Experimentation with Full-Duplex Wireless in the COSMOS Testbed

Tingjun Chen*, Jackson Welles*, Manav Kohli*, Mahmood Baraani Dastjerdi*, Jakub Kolodziejski†, Michael Sherman†, Ivan Seskar†, Harish Krishnaswamy*, and Gil Zussman*

*Electrical Engineering, Columbia University; † WINLAB, Rutgers University

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Outline

• COSMOS Overview

• Full-Duplex Wireless

• Compact Wideband Full-Duplex Wireless

• Integration with COSMOS
COSMOS architecture has been developed to realize ultra-high BW, low latency and tightly coupled edge computing.

Key design challenge: Gbps performance + full programmability at the radio level.

Developed a fully programmable multi-layered (i.e. radio, network and cloud) system architecture for flexible experimentation.

Supported technologies include: CRAN, Edge Cloud, mmWave.
COSMOS Testbed Deployment Vision

- West Harlem, area: ~1 sq. mile
- Fiber optic connection from most sites
- ~200 Small nodes
  - Including vehicular and hand-held
- Two sandboxes (Rutgers, Columbia)
  - Internal environments for controlled experimentation
COSMOS Experimental Research and Example

• Internal “Test Experiments” to help drive design requirements

• Experiment on Full-Duplex Wireless

FlexICoN

(Columbia, Krishnaswamy & Zussman)

• FlexICoN project: design and evaluate algorithms and protocols across various layers of the network stack (PHY, MAC and above) for IC-based full-duplex nodes

• Goals:
  • Make our customized hardware available for researchers to use for the design and evaluation of higher-layer algorithms and protocols suitable for full-duplex and heterogenous networks
  • Demonstrate successful installation of customized experimental hardware into COSMOS

Gen-2 wideband full-duplex radio integrated into COSMOS

Gen-2 canceller box
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**Full-Duplex Wireless**

- Legacy half-duplex (HD) wireless systems separate *transmission* and *reception* in either:
  - Time: Time Division Duplex (TDD)
  - Frequency: Frequency Division Duplex (FDD)

- (In-band) Full-duplex (FD) wireless: simultaneous *transmission* and *reception* on the same frequency channel

$$f_{TX} = f_{RX}$$

![TDD Diagram](TDD.png)

![FDD Diagram](FDD.png)

![Full-Duplex (FD) Diagram](FD.png)
Full-Duplex Wireless

- Benefits of full-duplex wireless:
  - Increased system throughput and reduced latency
  - More flexible use of the wireless spectrum

- Viability is limited by self-interference (SI)
  - Transmitted signal is billions of times \((10^9 \text{ or } 90 \text{ dB})\) stronger than the received signal
  - Requiring extremely powerful self-interference cancellation (SIC) across antenna, RF, and digital domains
How much is 90dB?

Self-interference (SI) X100
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Prior Work

- Challenges and opportunities of FD wireless [Sabharwal et al. 2014]
- Time-domain delay line-based wideband RF cancellers, where each fixed delay is associated with
  - One amplitude control [Bharadia et al. 2013], One amplitude control and one phase control [Korpi et al. 2016]
  - Multiple delay lines are combined to enhance performance
- A frequency-flat amplitude and phase-based analog self-interference (SI) canceller (Gen-1)
  - Integrated into ORBIT testbed alongside an NI USRP software-defined radio (SDR) for experimental evaluation

![Gen-1 RF SI C canceller](image1)
![Chip photo](image2)
![Self-Interference Cancellation (SIC) measurement](image3)

Compact Wideband Full-Duplex Wireless

- Delay line-based cancellers are not always suitable for compact IC-based implementations
  - Difficult to implement long delay lines in ICs due to space constraints

- **Main idea based on frequency-domain equalization (FDE):** The self-interference (SI) channel can be emulated in the frequency-domain using reconfigurable RF bandpass filters (BPFs) with amplitude and phase controls (Gen-2)
  - Each FDE tap has four degrees of freedom: BPF center frequency, BPF quality factor, amplitude, and phase

Experimental Evaluation

- Using previous version of FDE board connected to a USRP controlled with LabVIEW
- OFDM PHY with 20 MHz bandwidth and various modulation and coding schemes (BPSK-1/2 to 64QAM-3/4)
- TX Power: +10 dBm, RX noise floor: -85 dBm, overall SIC: 95 dB (52 dB in RF and 43 dB in digital)
- Benchmark: measure packet reception ratio (PRR) against signal to noise ratio (SNR) for HD/FD operation

The average FD link PRR is 93.5% of the average HD link PRR, resulting in an average FD link throughput gain of 1.87x
Gen-2 Wideband RF SI Canceller based on FDE

- Gen-2 RF SI canceller box with both a wideband frequency-domain equalization (FDE) path (Gen-2) and narrowband frequency-flat path (Gen-1)
  - Gen-2 canceller has two parallel FDE taps, each implemented as an RF bandpass filter (BPF) with amplitude and phase controls
  - BPF has a tunable center frequency and quality factor
  - Gen-1 canceller is a single path with amplitude and phase control only

Performance of PCB canceller when the circulator is (a) terminated by 50Ω and (b) connected to an antenna
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- COSMOS Overview
- Full-Duplex Wireless
- Compact Wideband Full-Duplex Wireless
- Integration with COSMOS
- Recap of goals:
  - Make our customized hardware available for any researcher to use for design and evaluation of higher-layer algorithms and protocols suitable for full-duplex and heterogenous networks
  - Demonstrate ability to install customized experimental hardware into COSMOS for evaluation
Integration with COSMOS

- Integrate the FDE board with Sub20 controller, antenna tuner, circulator and USRP N210 software defined radio
- Integrate this complete transceiver in COSMOS sandbox 2 (sb2)
  - Indoor environment suitable for controlled experimentation
Integration with COSMOS

Colocation Site and Data Center @32 AoA
Integration with COSMOS

- Optical Connections to COSMOS Server and 32 AoA
- Krypton x2 + N310 x2
- ToR Switch
- Optical Mux
- Pica8 Switch
- Node Power Supply
- FDE Node x2
- FD Server
OFDM Link Experiment

- To demonstrate and evaluate the performance of the integrated FD radios, we developed an OFDM framework in GNU radio
  - Visualization of Tx and Rx signal in both time and frequency domains at each radio, as well as packet decoding and digital SI canceller coeffs.
  - The FDE canceller configuration through a customized GNU radio out-of-tree (OOT) module
- TX Power: 0 dBm, RX noise floor: -85 dBm, overall SIC: 85 dB (50 dB in RF and 35 dB in digital)
OFDM Link Experiment

- We use two FD nodes integrated in COSMOS sandbox (sb2)
- Hardware
  - 2x USRP N210s
  - 2x FlexICon Gen-2 RF canceller boxes
  - 2x Sub20 USB->SPI/GPIO interfaces
  - PC with Ubuntu 16.04
- Software:
  - OFDM link built in GNU Radio, alongside customized OOT modules (C++) for digital SI cancellation
  - libusb and libsub (C/C++) for interfacing with the SUB-20 controller
  - The Eigen C++ library for channel estimation and digital SIC
- Demo to be presented later this evening!
- The detailed tutorial can be found on the COSMOS wiki ([https://wiki.cosmos-lab.org/wiki/tutorials/full_duplex](https://wiki.cosmos-lab.org/wiki/tutorials/full_duplex))
OFDM Link Experiment
Status and Future Work

• Two FDE-based full-duplex nodes integrated into the sandbox testbed
• Sandbox testbed accessed through the sb2.cosmos PC
• Tutorial on how to access the full-duplex radios and run experiments is on the COSMOS wiki
• More advanced example experiments being developed (e.g., real-time FDE canceller configuration)
• Work on integrating more hardware into testbed, including two more FDE-based full-duplex nodes

• Examples of supported research
  - Adaptive RF canceller configuration
  - Experimental evaluation of different digital SIC algorithms
  - Measurement- and trace-based evaluation of full-duplex rate gains
  - PHY layer security
  - Building blocks of MAC layer algorithms for full-duplex networks (design of frame structures, carrier sensing, etc.)
  - and many more...
Thank you!

https://cosmos-lab.org
https://flexicon.ee.columbia.edu

mpk2138@columbia.edu

http://wimnet.ee.columbia.edu/people/current-members/manav-kohli/