COSMOS Tutorial: Experimentation with Compact Full-Duplex Wireless

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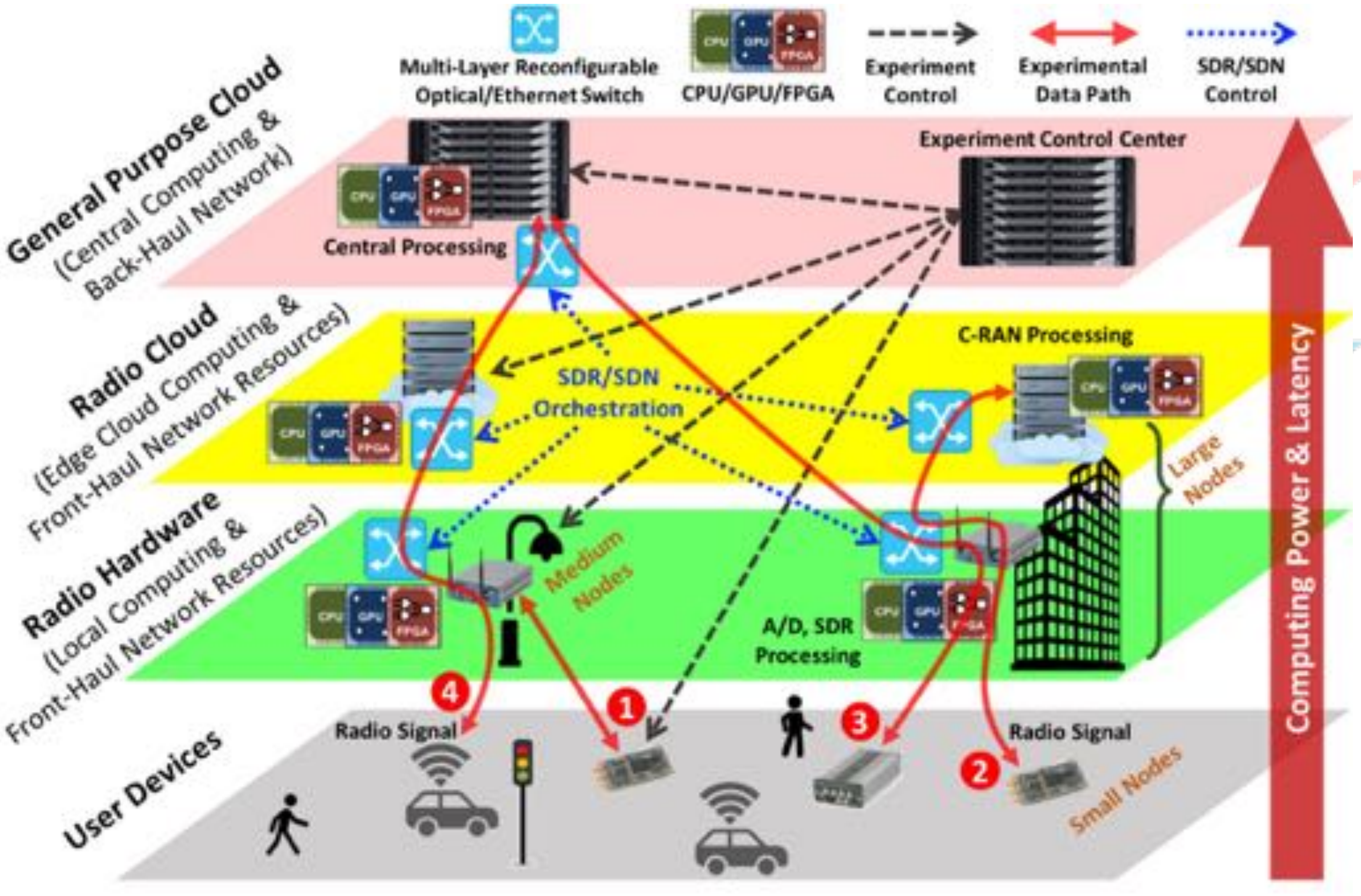
COSMOS Team: Rutgers, Columbia, and NYU in partnership with New York City, IBM, Silicon Harlem, City College of New York, U. Arizona

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

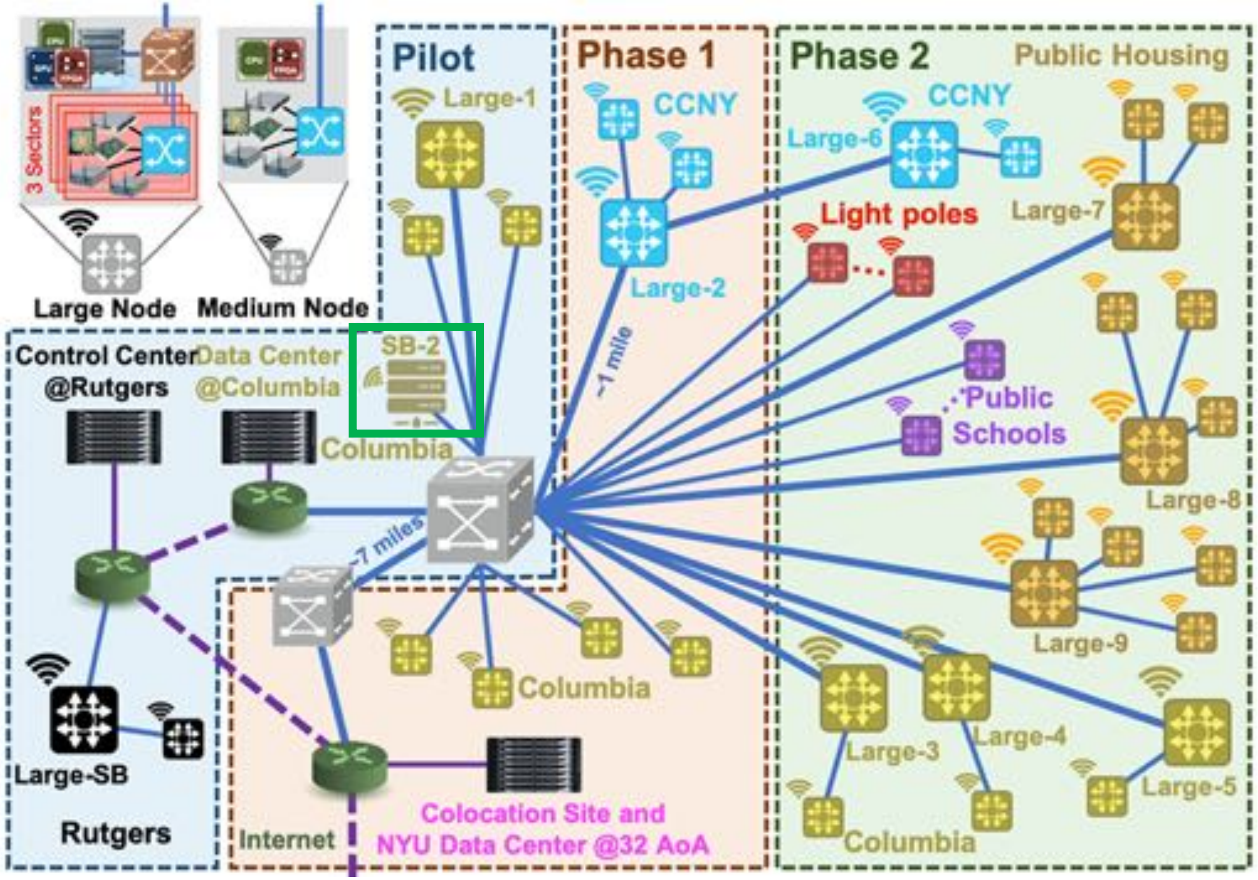


COSMOS' multi-layered computing architecture

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

Rutgers Columbia University in the City of New York NYU NYC <sh> The City College of New York IBM

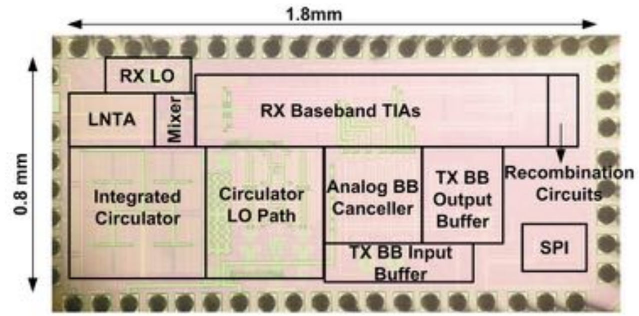
COSMOS Experimental Research and Example

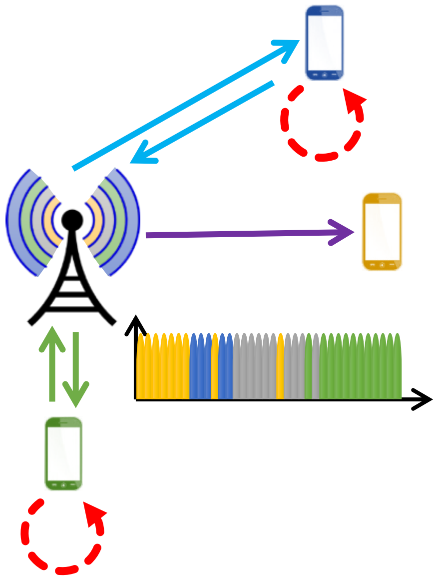
- Internal "Test Experiments" to help drive design requirements
- Experiment on **Full-Duplex Wireless**

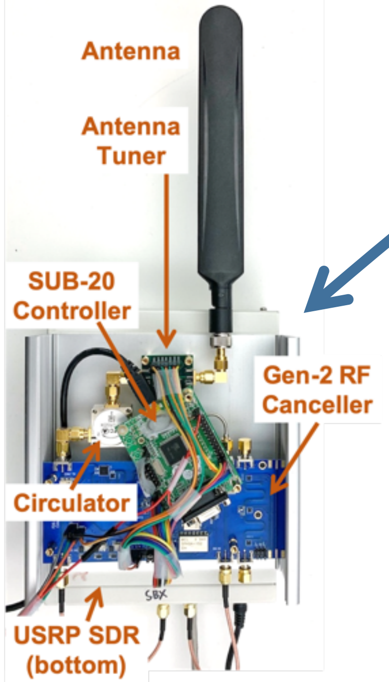
FlexICoN

(Columbia, Krishnaswamy & Zussman)

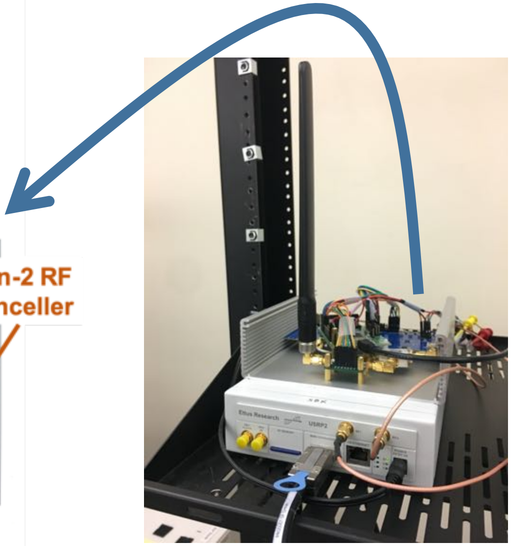
- FlexICoN project: design and evaluate algorithms and protocols across various layers of the network stack (PHY, MAC and above) for **IC-based full-duplex nodes**
- ***Goals:***
  - Make our customized hardware available for researchers to use for the design and evaluation of higher-layer algorithms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







Gen-2 canceller box



Gen-2 wideband full-duplex radio integrated into COSMOS

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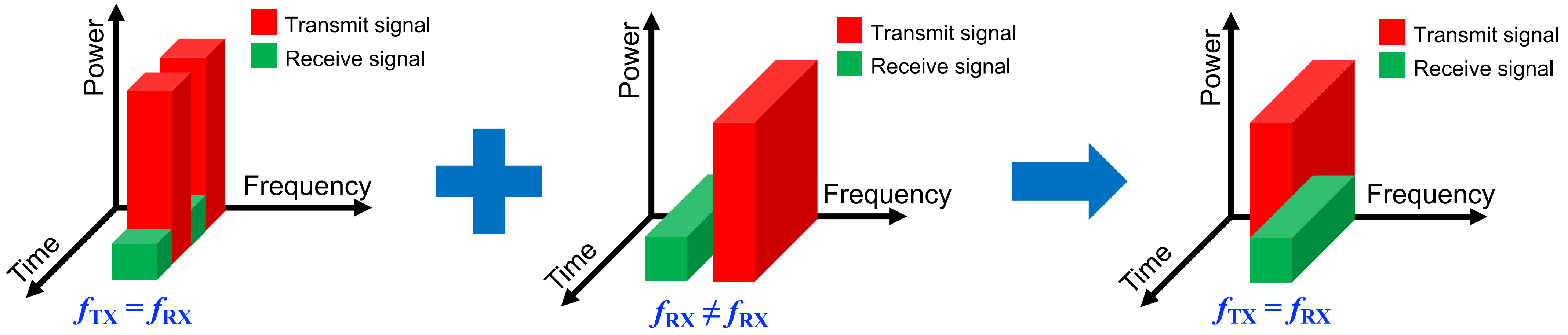
Full-Duplex Wireless

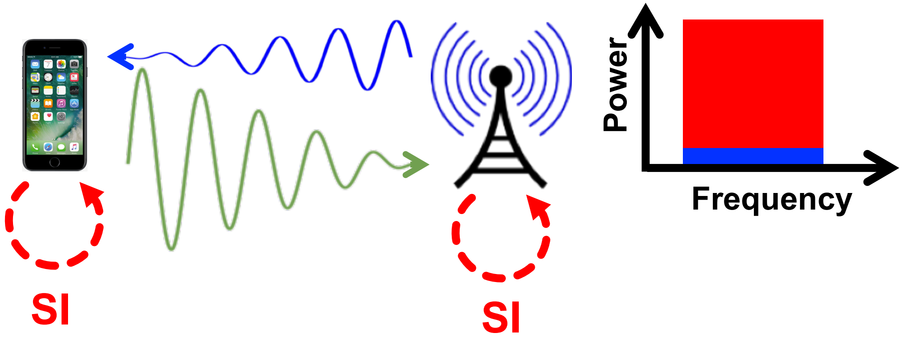
- Legacy half-duplex (HD) wireless systems separate transmission and reception in either:
  - Time: Time Division Duplex (TDD)
  - Frequency: Frequency Division Duplex (FDD)

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

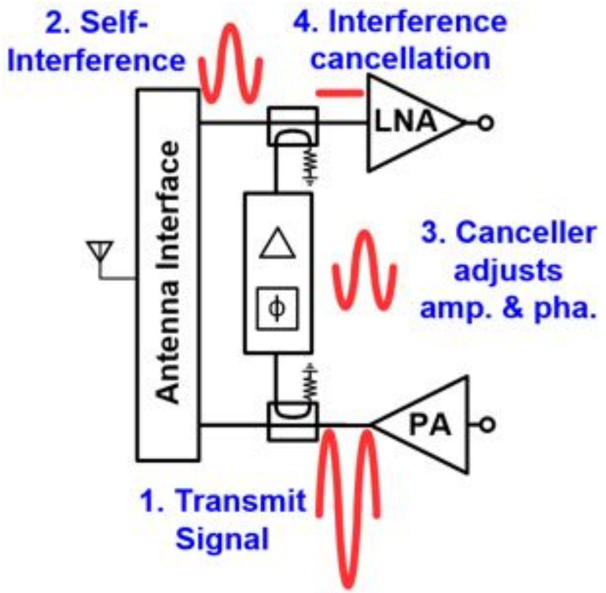


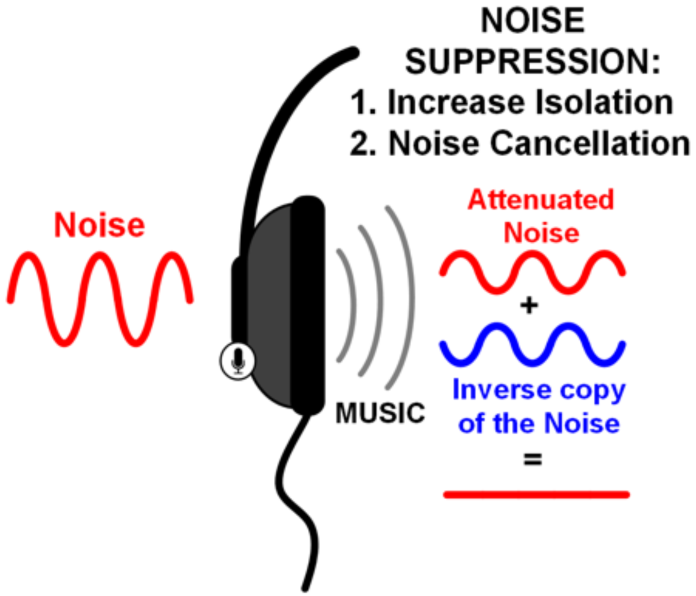
TDD **FDD** **Full-Duplex (FD)**

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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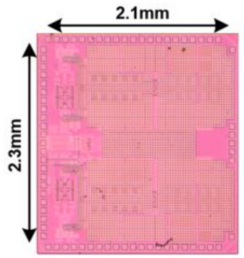
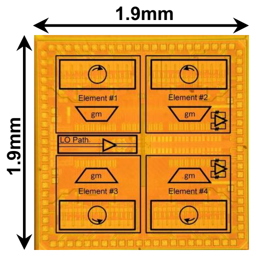
The Columbia FlexICoN Project

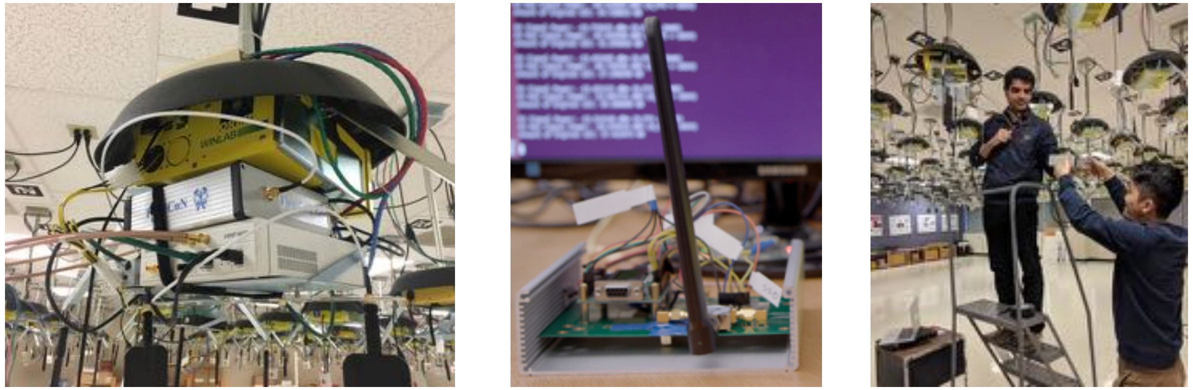
- **F**ull-Dup**lex** Wireless: From **I**ntegrated **C**ircuits t**o** **N**etworks (FlexICoN)
  - Focus on IC-based implementations of single- and multi-antenna full-duplex radios
  - Full-duplex radio/system development, algorithm design, and experimental evaluation
  - Integration of full-duplex capability in the open-access ORBIT and COSMOS testbeds



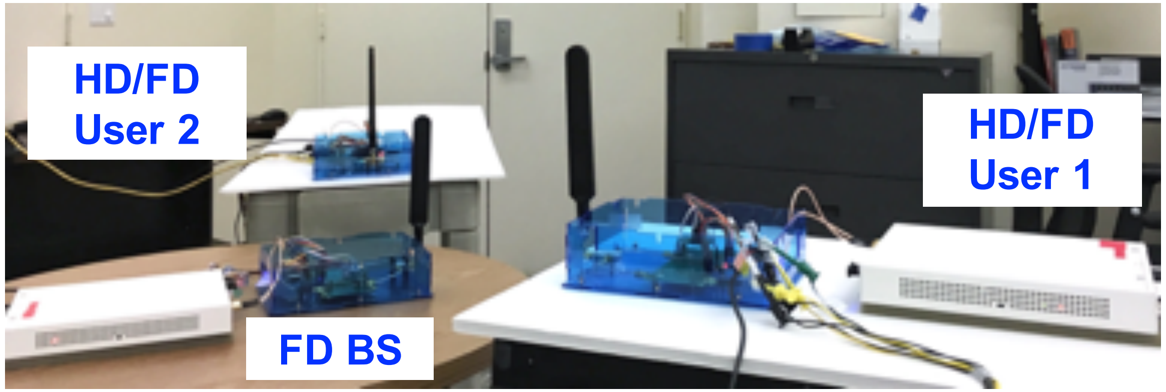
RFIC FD receiver



RFIC FD phased array



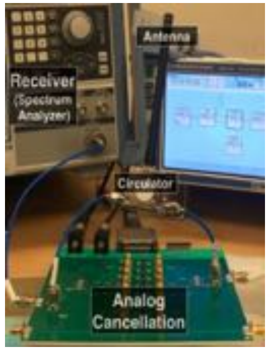
A programmable Gen-1 *narrowband* full-duplex node in ORBIT

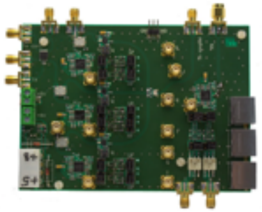


Gen-2 *wideband* full-duplex radios and testbed

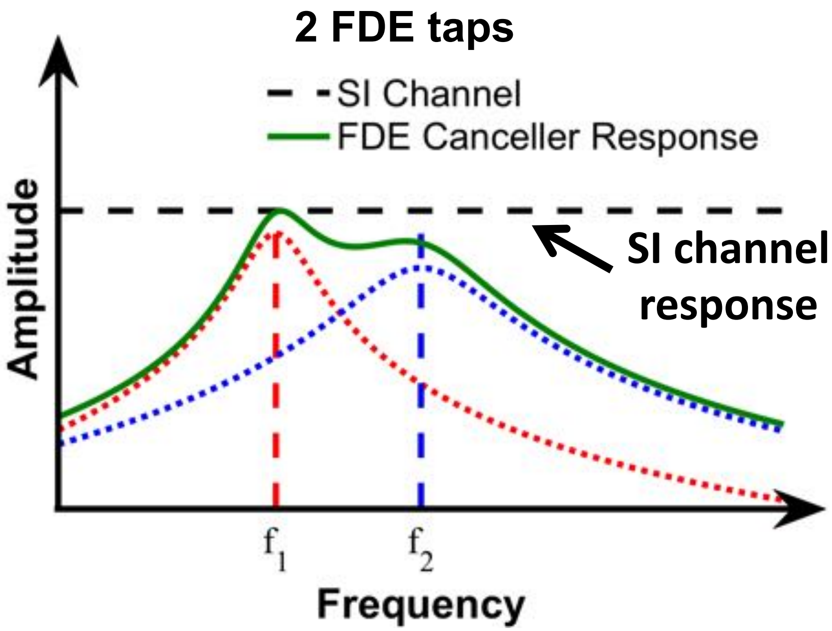
- **T. Chen**, M. Baraani Dastjerdi, H. Krishnaswamy, and G. Zussman, "Wideband full-duplex phased array with joint transmit and receive beamforming: Optimization and rate gains," in *Proc. ACM MobiHoc'19*, 2019. **Best Paper Finalist**
- **T. Chen**, J. Diakonikolas, J. Ghaderi, and G. Zussman, "Hybrid scheduling in heterogeneous half- and full-duplex wireless networks," in *Proc. IEEE INFOCOM'18*, 2018.
- **T. Chen**, J. Welles, M. Kohli, M. Baraani Dastjerdi, J. Kolodziejski, M. Sherman, I. Seskar, H. Krishnaswamy, and G. Zussman, "Experimentation with full-duplex wireless in the COSMOS testbed," in *Proc. IEEE ICNP'19 Workshop Midscale Education and Research Infrastructure and Tools (MERIT)*, 2019.
- **T. Chen**, M. Baraani Dastjerdi, G. Farkash, J. Zhou, H. Krishnaswamy, and G. Zussman,"Open-access full-duplex wireless in the ORBIT testbed," *arXiv preprint arXiv:1801.03069v2*, 2018. Demo presentation at *IEEE INFOCOM'18*.
- J. Zhou, N. Reiskarimian, J. Marasevic, T. Dinc, **T. Chen**, G. Zussman, and H. Krishnaswamy, "Integrated full-duplex radios," *IEEE Communications Magazine (invited)*, vol. 55, no. 4, pp. 142–151, Apr. 2017.
- "Tutorial: Full-duplex wireless in the COSMOS testbed," available at https://wiki.cosmos-lab.org/wiki/tutorials/full_duplex

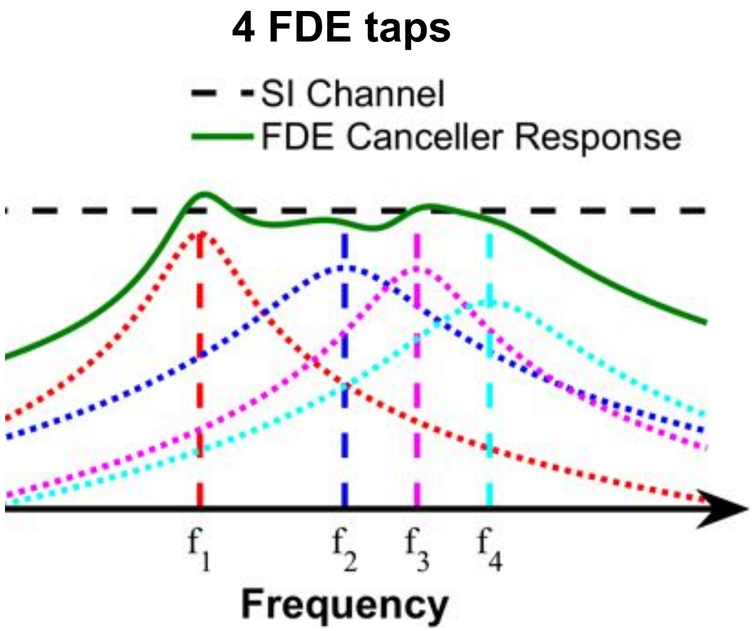
(Compact) Wideband Full-Duplex Wireless

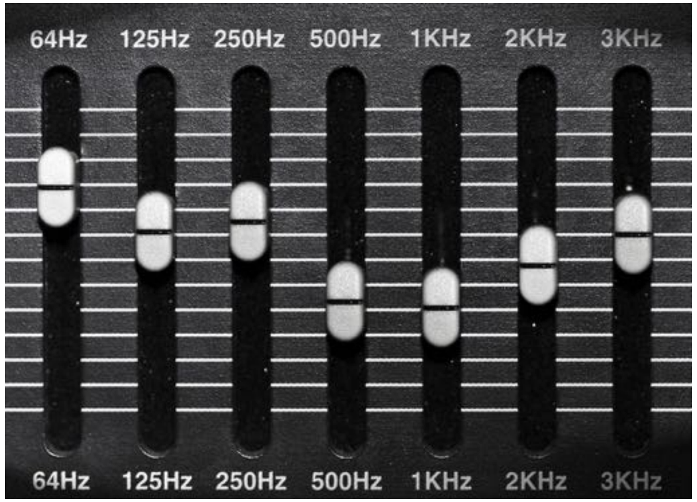




- Traditional RF SI cancellers using delay lines (i.e., ***time-domain equalization***) are more suitable for large-form-factor nodes (e.g., [*Bharadia et al. 2013*], [*Korpi et al. 2016*])
  - M delay lines (e.g., 8 or 16) are combined to achieve wideband canceller
  - The i^{th} delay line with a pre-configured fixed delay of τ_i has one amplitude A_i and/or phased control ϕ_i
- **Main idea**: The SI channel can be emulated using parallel reconfigurable RF bandpass filters (BPFs) with amplitude and phase controls (i.e., ***frequency-domain equalization [FDE]***)





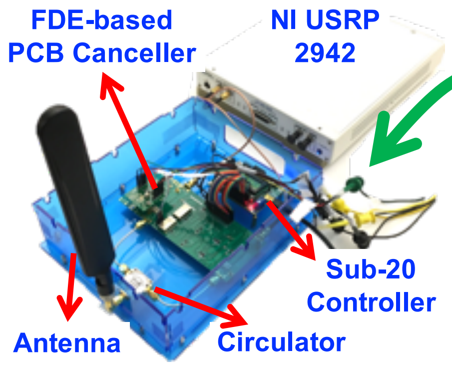


Audio Equalizer

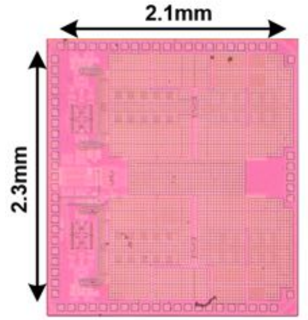
- **<u>T. Chen</u>**, M. Baraani Dastjerdi, J. Zhou, H. Krishnaswamy, and G. Zussman, “Wideband compact full-duplex wireless via frequency-domain equalization: Design and experimentation,” in *Proc. ACM MobiCom’19*, 2019.

FDE-based (Compact) Wideband RF SI Canceller

- Leveraging recent advances in the RFIC community on *N*-path filters grounded in IC implementations
- An FDE-based SI canceller implemented on a PCB
  - Two parallel FDE taps, each consists of a reconfigurable RF bandpass filter (BPF) with amplitude and phase controls and features four degrees of freedom (DoF)

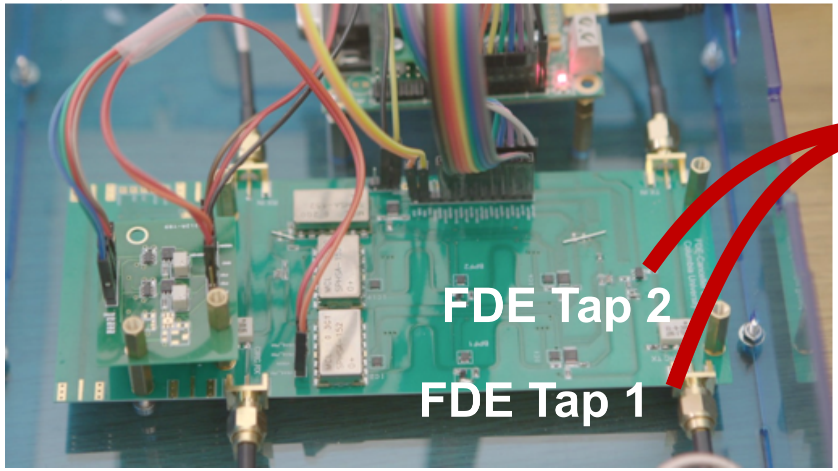


FD radio prototype



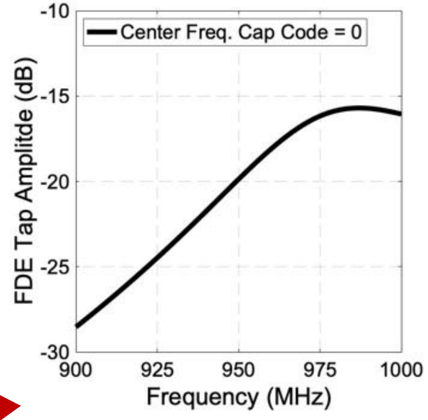
Chip photo

FDE-based PCB canceller

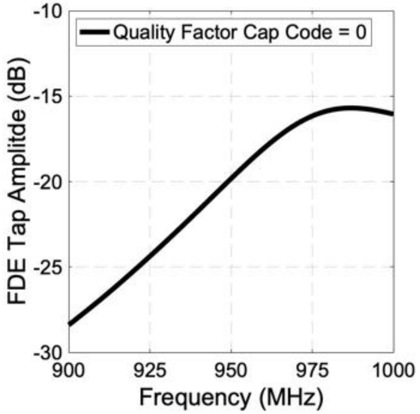


Emulating the RFIC canceller and facilitating experimentation at the system/network level

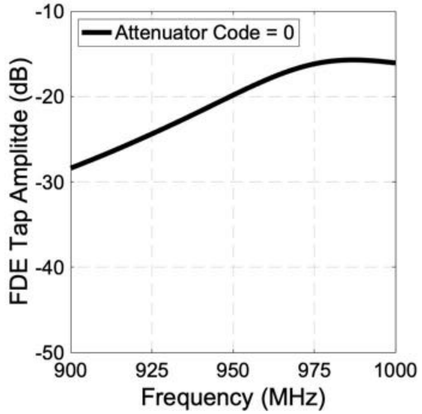
f_c – Center frequency



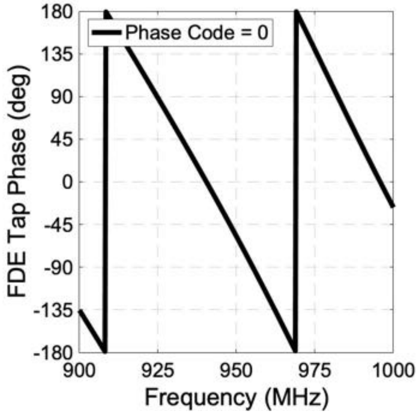
Q – Quality factor



A – Amplitude



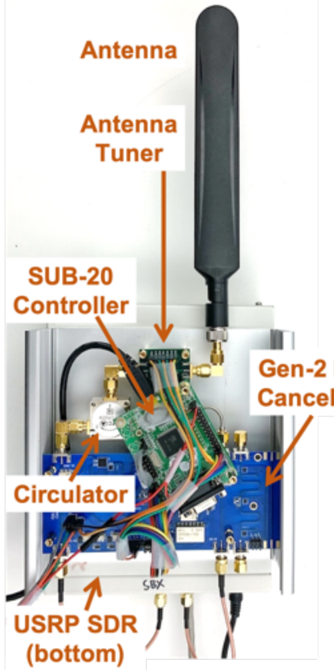
ϕ – Phase



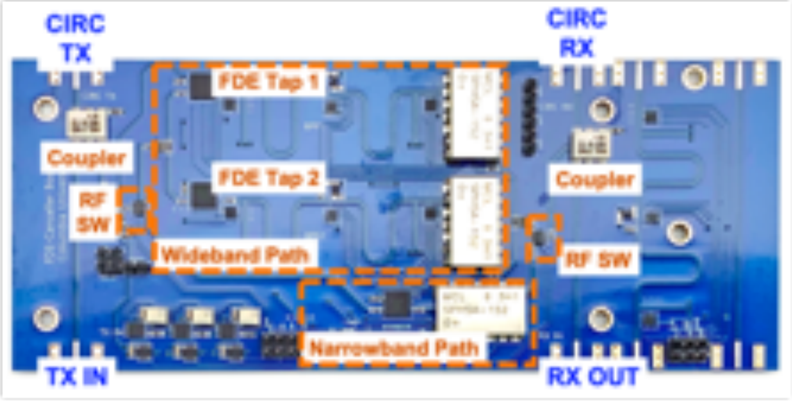
Programmable DoF of each FDE tap

FDE-based (Compact) Wideband RF SI Canceller

- 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

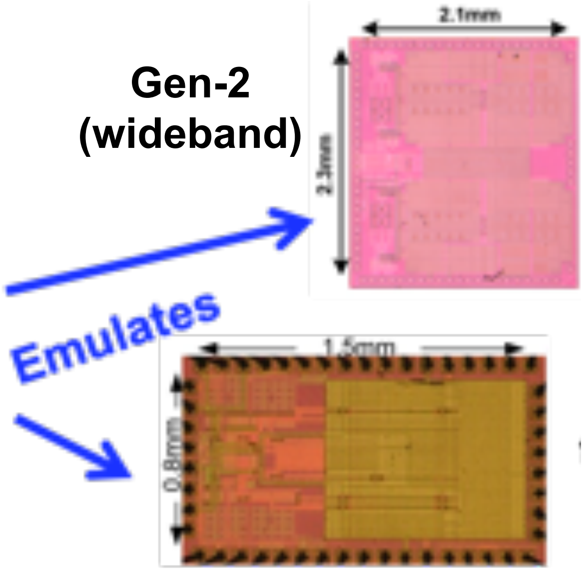


Gen-1 (narrowband) and Gen-2 (wideband) canceller boxes integrated in ORBIT

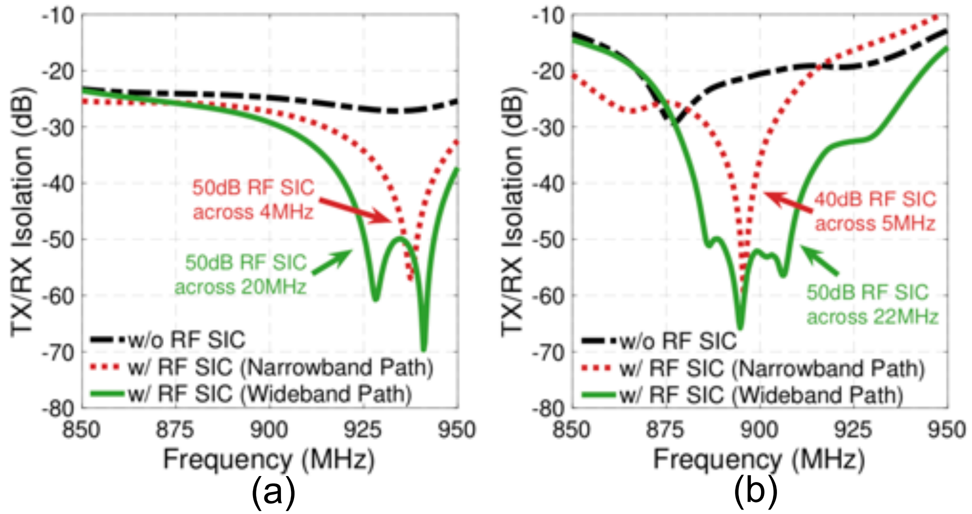


Gen-2/Gen-1 Printed circuit board (PCB)

Gen-2 (wideband)



Gen-1 (narrowband)



Measured RF SIC w/ the circulator is: (a) terminated by 50Ω and (b) connected to an antenna

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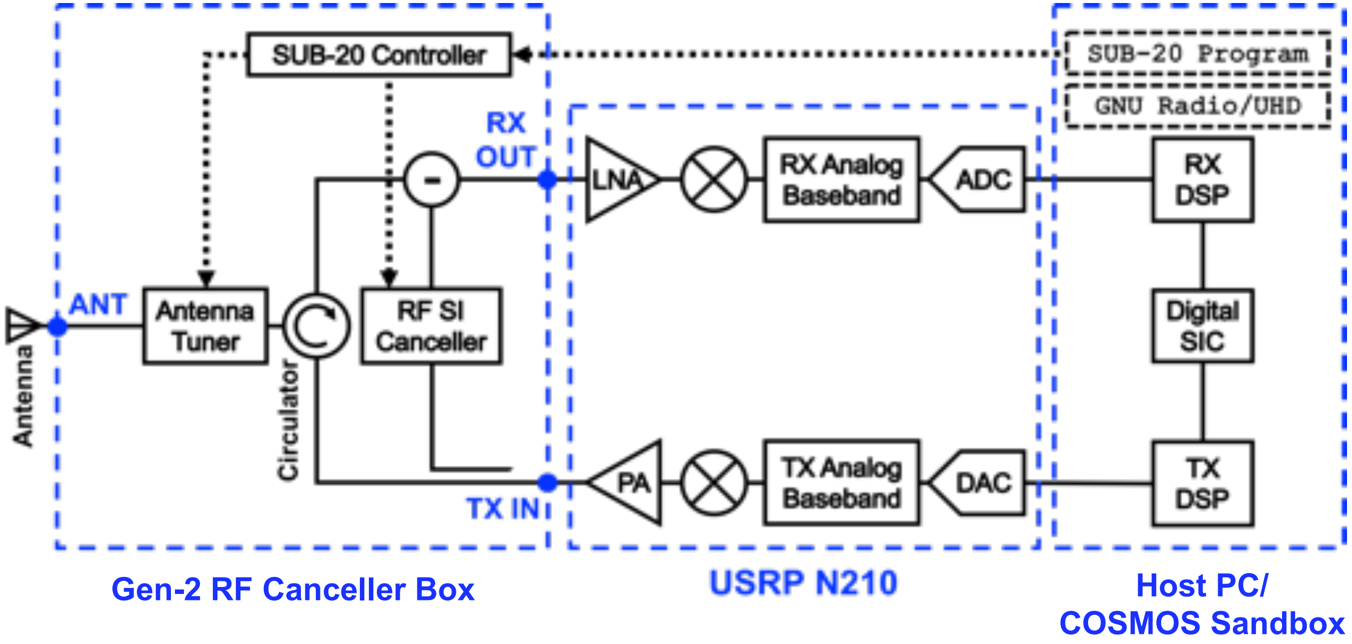
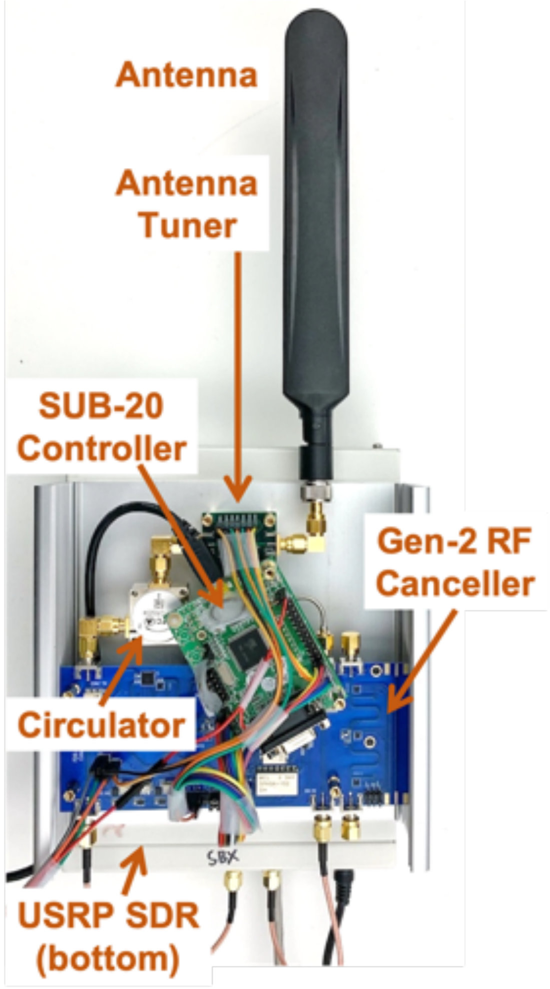
- ***Recap of goals:***
  - Make our customized hardware available for any researcher to use for design and evaluation of higher-layer algorithms and protocols suitable for full-duplex and heterogenous networks
  - Demonstrate ability to install customized experimental hardware into COSMOS for evaluation

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





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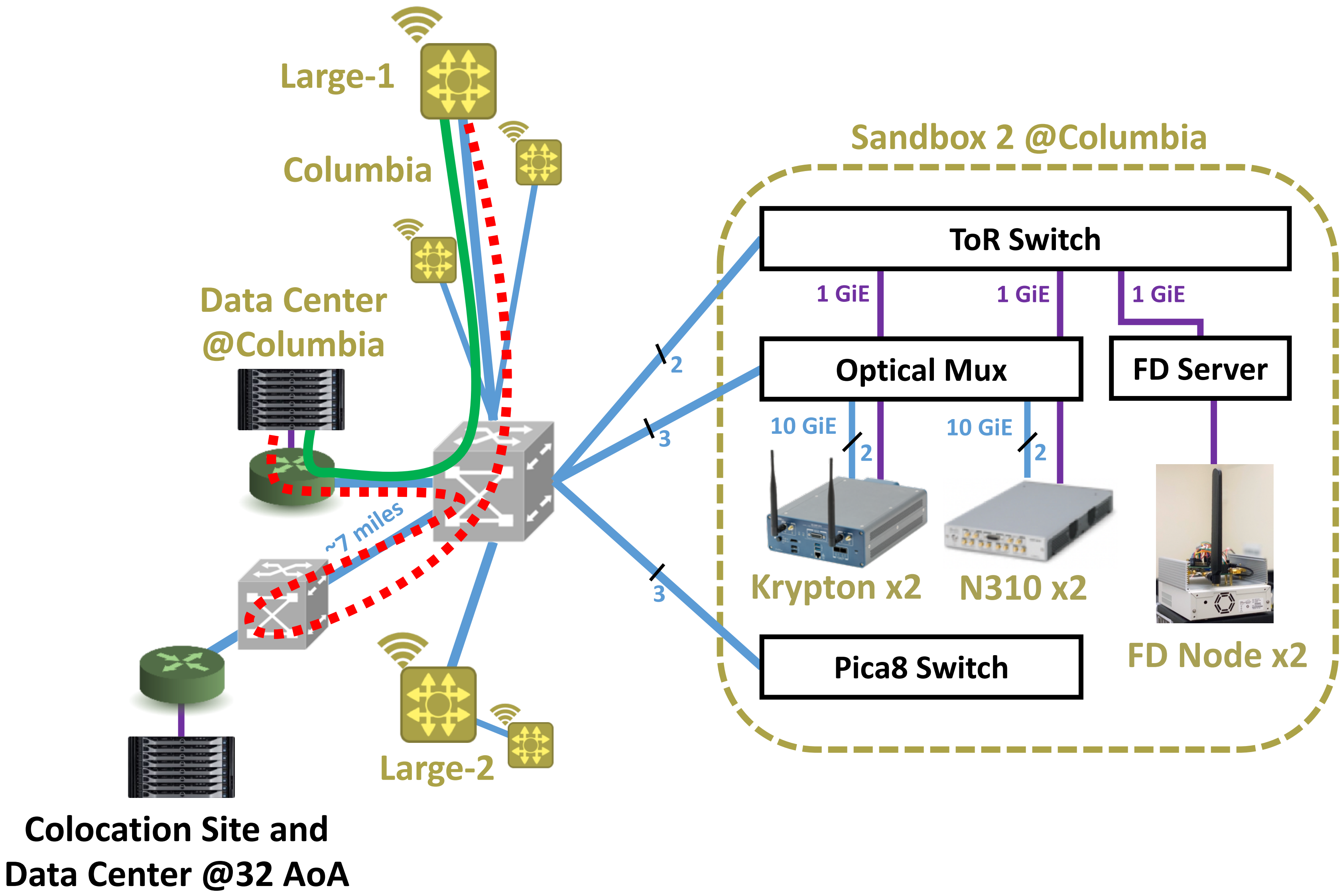
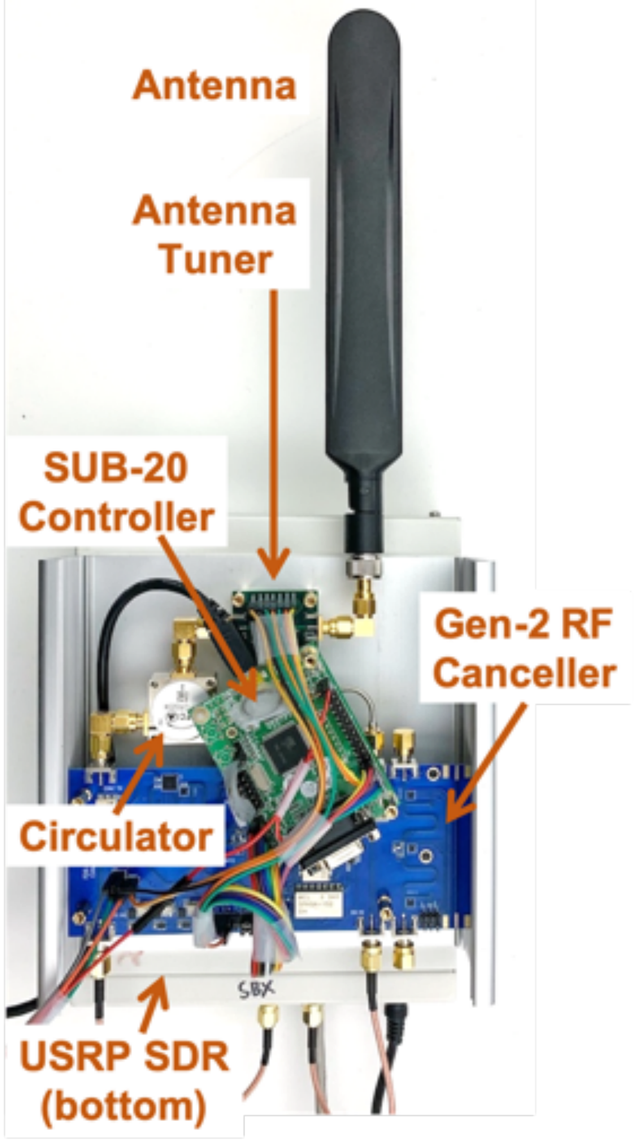
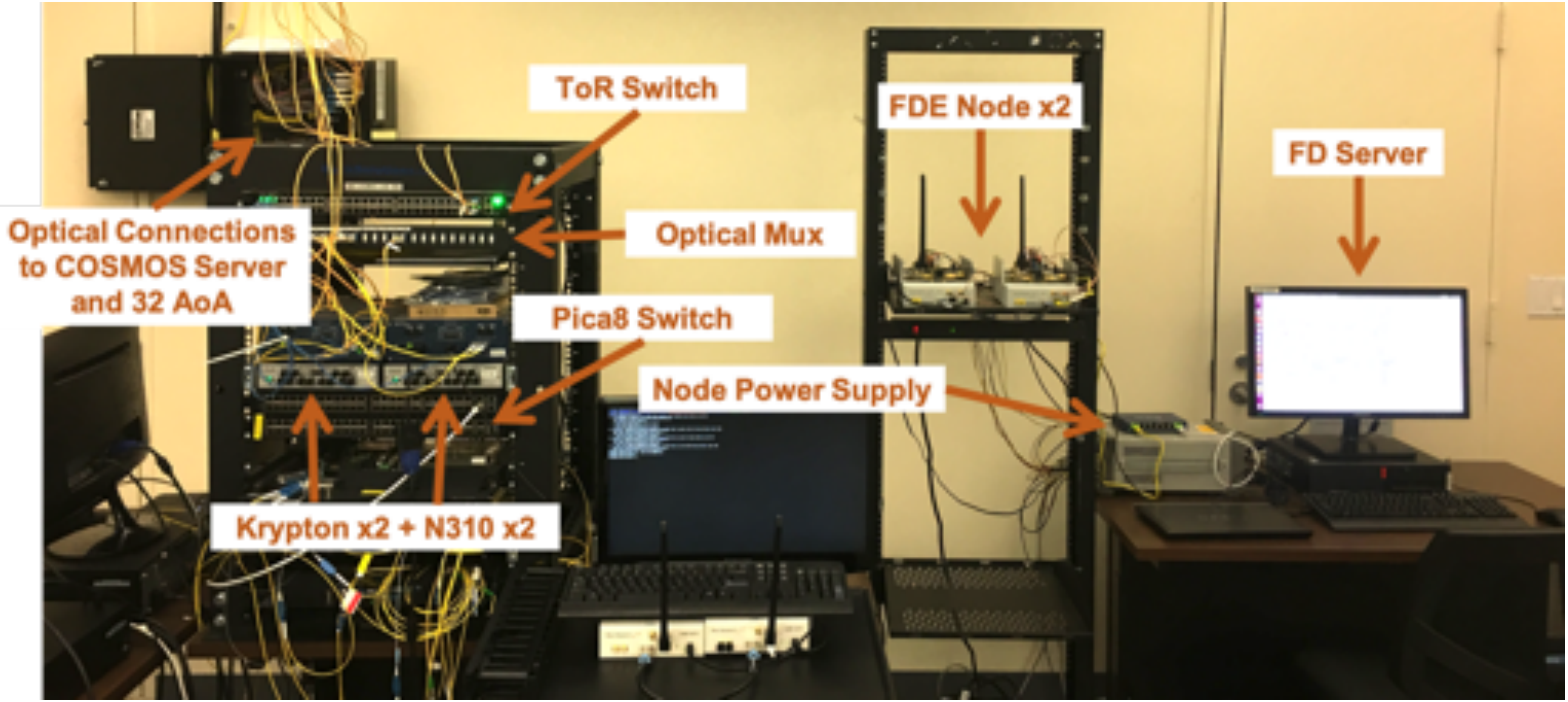
- “Tutorial: Full-duplex wireless in the COSMOS testbed,” available at https://wiki.cosmos-lab.org/wiki/tutorials/full_duplex. Source code available at https://github.com/Wimnet/flexicon_orbit

Integration with COSMOS





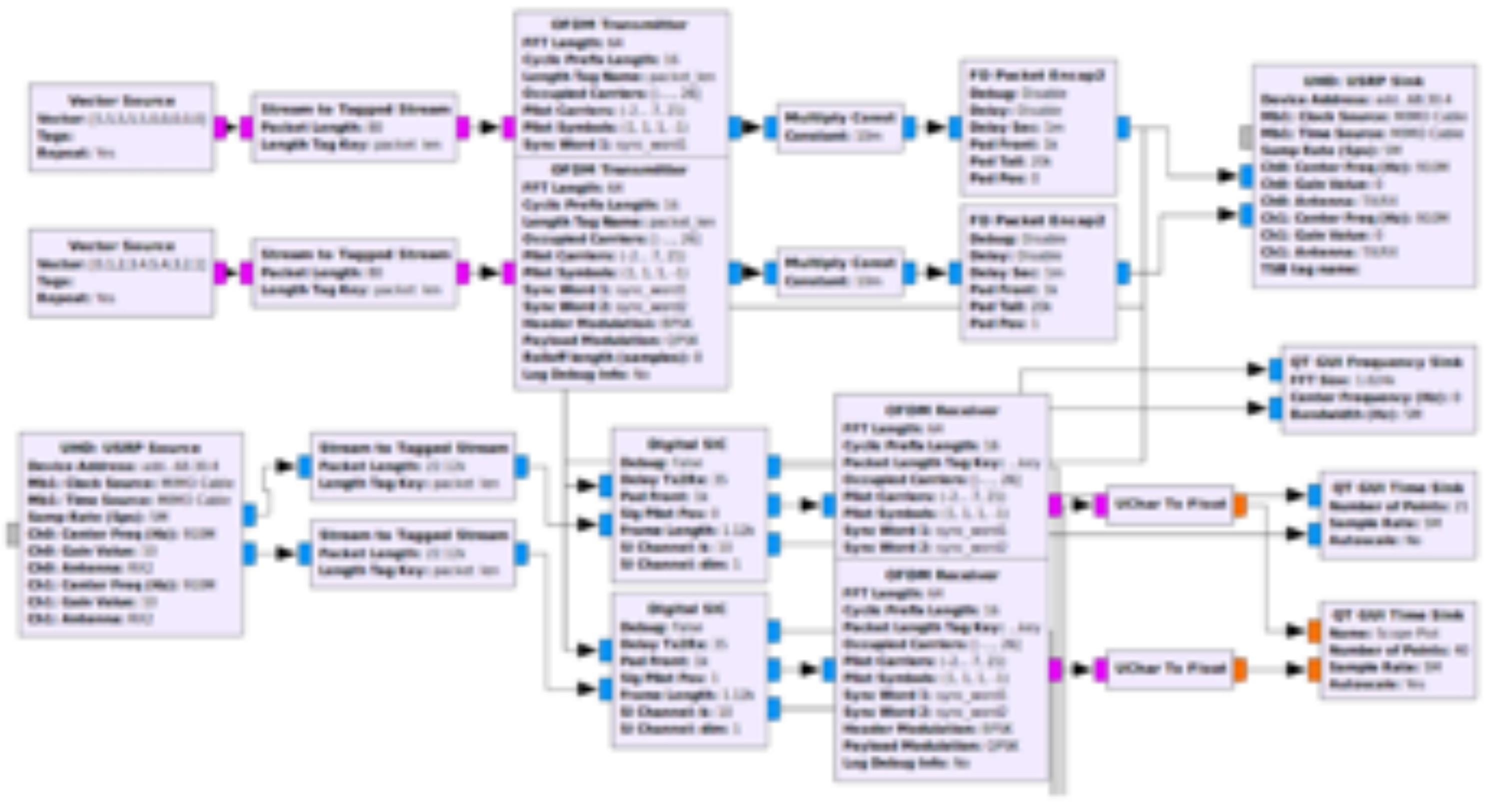
Integration with COSMOS

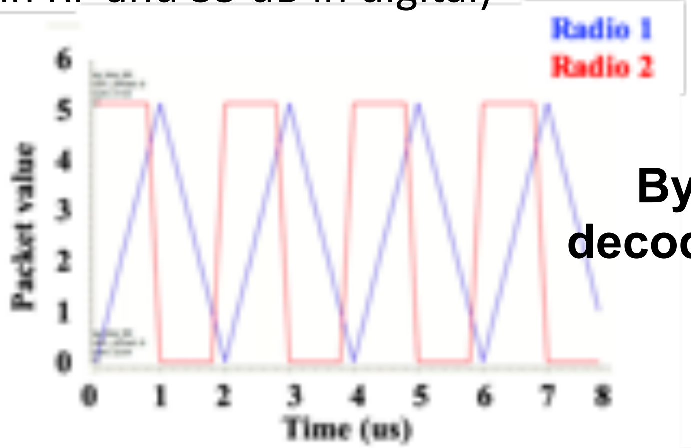


Integration with COSMOS

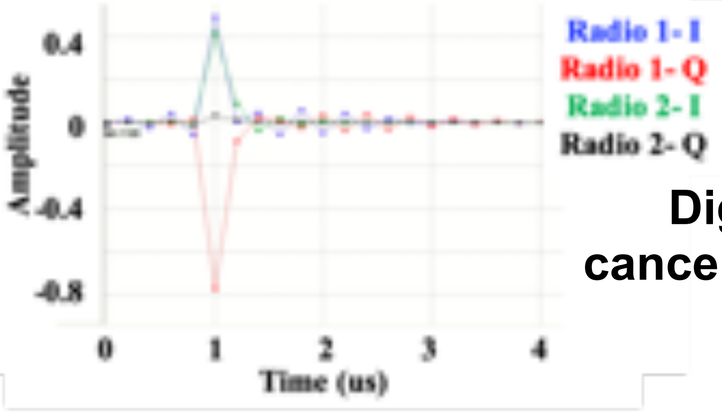
OFDM Link Experiment

- 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 coefficients.
  - 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

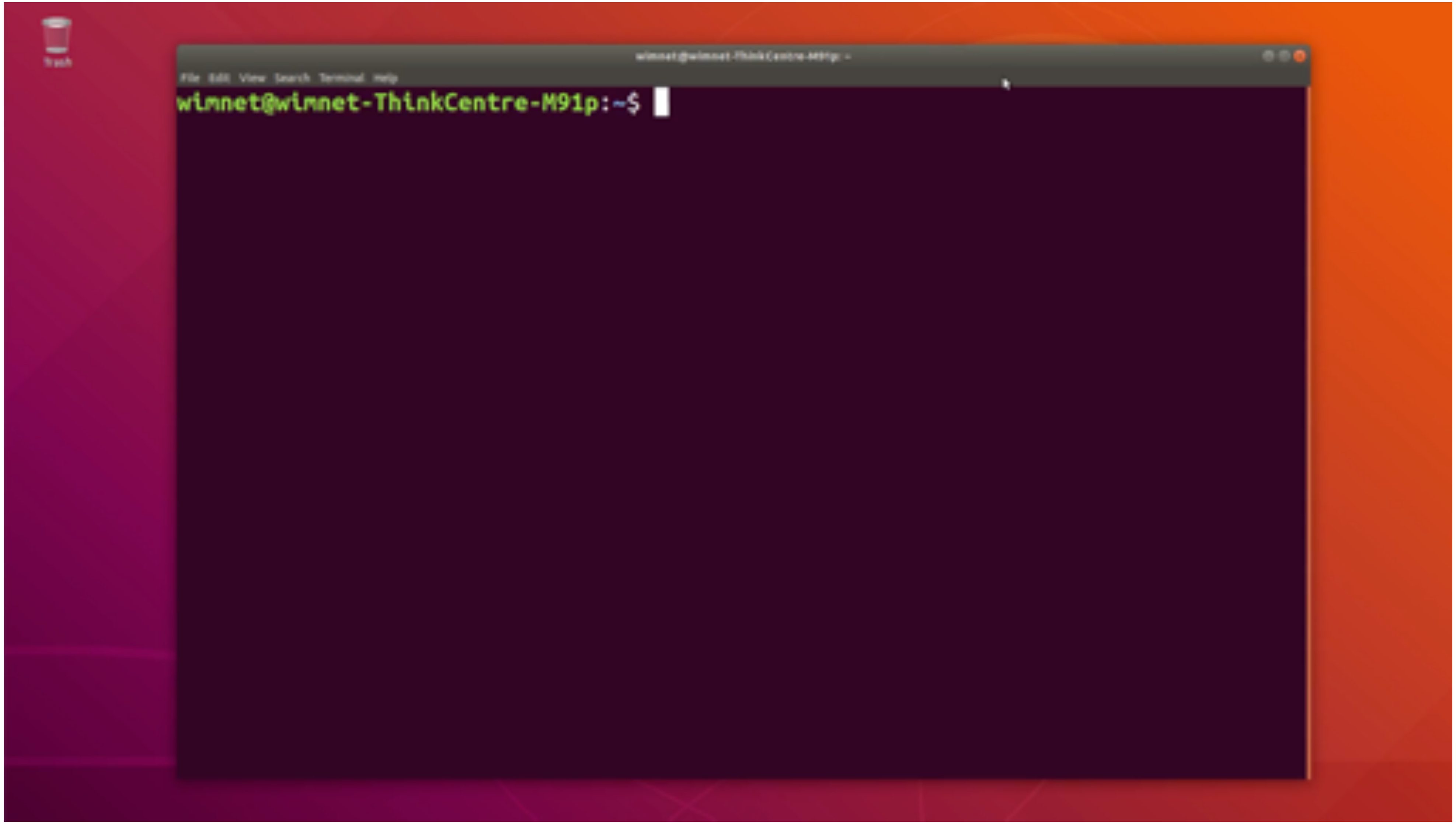


Digital SI canceller coeffs.

OFDM Link Experiment

- We use two FD nodes integrated in COSMOS sandbox (`sb2`)
- The detailed tutorial can be found on the COSMOS wiki (ADD LINK)
- 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

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

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http://wimnet.ee.columbia.edu/people/current-members/tingjun-chen/