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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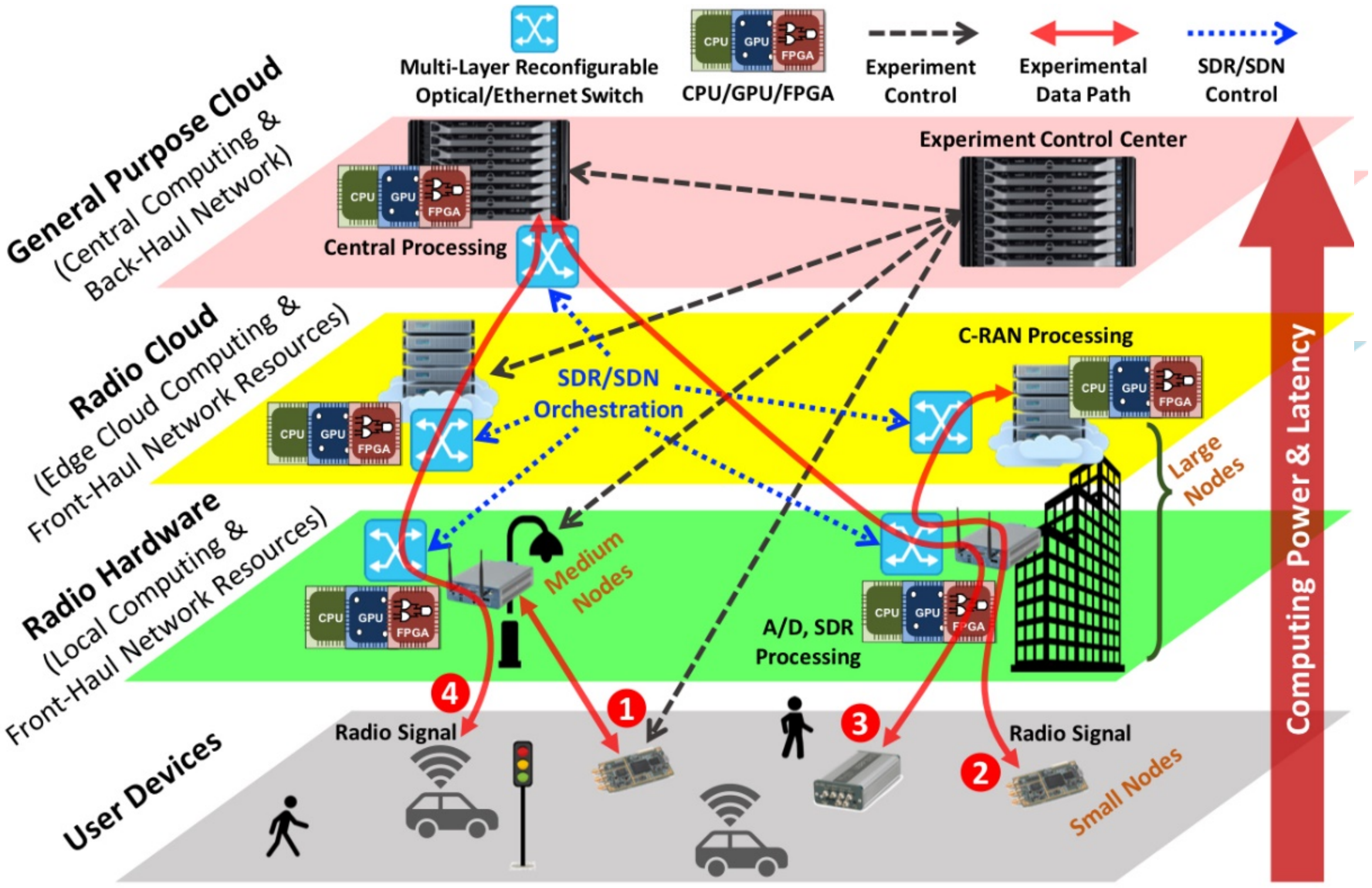
Outline

- **COSMOS Overview**
- Full-Duplex Wireless
- Compact Wideband Full-Duplex Wireless
- Integration with COSMOS

COSMOS Testbed Overview

- 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' multi-layered computing architecture

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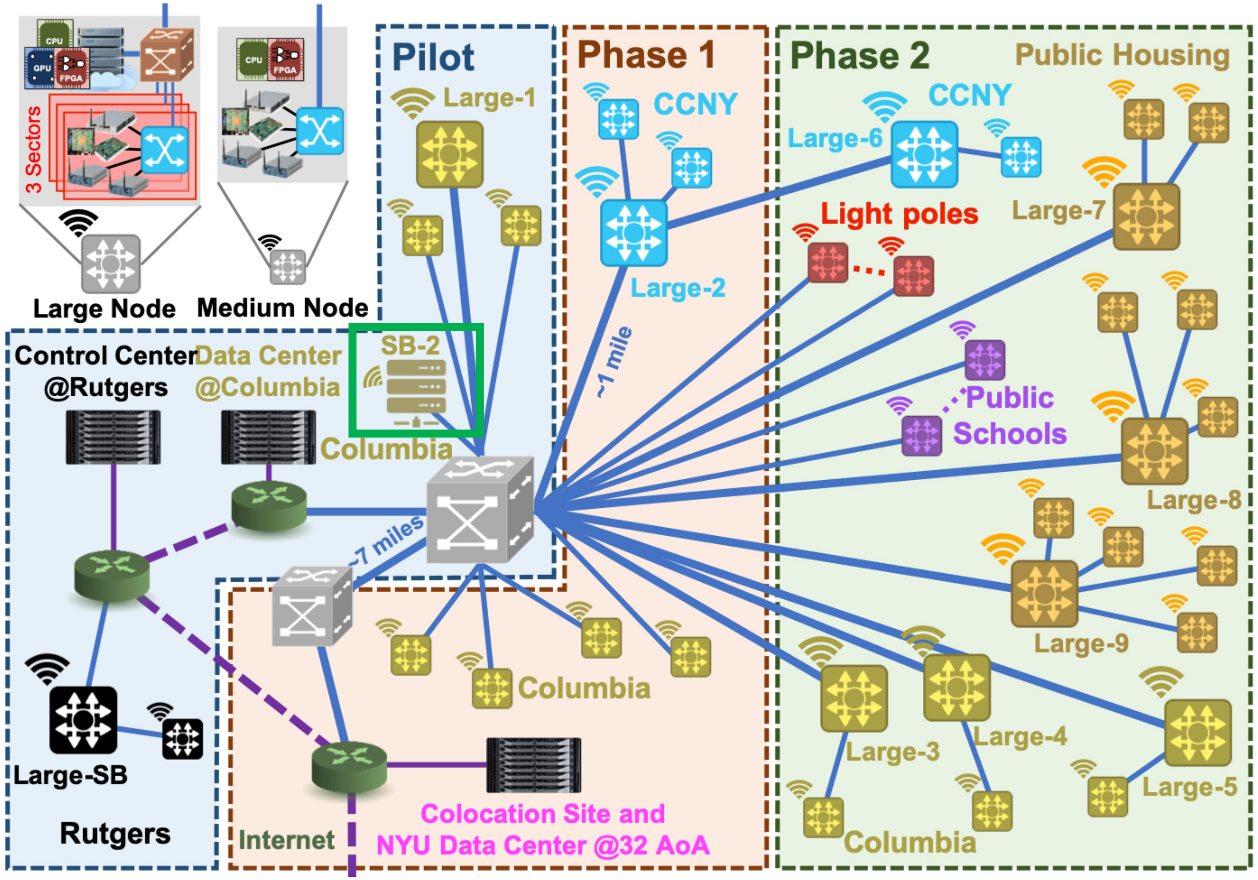
COSMOS Testbed Deployment Vision

- 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

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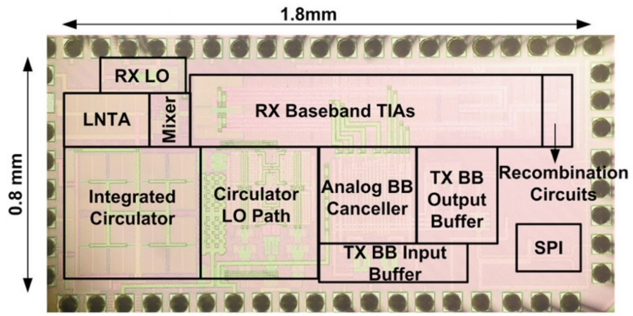
COSMOS Experimental Research and Example

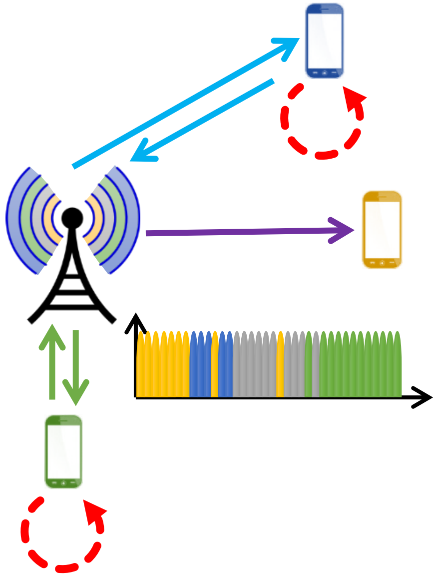
- Internal "Test Experiments" to help drive design requirements
- Experiment on **Full-Duplex Wireless**

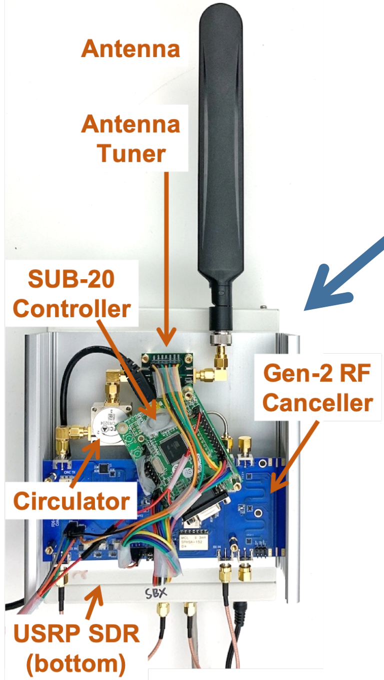
FlexICoN

(Columbia, Krishnaswamy & Zussman)

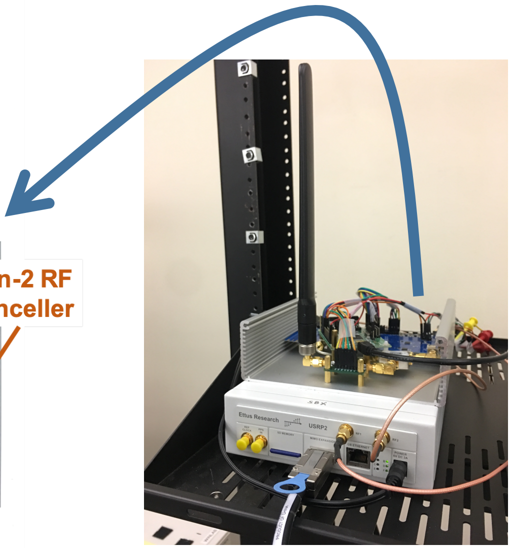
- FlexICoN project: design and evaluate algorithms and protocols across various layers of the network stack (PHY, MAC and above) for **IC-based full-duplex nodes**
- ***<u>Goals:</u>***
  - Make our customized hardware available for researchers to use for the design and evaluation of higher-layer algorithms and protocols suitable for full-duplex and heterogenous networks
  - Demonstrate successful installation of customized experimental hardware into COSMOS







Gen-2 canceller box



Gen-2 wideband full-duplex radio integrated into COSMOS

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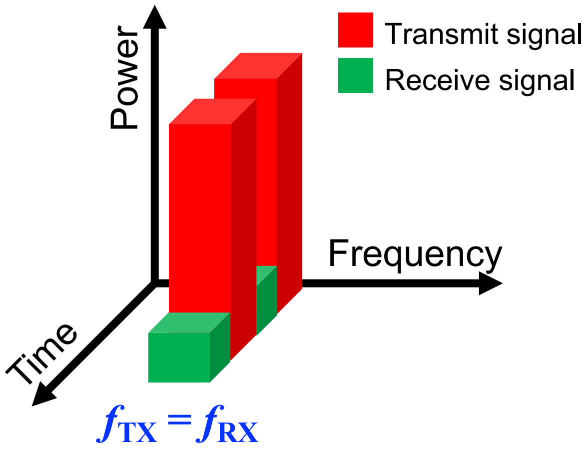
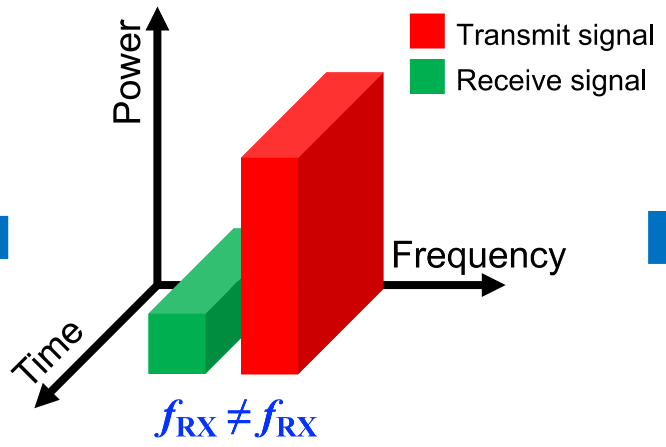
Full-Duplex Wireless

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

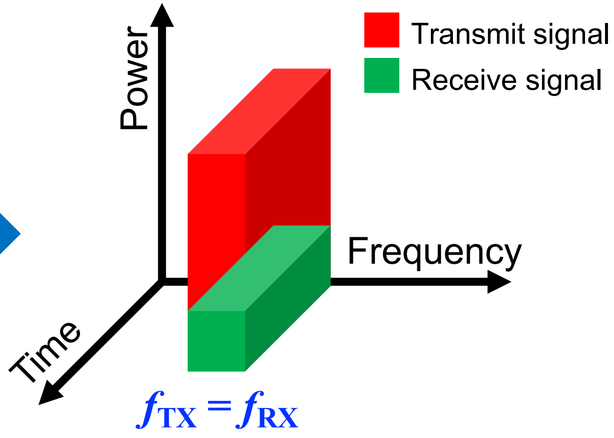
- (In-band) Full-duplex (FD) wireless: simultaneous transmission and reception on the same frequency channel



TDD

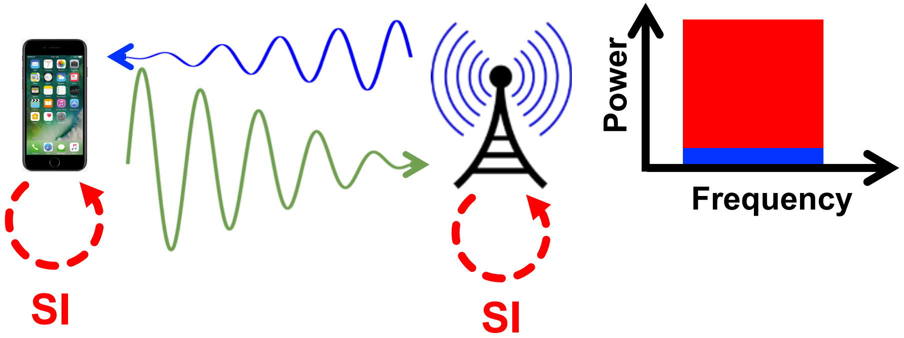


FDD

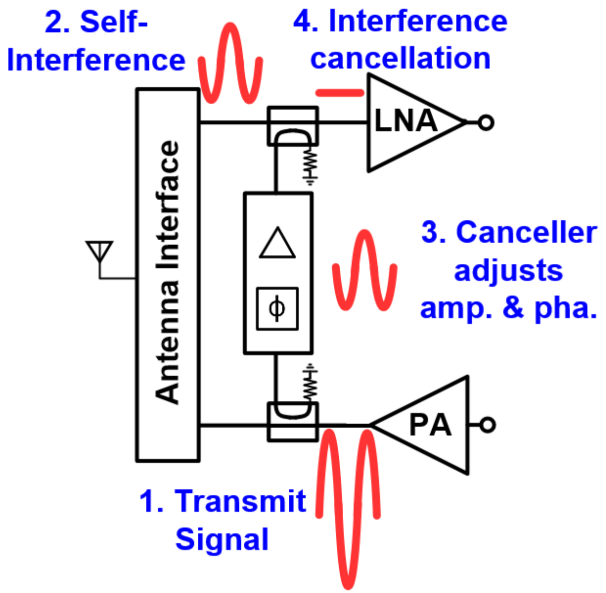


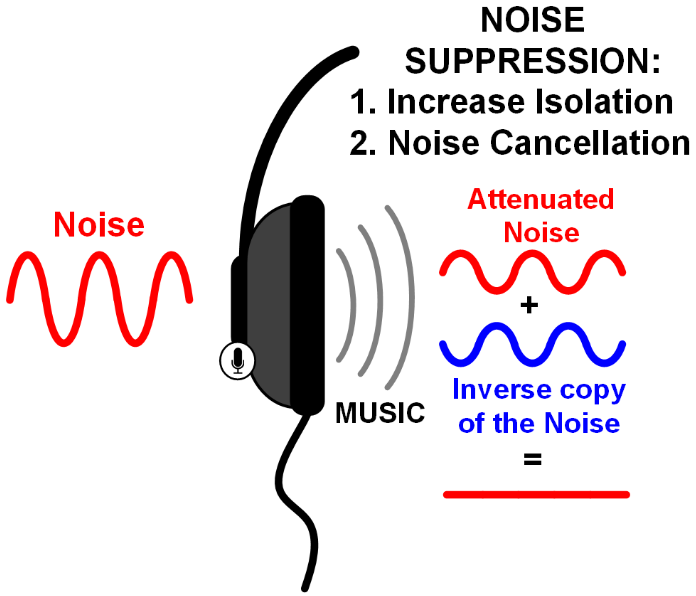
Full-Duplex (FD)

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 or 90 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)

Desired signal

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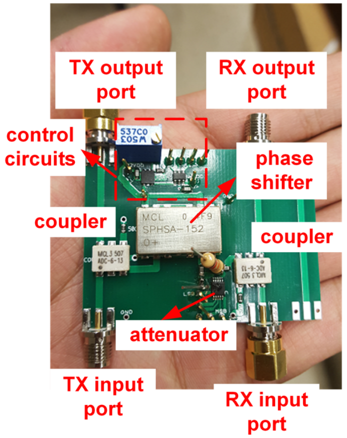
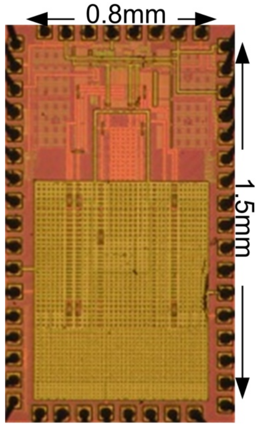
Prior Work

- 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

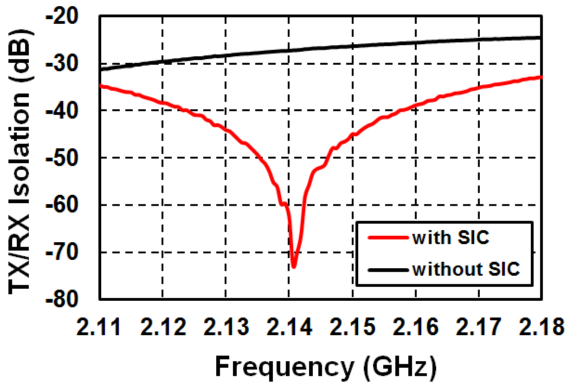


Gen-1 RF SI Canceller

Emulating the RFIC SI canceller



Chip photo



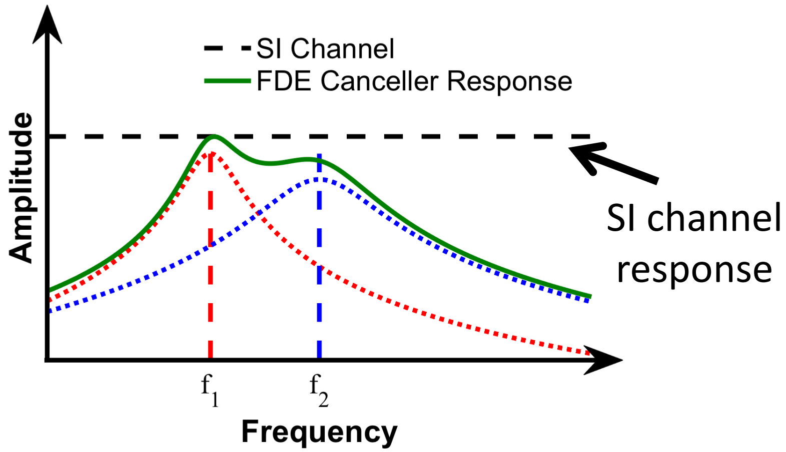
Self-Interference Cancellation (SIC) measurement

Integration in ORBIT Testbed

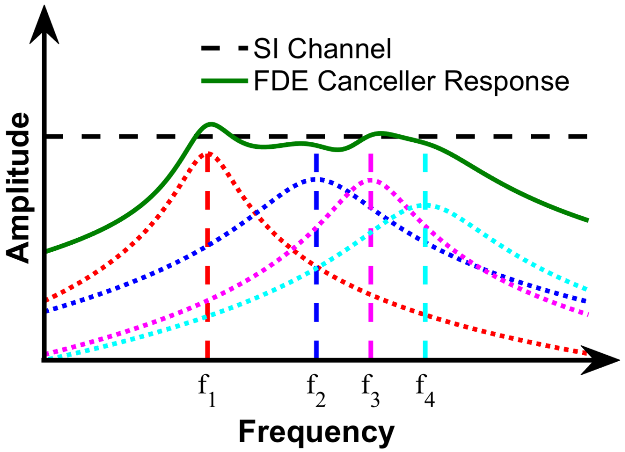
- J. Zhou, A. Chakrabarti, P. Kinget and H. Krishnaswamy, "Low-noise active cancellation of transmitter leakage and transmitter noise in broadband wireless receivers for FDD/co-existence," *IEEE J. of Solid-State Circuits*, vol. 49, no. 12, pp. 3046-3062, Dec. 2014.
- T. Chen, J. Zhou, N. Grimwood, R. Fogel, J. Marasevic, H. Krishnaswamy, and G. Zussman, "Demo: Full-duplex wireless based on a small-form-factor analog self-interference canceller," in *Proc. ACM MobiHoc'16*, 2016.
- T. Chen, M. Baraani Dastjerdi, G. Farkash, J. Zhou, H. Krishnaswamy, and G. Zussman, "Demo abstract: Open-access full-duplex wireless in the ORBIT testbed," in *Proc. IEEE INFOCOM'18*, 2018. (Technical report available at *arXiv preprint arXiv:1801.03069*)

Compact Wideband Full-Duplex Wireless

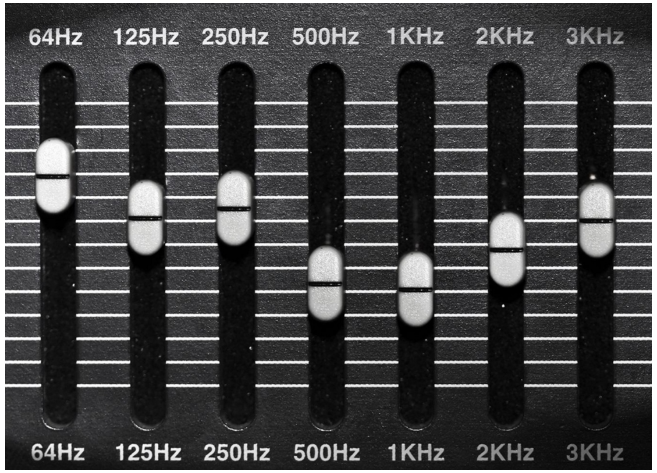
- Delay line-based cancellers are not always suitable for compact IC-based implementations
  - Difficult to implement long delay lines in ICs due to space constraints
- **Main idea based on frequency-domain equalization (FDE)**: The self-interference (SI) channel can be emulated in the *frequency-domain* 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



2 FDE taps



4 FDE taps

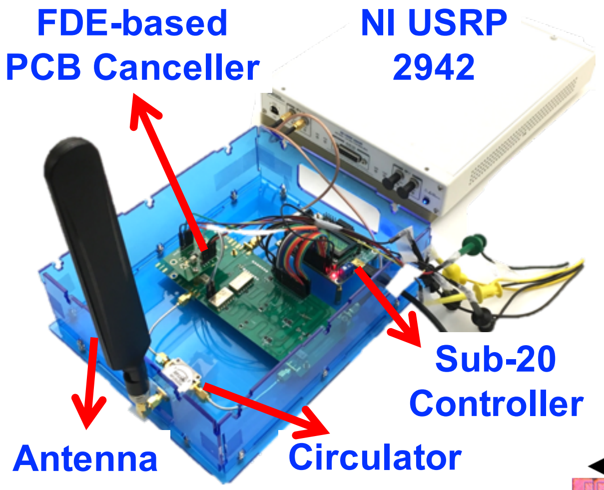


Audio Equalizer

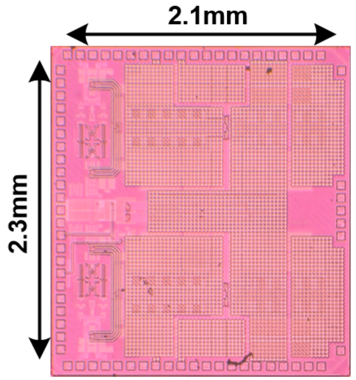
- T. Chen, M. Baraani Dastjerdi, J. Zhou, H. Krishnaswamy, and G. Zussman, “Wideband compact full-duplex wireless via frequency-domain equalization: Design and experimentation,” in *Proc. ACM MobiCom’19 (to appear)*, 2019.

Experimental Evaluation

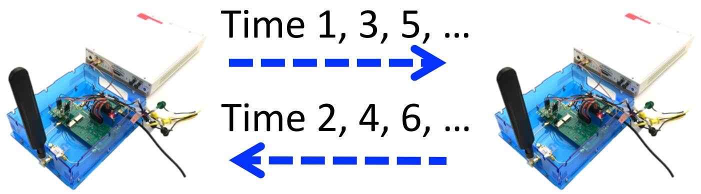
- Using previous version of FDE board connected to a USRP controlled with LabVIEW
- OFDM PHY w/ **20 MHz** bandwidth and various modulation and coding schemes (BPSK-1/2 to 64QAM-3/4)
- TX Power: **+10 dBm**, RX noise floor: **-85 dBm**, overall SIC: **95 dB** (52 dB in RF and 43 dB in digital)
- Benchmark: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



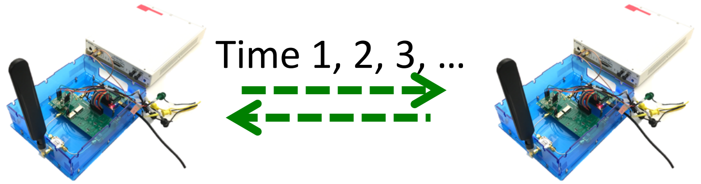
Emulating the FDE-based RFIC canceller

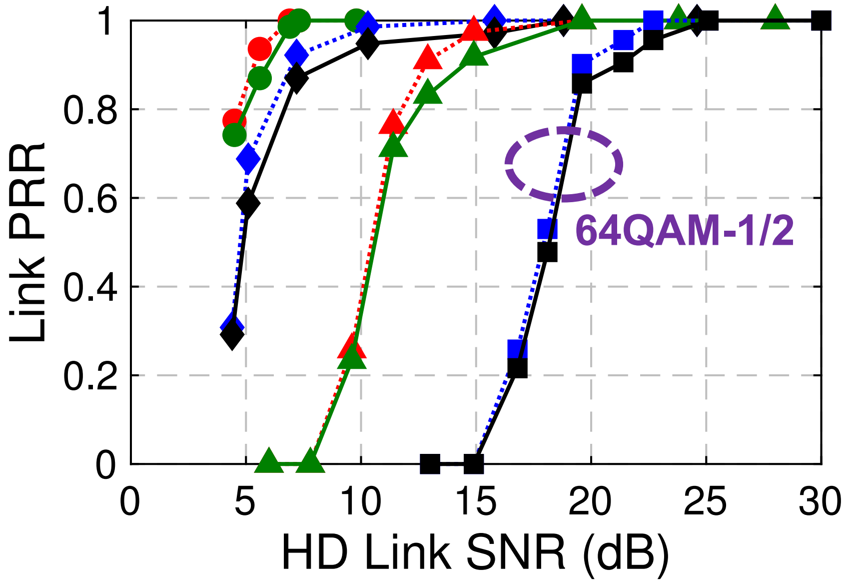


HD Link: Alternate transmissions



FD Link: Simultaneous transmissions





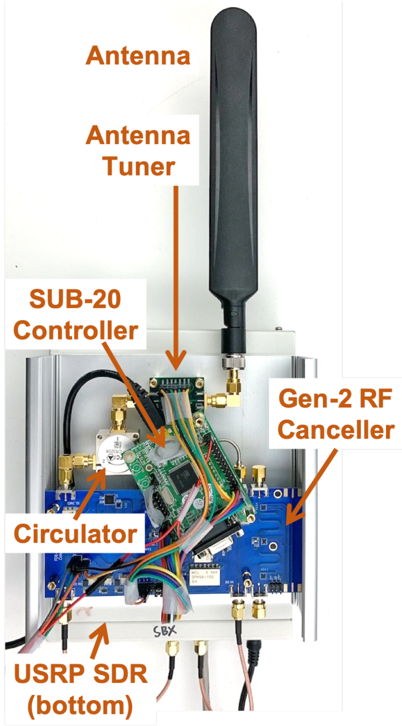
Coding rate 1/2

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**

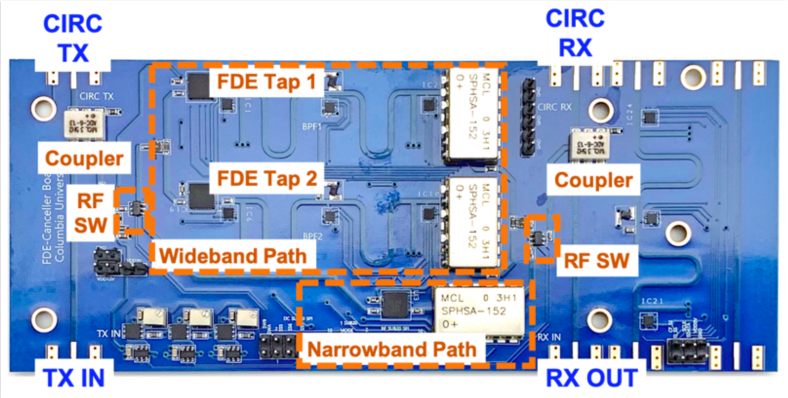
Gen-2 Wideband RF SI Canceller based on FDE

- 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

Gen-1 canceller box, as integrated in ORBIT



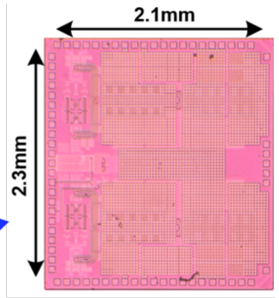
Gen-2 canceller box

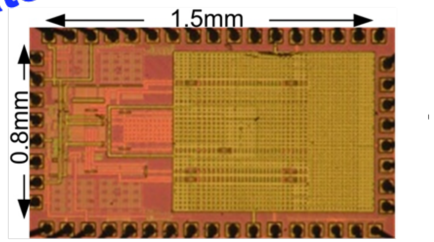


Gen-2/Gen-1 Printed circuit board (PCB)

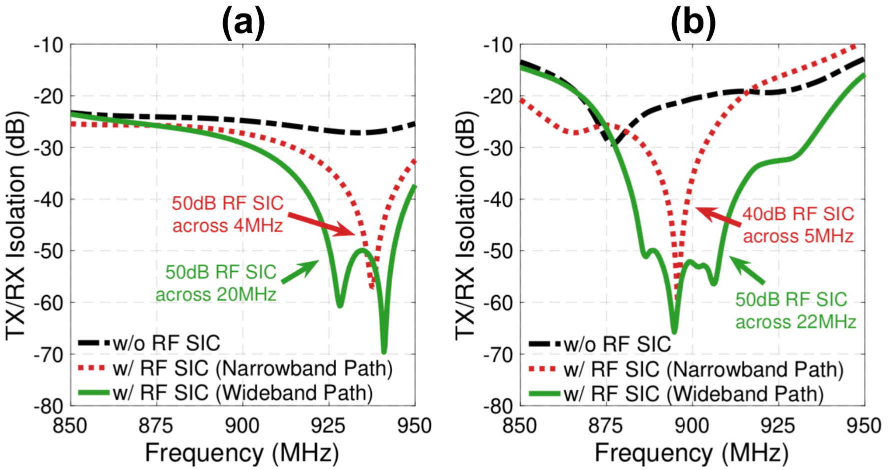
Emulates

Gen-2 (wideband)





Gen-1 (narrowband)



Performance of PCB canceller when the circulator is (a) terminated by 50Ω and (b) connected to an antenna

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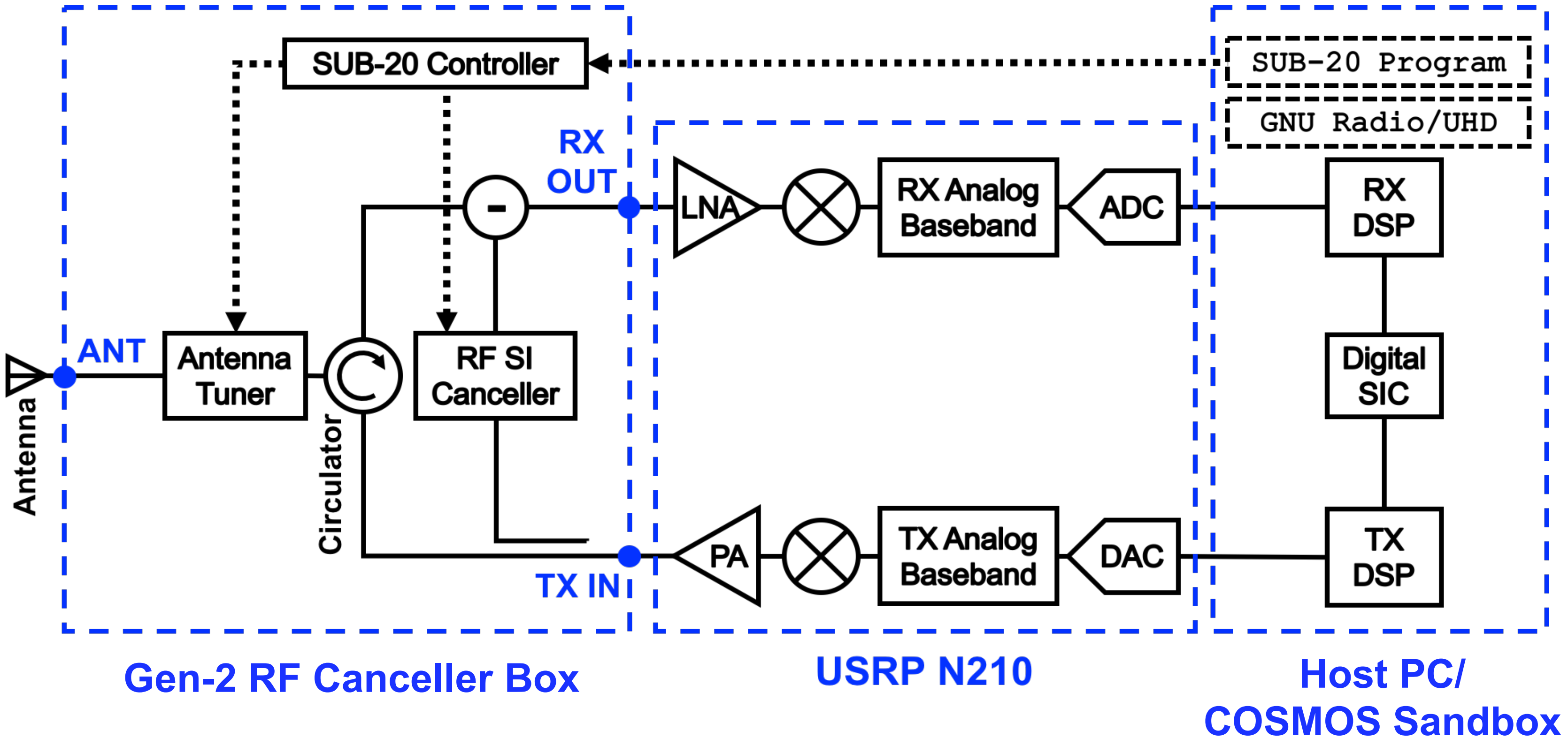
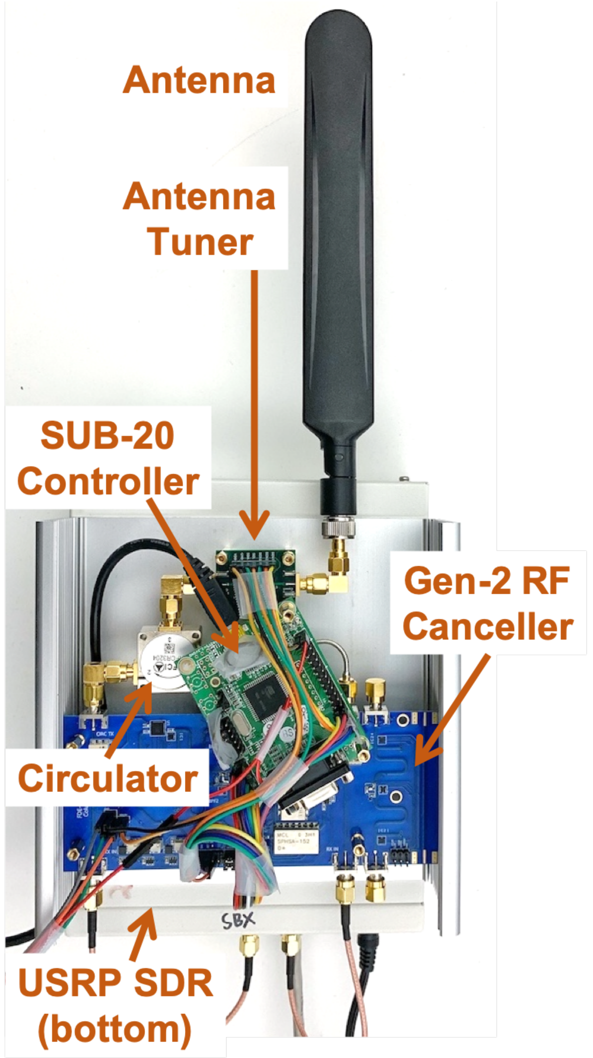
- ***Recap of goals:***
  - Make our customized hardware available for any researcher to use for design and evaluation of higher-layer algorithms and protocols suitable for full-duplex and heterogenous networks
  - Demonstrate ability to install customized experimental hardware into COSMOS for evaluation

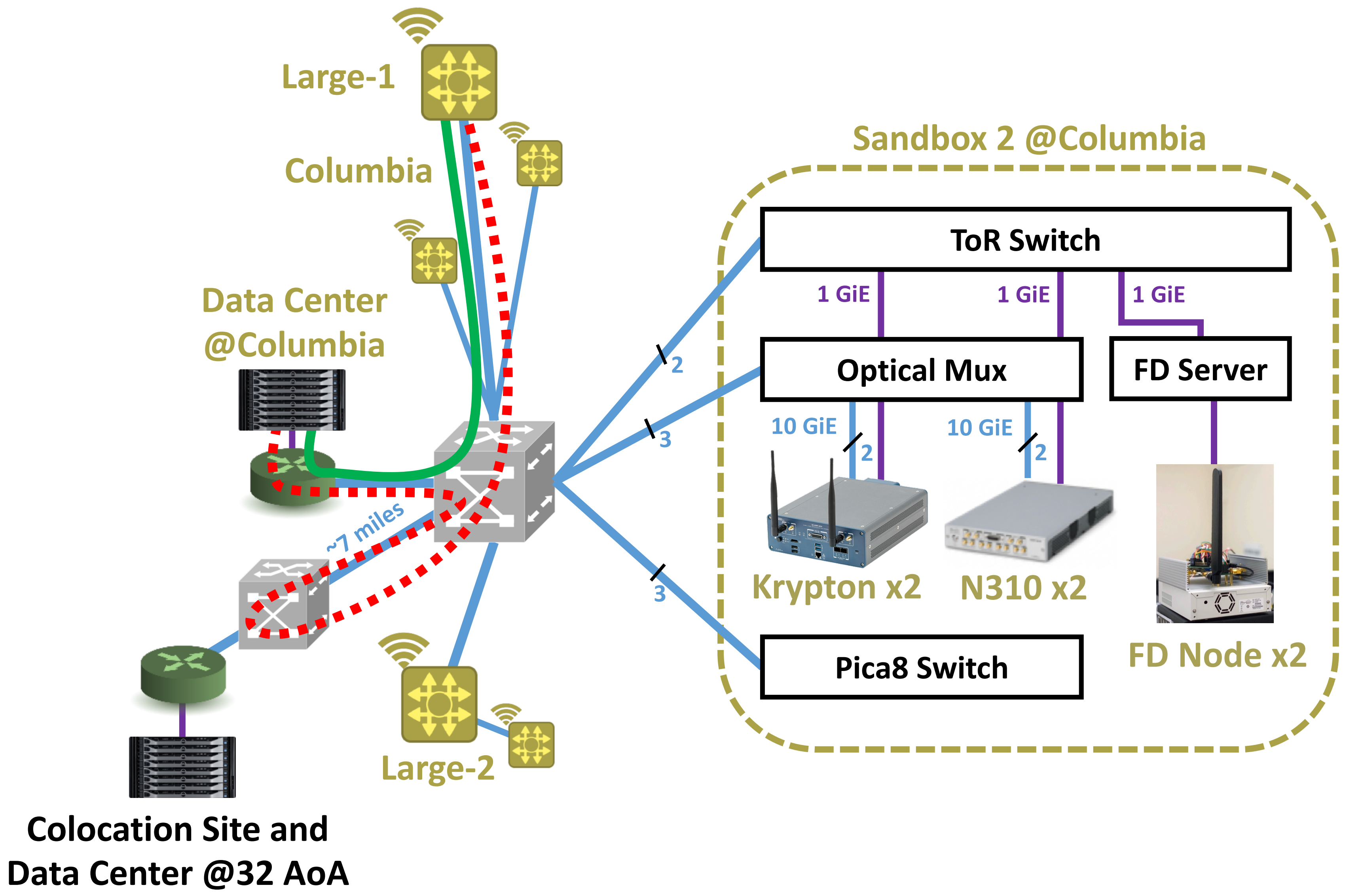
Integration with COSMOS

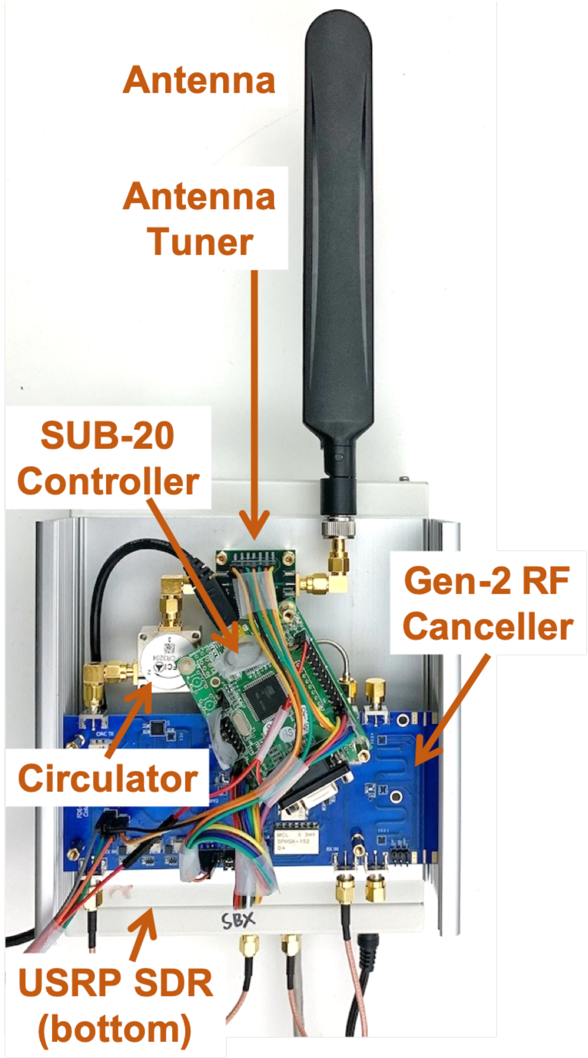
- Integrate the FDE board with Sub20 controller, antenna tuner, circulator and USRP N210 software defined radio
- Integrate this complete transceiver in COSMOS sandbox 2 (`sb2`)
  - Indoor environment suitable for controlled experimentation



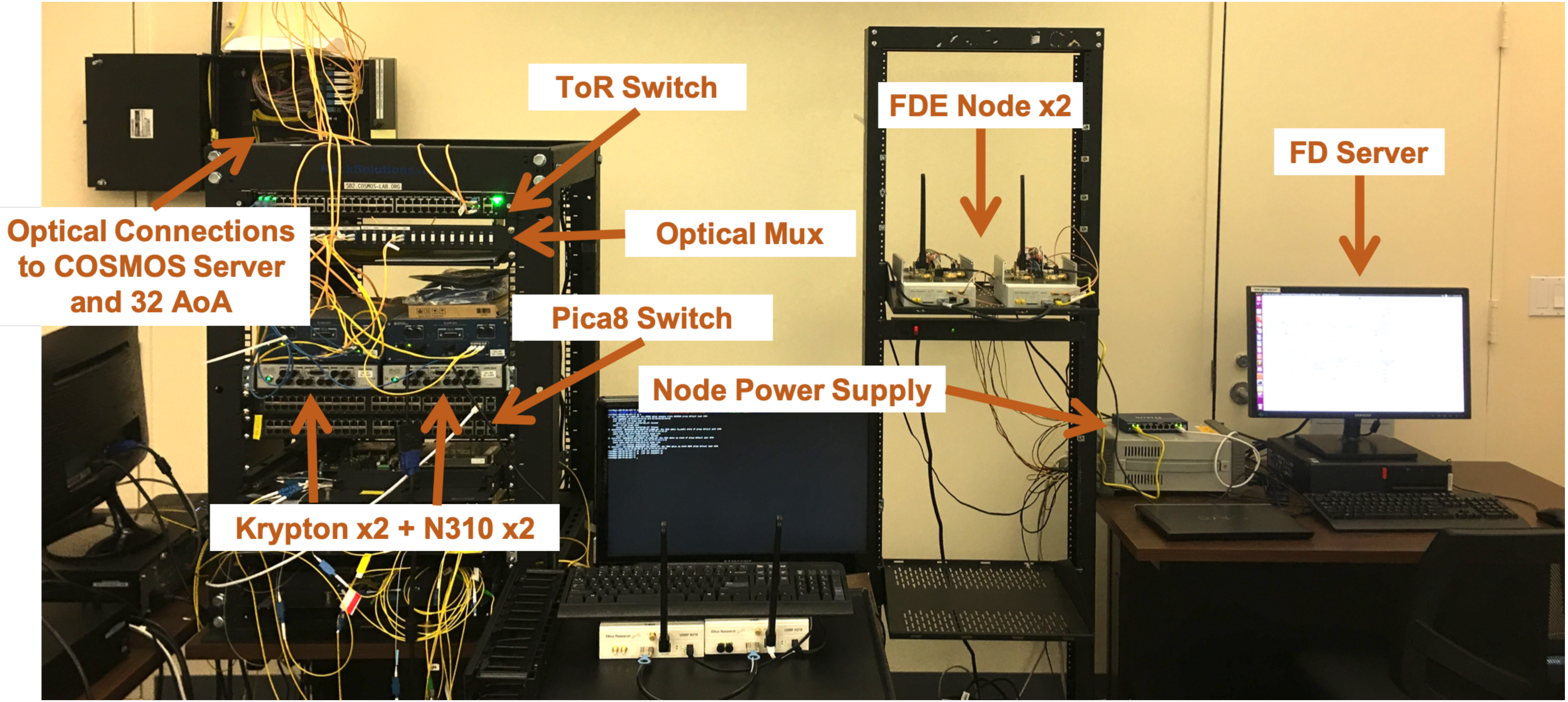


Integration with COSMOS



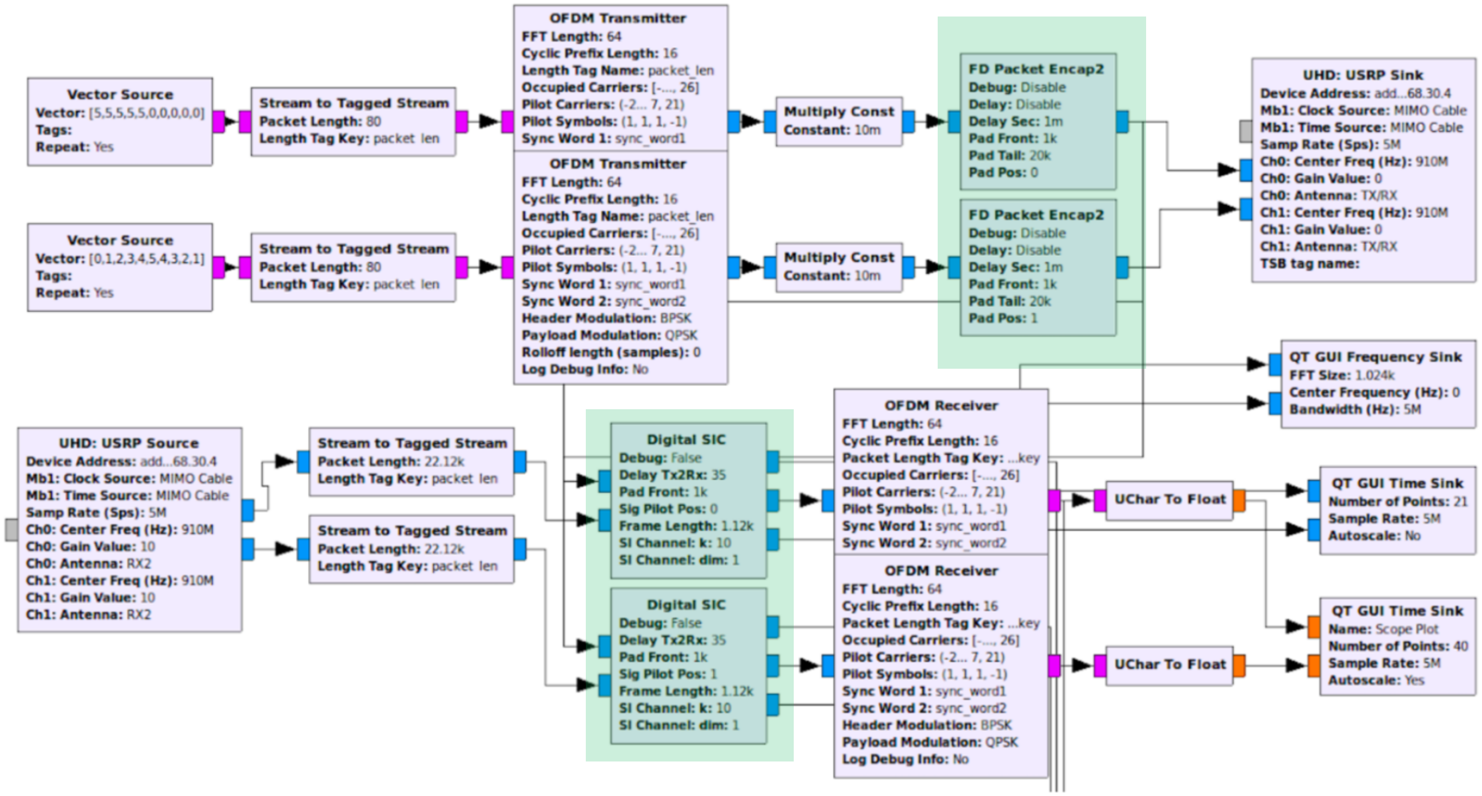


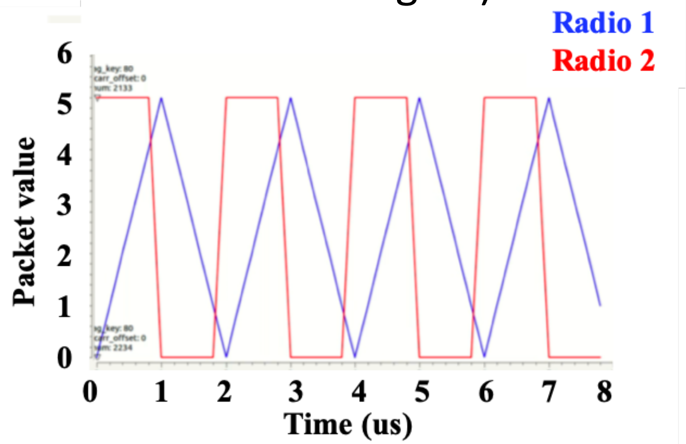
Integration with COSMOS



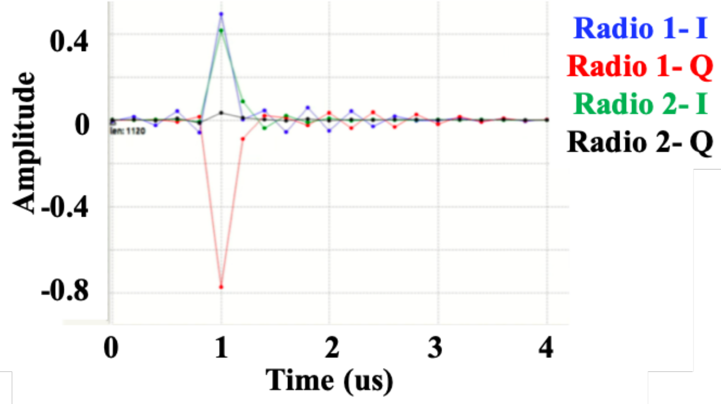
OFDM Link Experiment

- 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)





Bytes from decoded packets

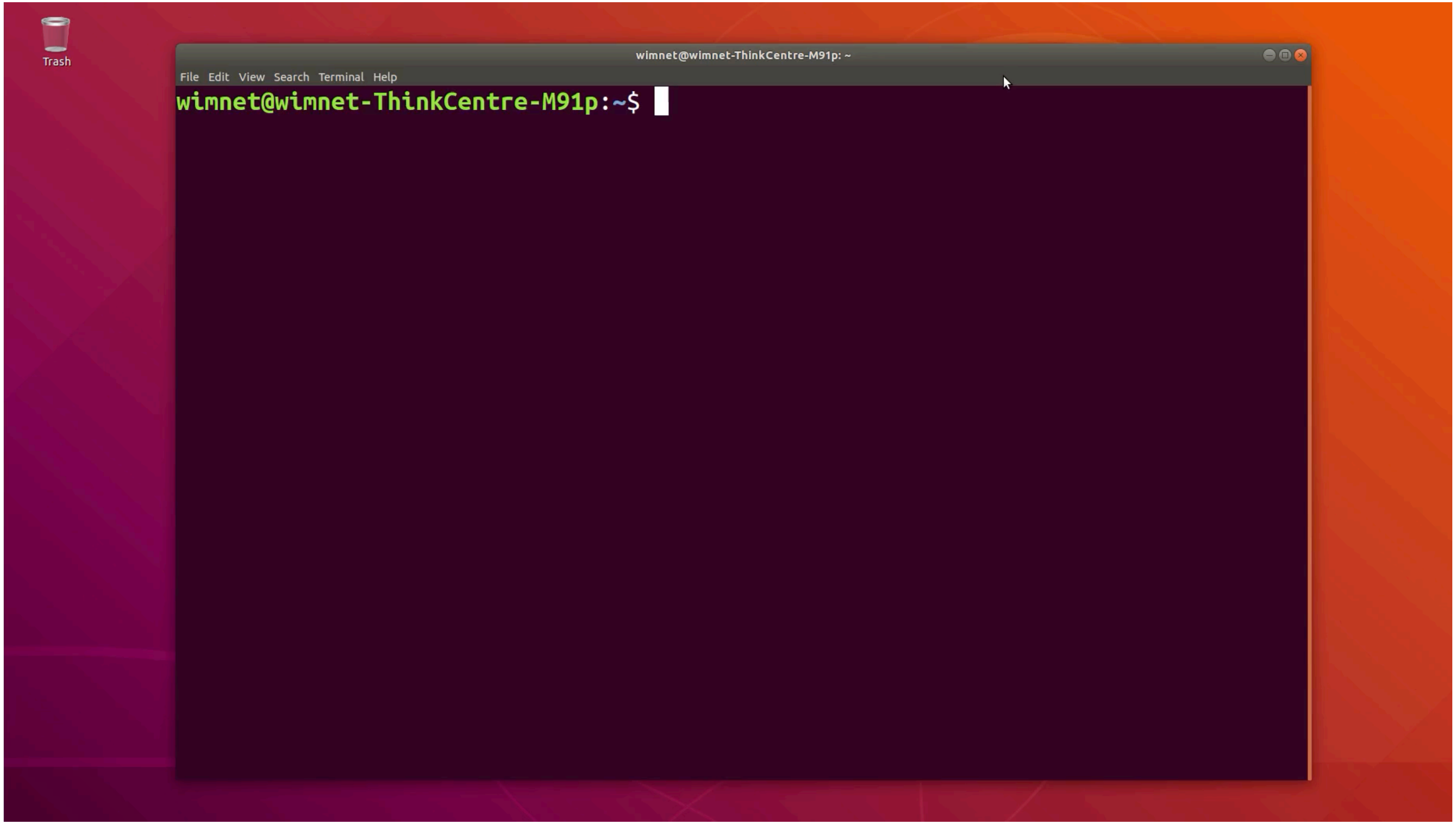


Digital SI canceller coeffs.

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)

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/

COSMOS FlexICoN wim.net Wireless & Mobile Networking Lab WINLAB CoSMIC