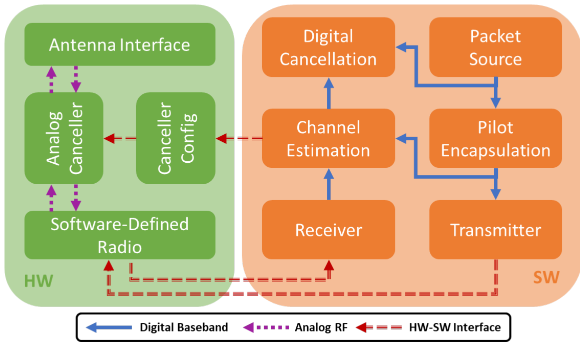

Figure 2: Conceptual framework for a practical FD transceiver. The hardware domain (left) consists of the RF chain and analog SIC; the software domain (right) implements digital processing and adaptive control.

In this context, I integrated a time-domain RFIC canceller, consisting of sixteen taps with independently programmable gains and delays and over 10^{19} delay-selection options, as the RF frontend of an SDR-based FD transceiver. Given the impracticality of a brute force algorithm for optimally configuring the canceller, I instead considered an approach that would (i) reflect the device-specific performance of the canceller, and (ii) leverage the inherent sparsity of the canceller's operating principles. We developed an FPGA-based two-stage optimization process consisting of an initial sparse reconstruction-based selection of gain and delay settings, followed by multiple iterations of gradient descent-based fine-tuning. Both stages employed offline characterizations of the individual canceller taps for the optimization, using regular SI channel estimates obtained from packets transmitted by the SDR and received as SI.

We showcased the system's adaptive capabilities in two demonstrations. In [2], we established an end-to-end adaptive cancellation pipeline that included, in addition to the proposed analog canceller optimization, a circulator-based antenna interface and linear digital SIC, achieving noise floor-level cancellation over a 50 MHz bandwidth. Subsequently, in [1], we showed the system's capacity to adapt to varying electromagnetic environments, ranging from a simple anechoic chamber to a highly complex scenario with multiple nearby reflectors. These demonstrations thus establish a practical, hardware-validated foundation for adaptive FD wireless, realized through the successful integration of a dedicated RFIC canceller into an SDR-based communication chain.

3 Software-Defined FD Communication

Fundamental to the performance of the wideband adaptive FD radio were the dedicated software-based signal processing and control processes operating on a host PC and interacting with the FPGA and the SDR. Drawing on three generations of SDR-based FD radio development, we developed a conceptual framework for a practical FD transceiver architecture, as shown in Figure 2, and presented an overview of the design considerations and implementation techniques for realizing FD wireless in GNU Radio [3].

A major component of this architecture is the interplay between the communications and the adaptive SIC aspects of the system. On the transmit side, data packets are encapsulated with unique pilot symbols that allow for both robust synchronization and accurate SI channel estimation. As packets are received, their pilots are fed into a channel estimator whose measurements drive both the analog canceller optimization and digital SIC applied to the data payload, with the overall end-to-end SIC converging to a maximum over multiple iterations to reveal the desired incoming signal.

Coordinating all of these functions requires a single centralized controller block, which communicates control messages to and from the various hardware and software components of the system. Through this orchestration mechanism, the FD radio gains the flexibility to operate in various regimes, including fixed hardware configuration states, environment-aware optimization schemes designed for mobility, and hardware error recovery processes.

With this framework in mind, a broad range of experimentation can now become available for evaluating the performance of FD systems under real-world conditions, from novel SIC approaches to higher-layer protocol design. Particularly, the integration of AI-driven optimization into adaptive FD systems presents a promising direction, with the potential to further improve cancellation performance and adaptability in dynamic environments. To enable this, I am working on extending this framework into an open-source GNU Radio library with open-access hardware on the COSMOS testbed, providing the broader research community with the tools necessary to accelerate the path toward practical FD wireless.

Biography

Alon S. Levin is a fifth-year PhD candidate in Electrical Engineering at Columbia University, advised by Prof. Gil Zussman at the Wireless and Mobile Networking (WiMNet) Lab. He has received the NDSEG Fellowship, the Columbia Engineering Byron Fellowship, and First Place in the 2023 ACM SIGCOMM Student Research Competition. His research interests are in next-generation communications systems, with a focus on adaptive full-duplex wireless.

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