# Open-Access Full-Duplex Wireless in the ORBIT and COSMOS Testbeds

**Manav Kohli**[*], Tingjun Chen, Jackson Welles[*], 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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ORBIT COSMOS FlexICoN CoSMIC wim.net Wireless & Mobile Networking Lab WINLAB

# Introduction

- Demand for wireless testbeds has increased - need for well-controlled wireless experimentation
- ORBIT testbed established in 2005: an **open-access** testbed for users in academia and industry
- New demand for an outdoor testbed for research into technologies such as mmWave and 5G
- PAWR COSMOS testbed currently being deployed in New York City to support **open-access** experimentation in a realistic, city-scale environment
- Opportunity for experimentation with custom hardware, e.g. **full-duplex wireless**

- D. Raychaudhuri, I. Seskar, M. Ott, S. Ganu, K. Ramachandran, H. Kremo, R. Siracusa, H. Liu, and M. Singh, "Overview of the ORBIT radio grid testbed for evaluation of next-generation wireless network protocols," in *Proc. IEEE Wireless Communications and Networking Conference, 2005*.
- D. Raychaudhuri, I. Seskar, G. Zussman, T. Korakis, D. Kilper, T. Chen, J. Kolodziejski, M. Sherman, Z. Kostic, X. Gu, H. Krishnaswamy, S. Maheshwari, P. Skrimponis, and C. Gutterman, “Challenge: COSMOS: A City-Scale Programmable Testbed for Experimentation with Advanced Wireless,” in *Proc. ACM MobiCom’20, 2020.*

# Outline

- ORBIT and COSMOS testbeds
- Full-Duplex (FD) Wireless
  - IC-Based Full-Duplex Wireless
  - Design of the Integrated Full-Duplex Radios
- The Integrated Gen-1 Narrowband FD Radio - ORBIT
- The Integrated Gen-2 Wideband FD Radio - COSMOS
- Experiments
  - Example experiment: Real-time Packet Reception Ratio

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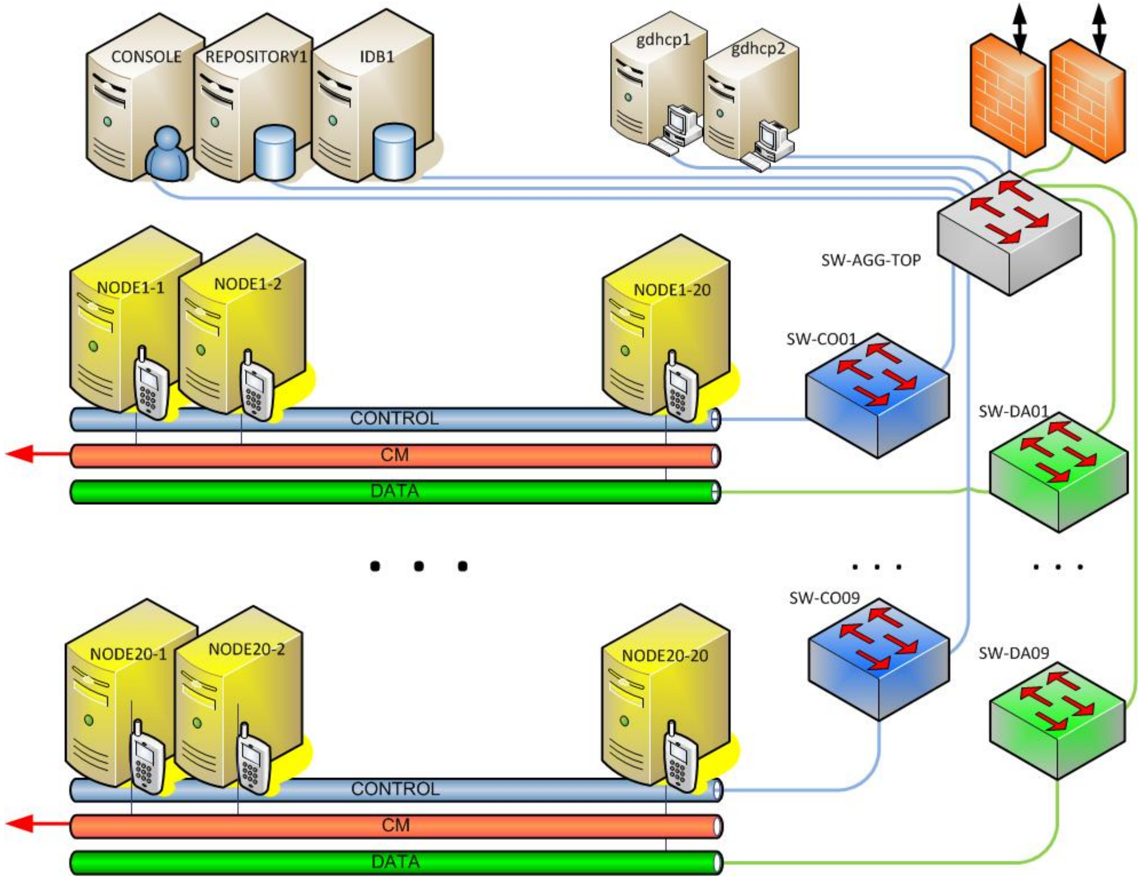
# ORBIT Testbed Overview

- The ORBIT grid consists of an array of several hundred wireless nodes
- Nodes may be orchestrated to perform a wide range of wireless experiments
- Indoor location allows for a well-controlled experimental environment
- Nodes can be outfitted with **custom hardware**
- Enables **remotely-accessible** wireless experimentation in an indoor environment




ORBIT grid architecture

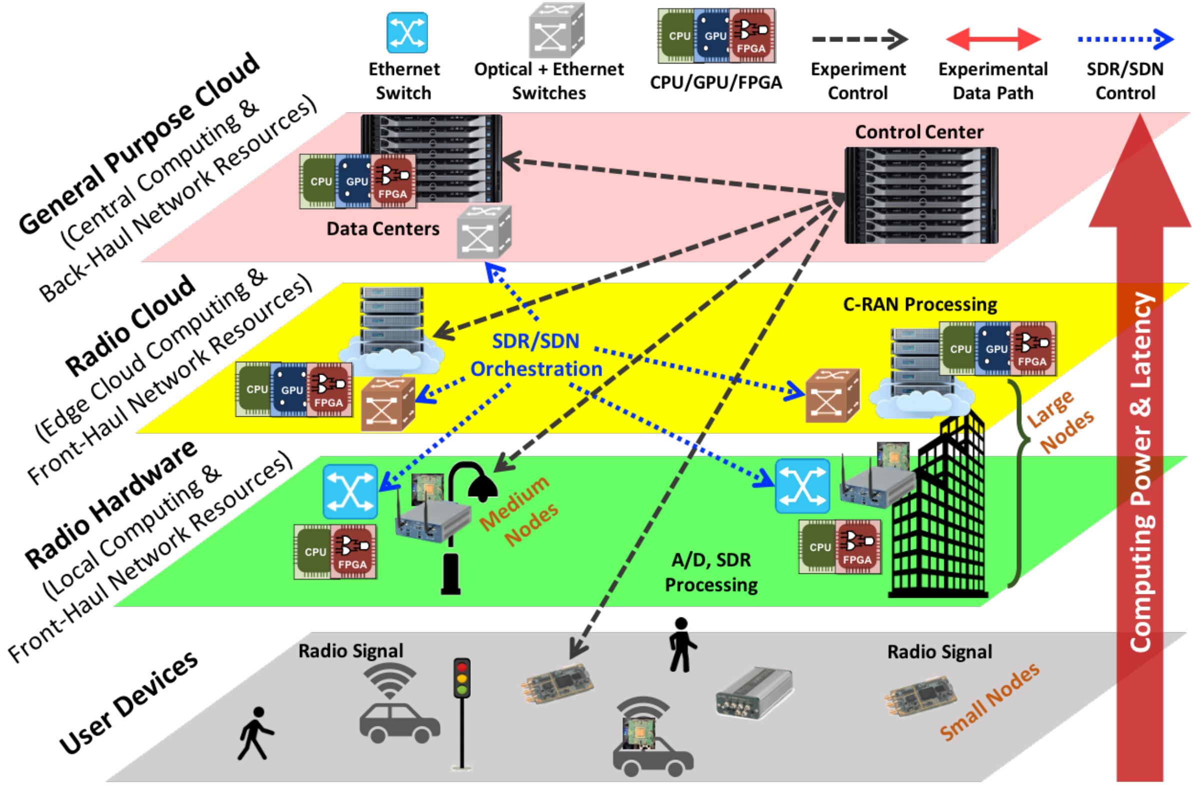
WINLAB

- D. Raychaudhuri, I. Seskar, M. Ott, S. Ganu, K. Ramachandran, H. Kremo, R. Siracusa, H. Liu, and M. Singh, "Overview of the ORBIT radio grid testbed for evaluation of next-generation wireless network protocols," in *Proc. IEEE Wireless Communications and Networking Conference, 2005*.

# COSMOS Testbed Overview

- COSMOS aims to address the needs of next-generation wireless communications:
  - Low latency (<5ms) and ultra-high bandwidth (multi-Gb/s)
  - Abundant compute resources
  - Real-time applications
  - Real-world investigation of urban environments

- Enablers:
  - 10s of 64 element mmWave arrays
  - 10s of miles of Manhattan dark fiber
  - B5G edge cloud base stations
  - Edge compute
  - **Integration of custom hardware**



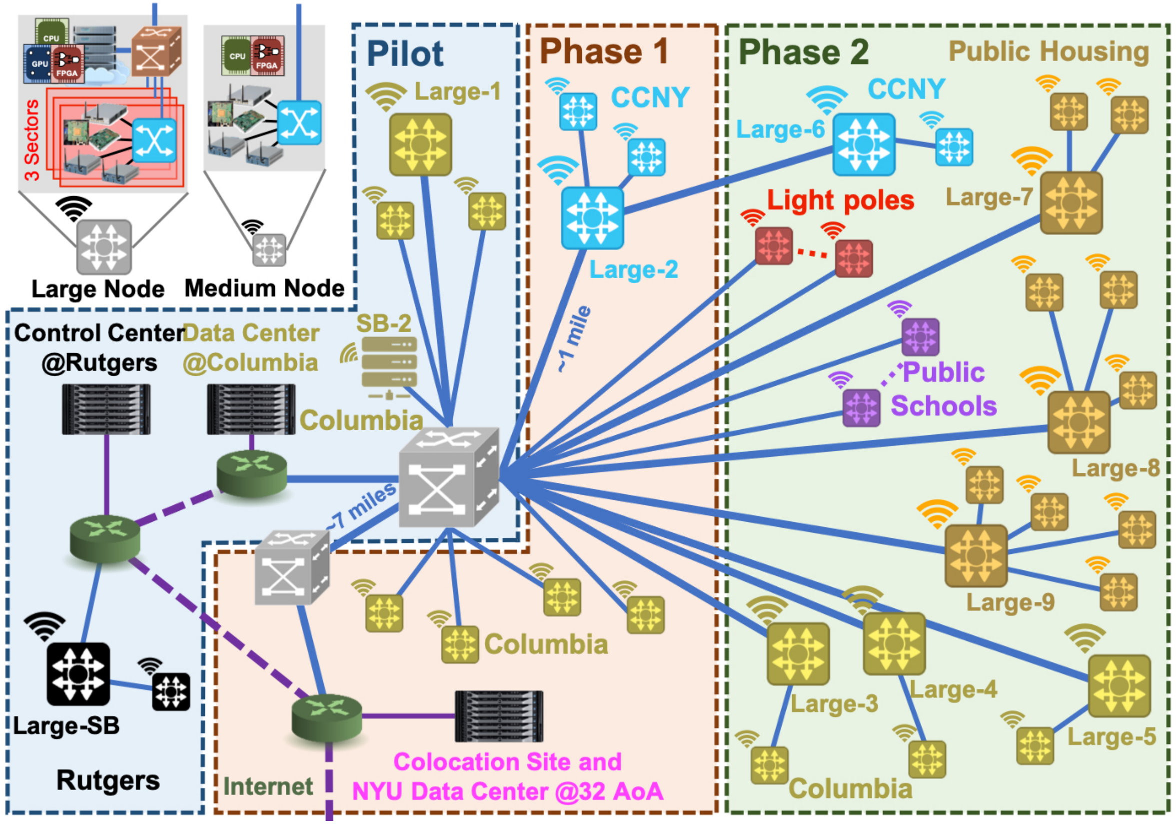

**COSMOS' multi-layered computing architecture**

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


- D. Raychaudhuri, I. Seskar, G. Zussman, T. Korakis, D. Kilper, T. Chen, J. Kolodziejski, M. Sherman, Z. Kostic, X. Gu, H. Krishnaswamy, S. Maheshwari, P. Skrimponis, and C. Gutterman, "Challenge: COSMOS: A City-Scale Programmable Testbed for Experimentation with Advanced Wireless," in *Proc. ACM MobiCom'20, 2020.*

# COSMOS Testbed Deployment Vision

- West Harlem, area: ~1 sq. mile
- Phased approach:
  - May 2019: Pilot completion
  - Sept. 2019: FCC Innovation Zone
  - June 2020: Generally available
  - During 2021: Phase 1 completion
- Fiber optic connection from most sites
- Fiber optic connection to Rutgers, NYU Datacenter at 32 Ave. of the Americas, GENI, Internet2, etc.




- Two sandboxes (Rutgers, Columbia)
  - Internal environments for controlled experimentation

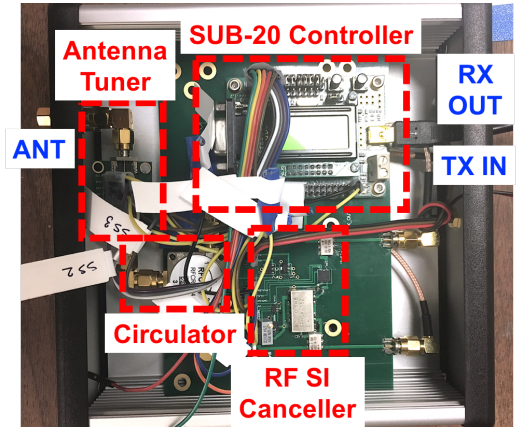
# Open-Access Custom Hardware and Experiments

- Development of the COSMOS testbed driven by deployment of **custom hardware**
- Pilot experiment: **Full-Duplex (FD) Wireless**

FlexICoN
Full-duplex wireless: from Integrated Circuits to Networks

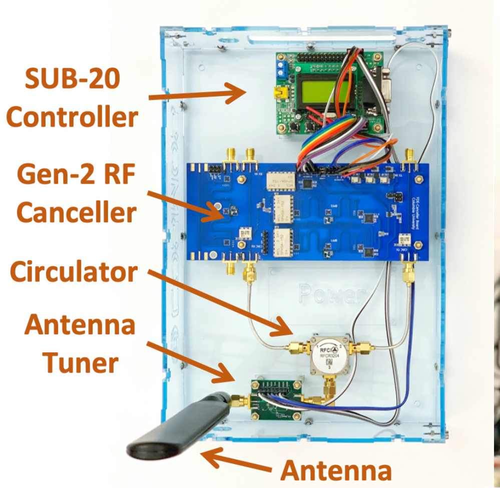
**(Columbia, COSMIC & WiMNeT groups)**

- FlexICoN project: design and evaluate algorithms and protocols across various layers of the network stack for **IC-based full-duplex nodes**
- ***Goals:***
    - Make our customized hardware **openly-accessible** to researchers
    - Demonstrate successful integration of customized experimental hardware into ORBIT and COSMOS




**Gen-1 canceller box**


**Gen-1 narrowband full-duplex radio integrated into ORBIT**




**Gen-2 canceller box**


**Gen-2 wideband full-duplex radio integrated into COSMOS**

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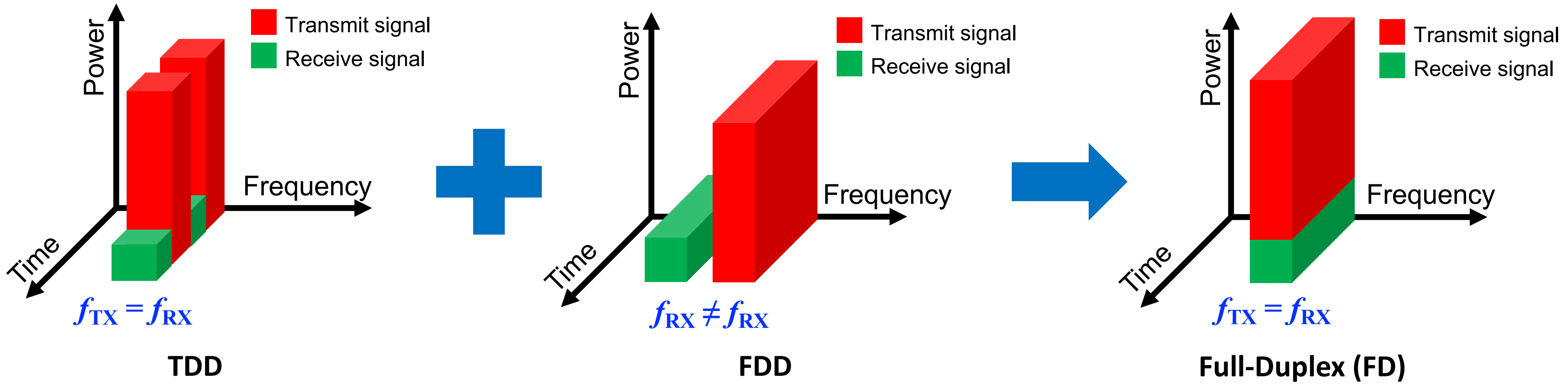
# Full-Duplex Wireless

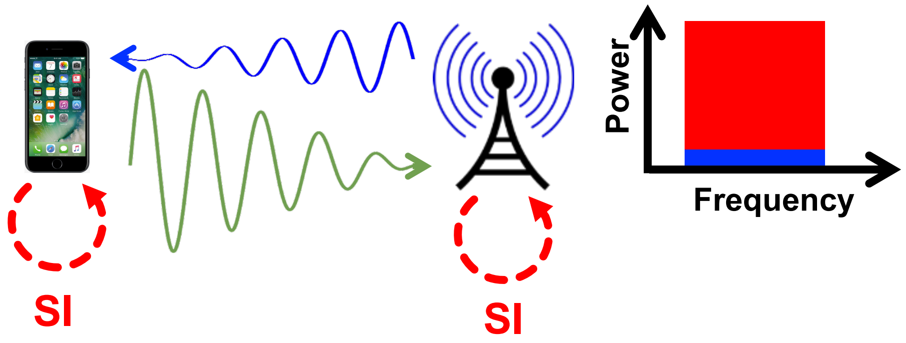
- Legacy half-duplex (HD) wireless systems separate transmission and reception in either:
  - Time: Time Division Duplex (TDD)
  - Frequency: Frequency Division Duplex (FDD)

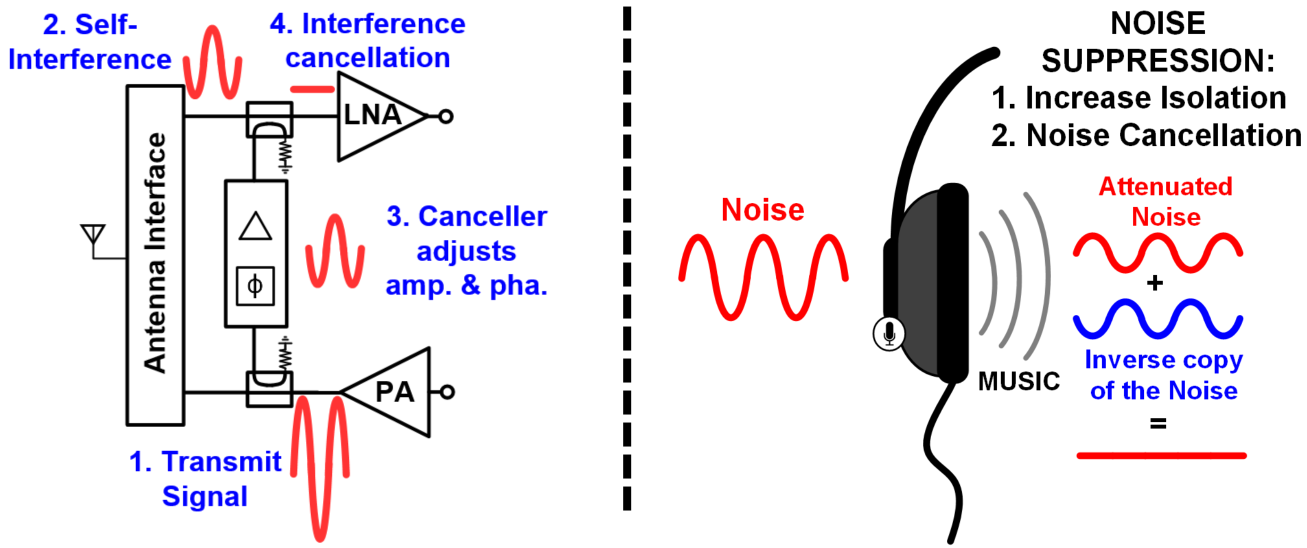
- (In-band) **Full-duplex (FD)** wireless: simultaneous transmission and reception on the same frequency channel



# Full-Duplex Wireless

- Benefits of FD wireless:
  - Increased system throughput and reduced latency
  - More flexible use of the wireless spectrum
- One of the main challenges: self-interference (SI)
  - Transmitted signal is **billions** of times (**$10^9$ or 90 dB**) stronger than the received signal
  - Requires extremely powerful SI cancellation (SIC) across ***antenna***, ***RF***, and ***digital*** domains



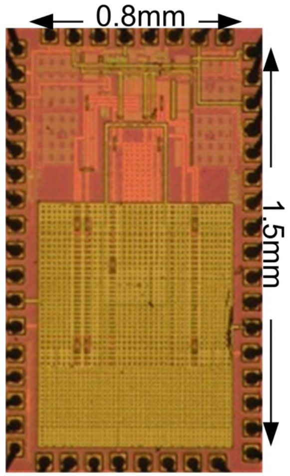



# Prior Work

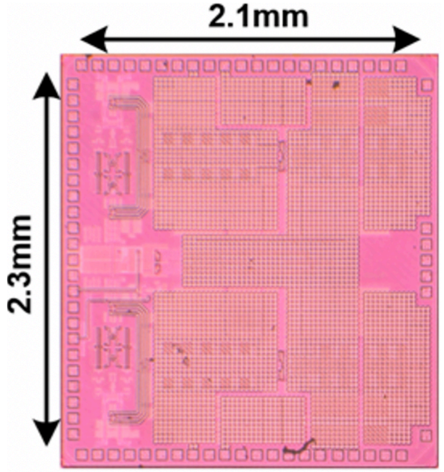
- Surveys of FD wireless systems [*Sabharwal et al.* 2014, *Kolodziej et al.* 2019]
- Time-domain delay line-based wideband RF cancellers: each fixed delay line associated with one amplitude control [*Bharadia et al.* 2013], or one amplitude and phase control [*Korpi et al.* 2016]
- Tx and Rx antenna pairs used to achieve Tx/Rx isolation at the antenna interface [*Choi et al.* 2010*, Radunovic et al.* 2010*, Jain et al.* 2011]
- FD phased array with narrowband analog Tx beamforming [*Aryafar & Haddad*, 2018]
- FD relays for wireless networks [*Shaboyan et al*. 2020]
- Analysis of FD rate gains in wireless networks [*Nguyen et al.* 2014, *Wang et al.* 2017]
- FD systems predominantly evaluated in simulation or lab-based testbeds [*Hsu et al.* 2017*, Chen et al.* 2017]

# Compact Full-Duplex Wireless

- Delay line-based cancellers [*Bharadia et al. 2013*, *Korpi et al. 2016*] difficult to implement in compact integrated circuits (IC)s due to space constraints
- FlexICoN project: two generations of **compact, IC-based** RF SI cancellers: *narrowband* 1st-generation (Gen-1) and *wideband* 2nd-generation (Gen-2), suitable for **handheld devices**
- Gen-1 and Gen-2 RF SI cancellers **both implemented as ICs**




**Gen-1 die photograph**

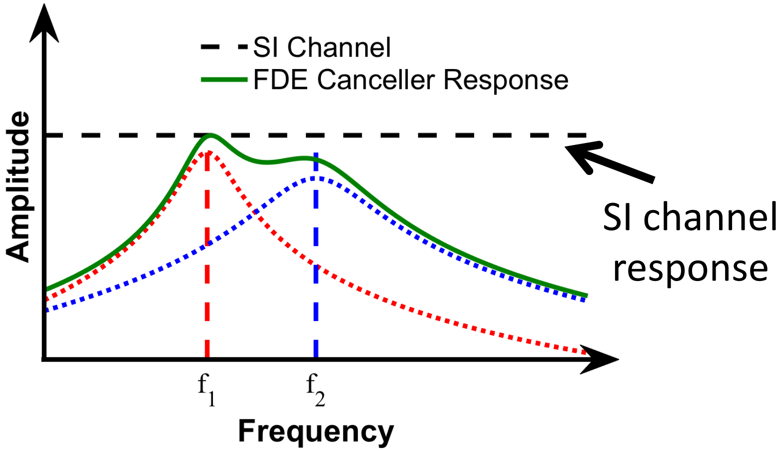



**Gen-2 die photograph**

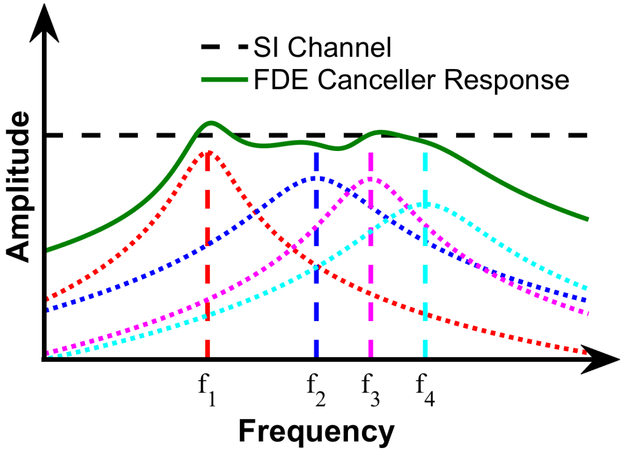

- J. Zhou, A. Chakrabarti, P. Kinget and H. Krishnaswamy, "Low-noise active cancellation of transmitter leakage and transmitter noise in broadband wireless receivers for FDD/co-existence," *IEEE J. Solid-State Circuits*, vol. 49, no. 12, pp. 3046–3062, Dec. 2014
- J. Zhou, T. Chuang, T. Dinc, and H. Krishnaswamy, "Integrated Wideband Self-Interference Cancellation in the RF Domain for FDD and Full-Duplex Wireless", *IEEE J. Solid-State Circuits*, vol. 50, no. 12, pp. 3015–3031, 2015.

# Wideband Full-Duplex Wireless

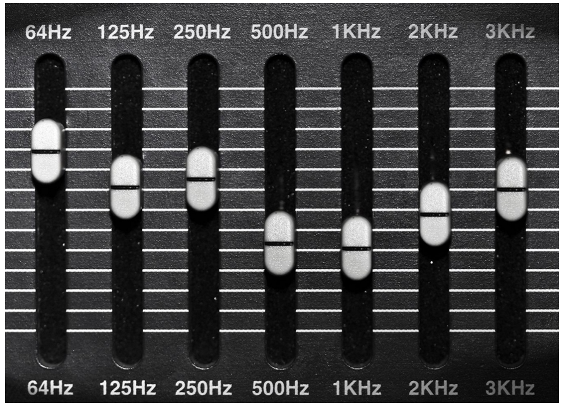
- **Frequency-domain equalization (FDE) based canceller**: The SI channel can be emulated in the *frequency domain* using reconfigurable RF bandpass filters (BPFs) with amplitude and phase controls. Multiple FDE taps used to enable **wideband** operation
  - Suitable for compact IC-based implementations
  - Each FDE tap has four variables: BPF center frequency, BPF quality factor, amplitude, and phase
- Currently the only example of an FDE-based RF SI canceller




**2 FDE taps**




**4 FDE taps**




**Audio Equalizer**


- J. Zhou, T. Chuang, T. Dinc, and H. Krishnaswamy, “Integrated Wideband Self-Interference Cancellation in the RF Domain for FDD and Full-Duplex Wireless”, *IEEE J. Solid-State Circuits*, vol. 50, no. 12, pp. 3015–3031, 2015.

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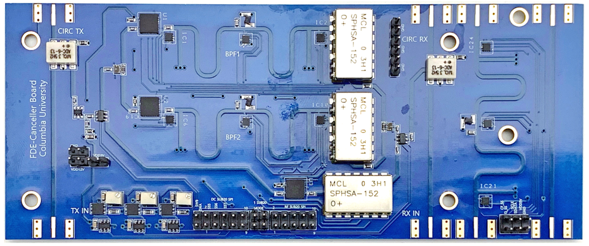
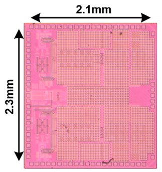
# Design of the Integrated Full-Duplex Radios

- Successful FD communication needs at least 90 dB of self-interference cancellation (SIC) across the RF and digital domains
- We emulate the IC-based FD cancellers on a printed circuit board (PCB) to provide an easy interface to the SDR
  - Also provides better noise figure and lower DC power consumption than the IC-based canceller



Emulates

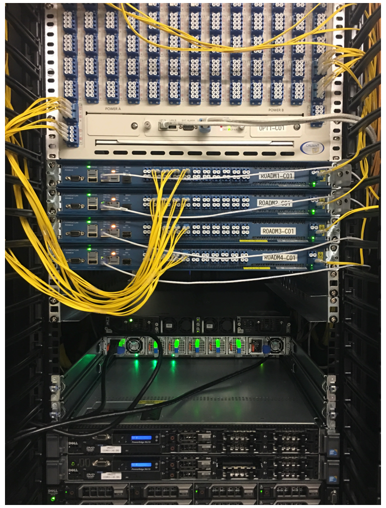



**RF SI Canceller PCB and components**

+

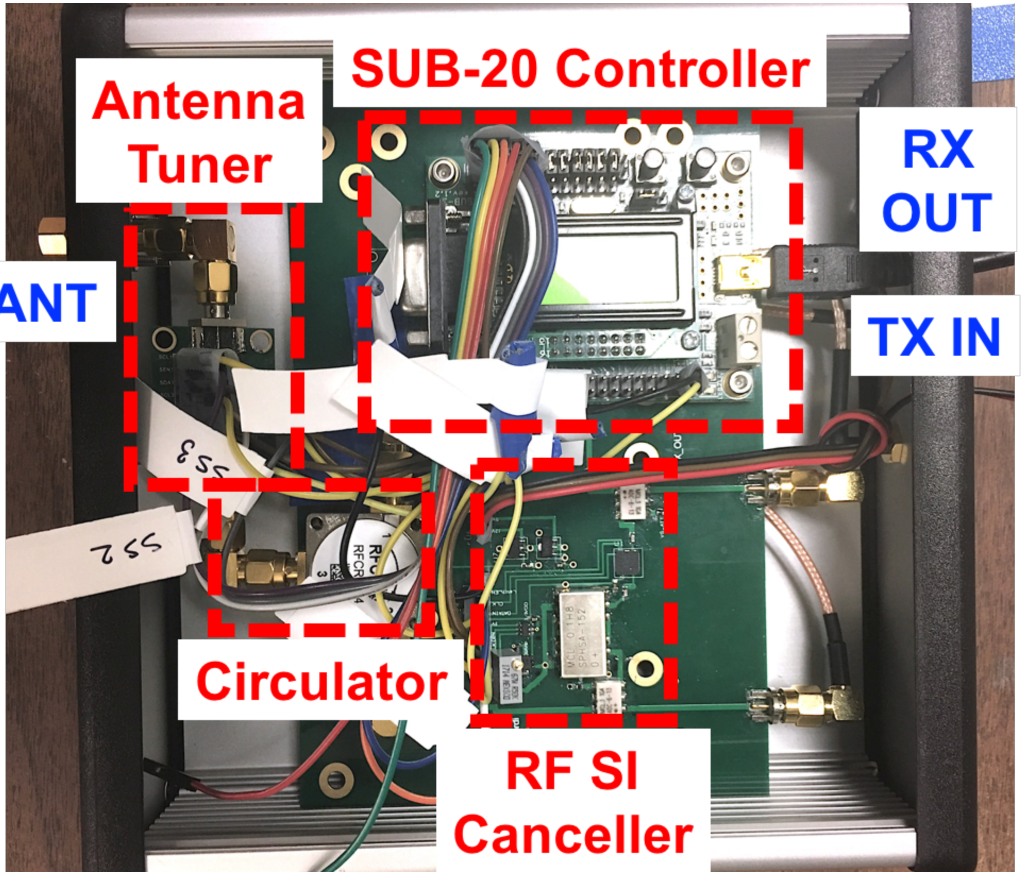
**Software-defined radio (SDR)**

+

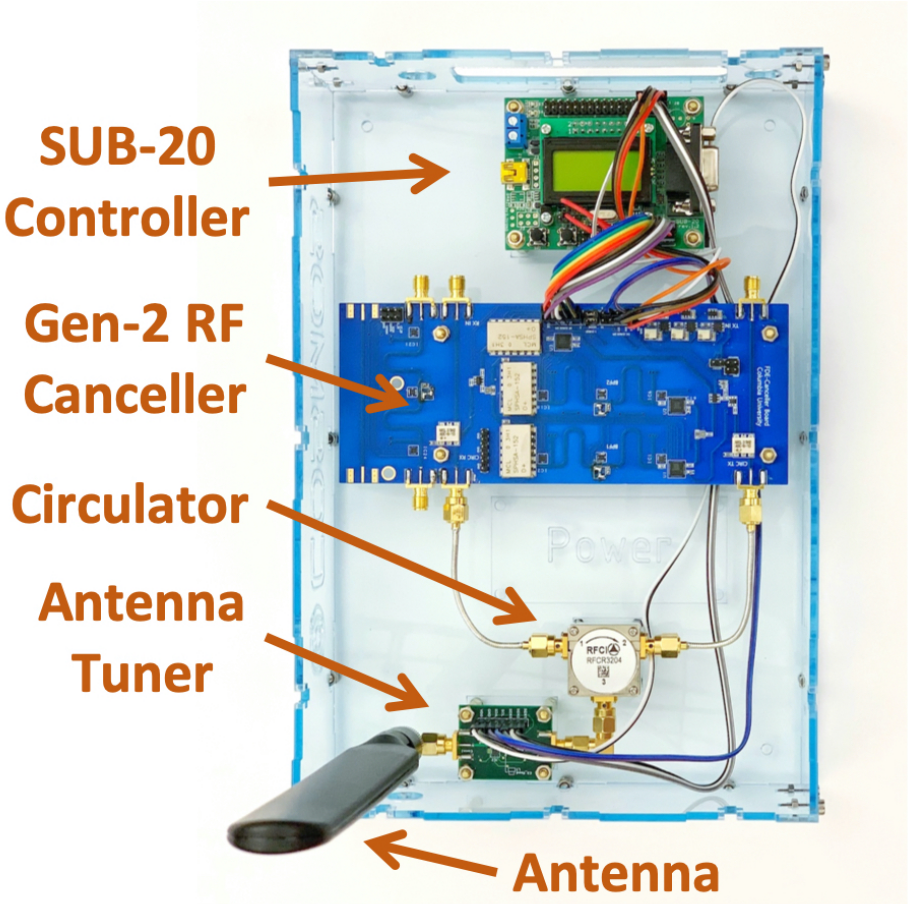


**Remote-access compute**

# Design of the Gen-1/Gen-2 Canceller Boxes




Gen-1 canceller box integrated in the ORBIT testbed




Gen-2 canceller box integrated in the COSMOS testbed

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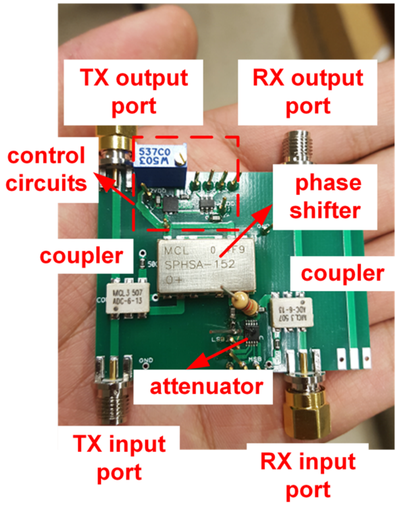
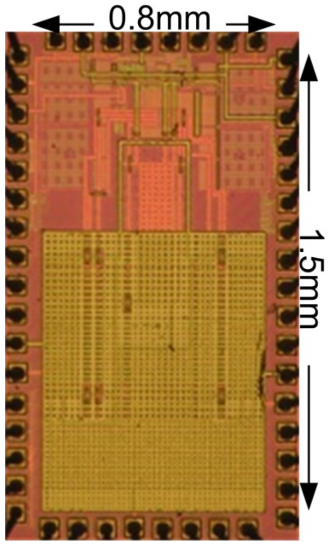
# Gen-1 Narrowband RF SI Canceller

- Emulates the narrowband RFIC canceller on a PCB
- The canceller PCB has two tunable components
  - Phase shifter is controlled by an 8-bit DAC, giving full 360 degree tuning range
  - Attenuator has 7-bit control and 31.5 dB tuning range
- Both components programmed through the SUB-20 API

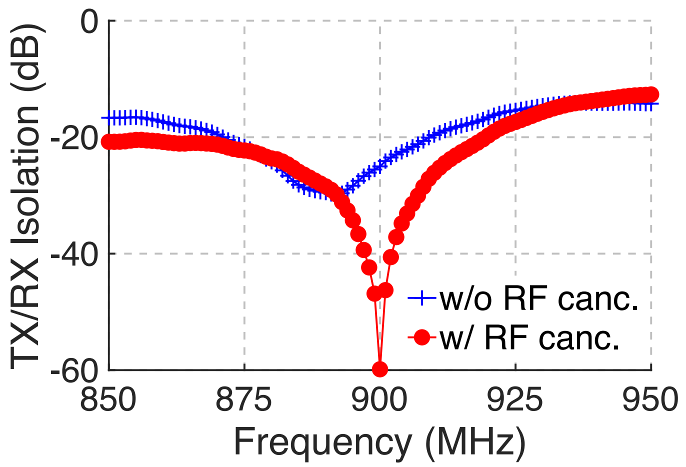



**Gen-1 RF SI Canceller**

Emulates the RFIC SI canceller



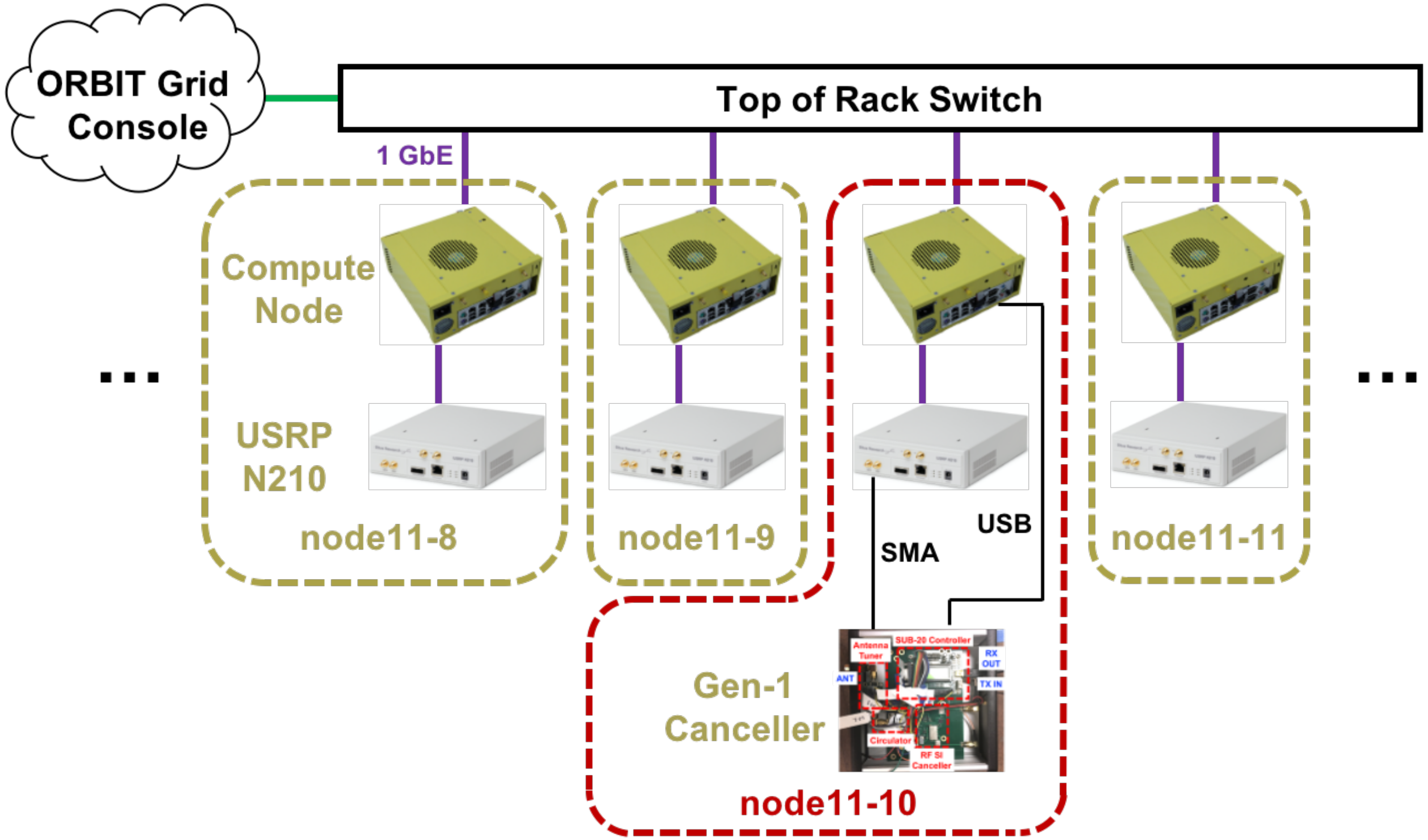

**Chip photo**




**Self-Interference Cancellation (SIC) measurement**

**Integration in ORBIT Testbed**

# Integration with ORBIT





Gen-1 RF canceller box with USRP N210 SDR integrated in ORBIT

The ORBIT grid array

- The integrated Gen-1 FD radio at node11-10 is **remotely accessible** to experimenters through the ORBIT grid console

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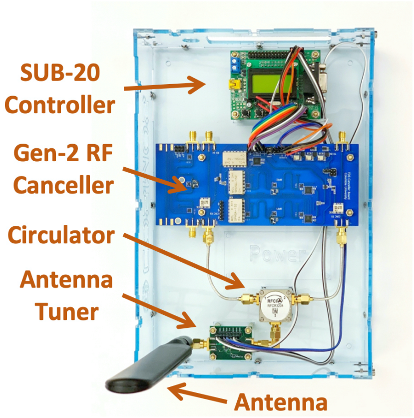
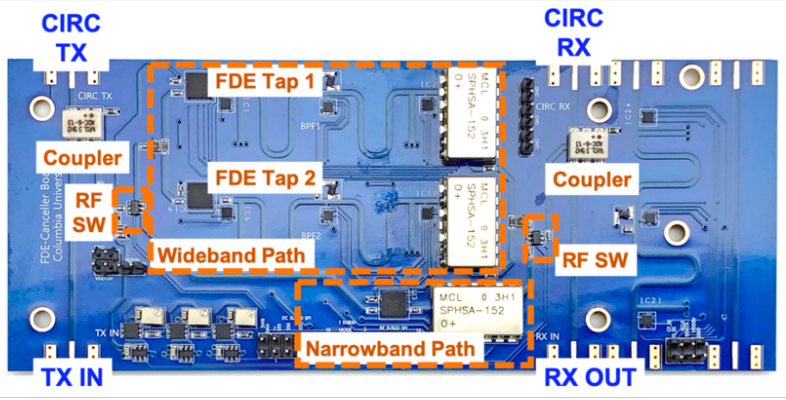
# Gen-2 Wideband RF SI Canceller

- The Gen-2 PCB also emulates the narrowband Gen-1 canceller. The experimenter can select this path by configuring the RF Switch on the PCB

- Two Gen-2 RF canceller boxes are integrated with USRP2 SDRs and a compute node in COSMOS Sandbox 2

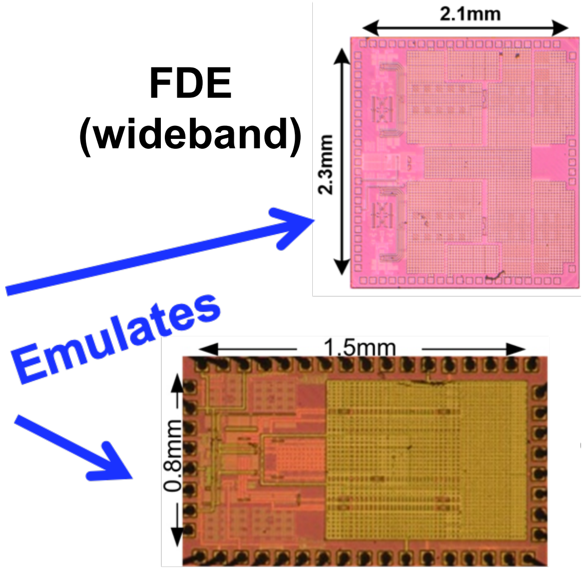



**Gen-2 RF canceller box**

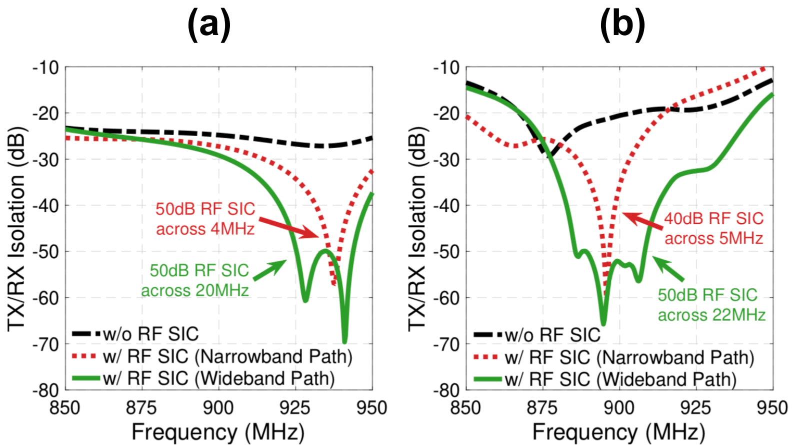



**Gen-2 RF canceller PCB**

**FDE (wideband)**




**Gen-1 (narrowband)**

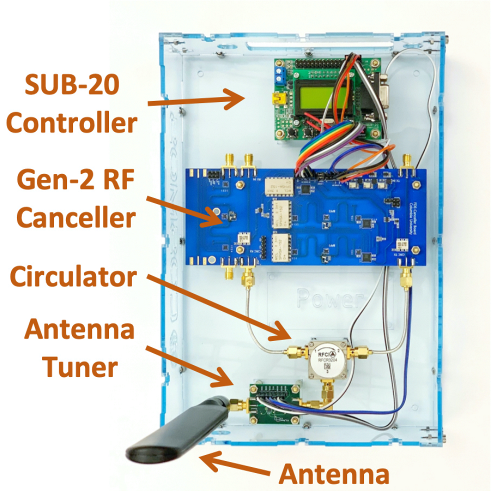



**Performance of canceller PCB when the circulator is (a) terminated by 50Ω and (b) connected to an antenna**

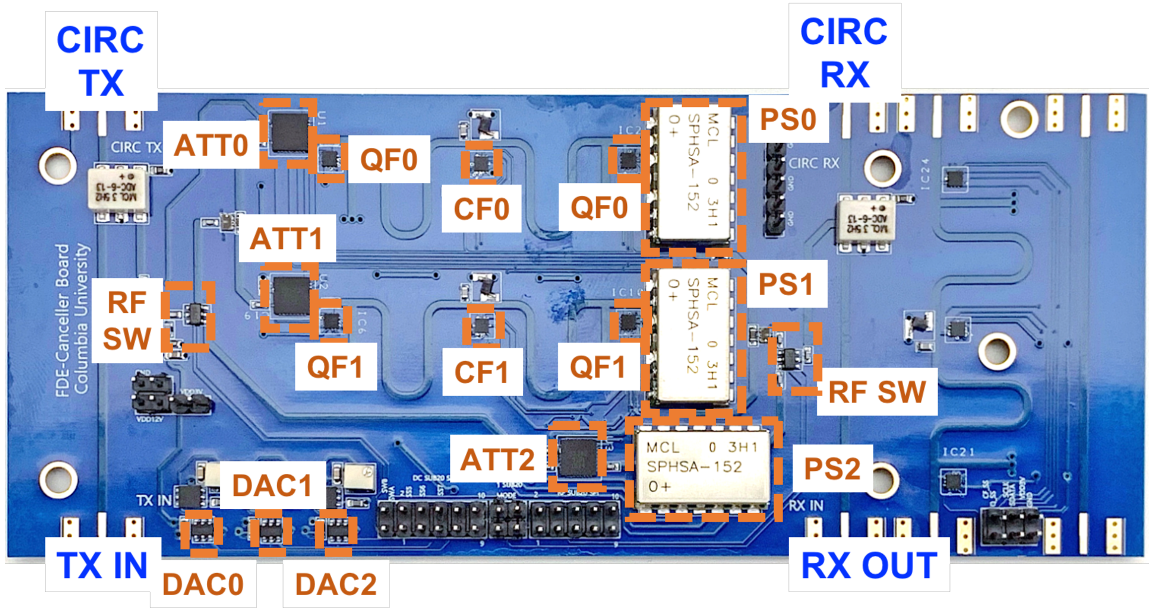

- T. Chen, M. Baraani Dastjerdi, J. Zhou, H. Krishnaswamy, and G. Zussman, "Wideband compact full-duplex wireless via frequency-domain equalization: Design and experimentation," in *Proc. ACM MobiCom'19,* 2019.

# Gen-2 Wideband RF SI Canceller

- The Gen-2 board has a total of 11 tunable components:
  - 3x attenuators (`ATT`)
  - 3x phase shifters (`PS`) controlled via 3x DAC (`DAC`)
  - 2x center frequency capacitors (`CF`)
  - 2x quality factor capacitors (`QF`)
  - 1x RF switch (`SW`)



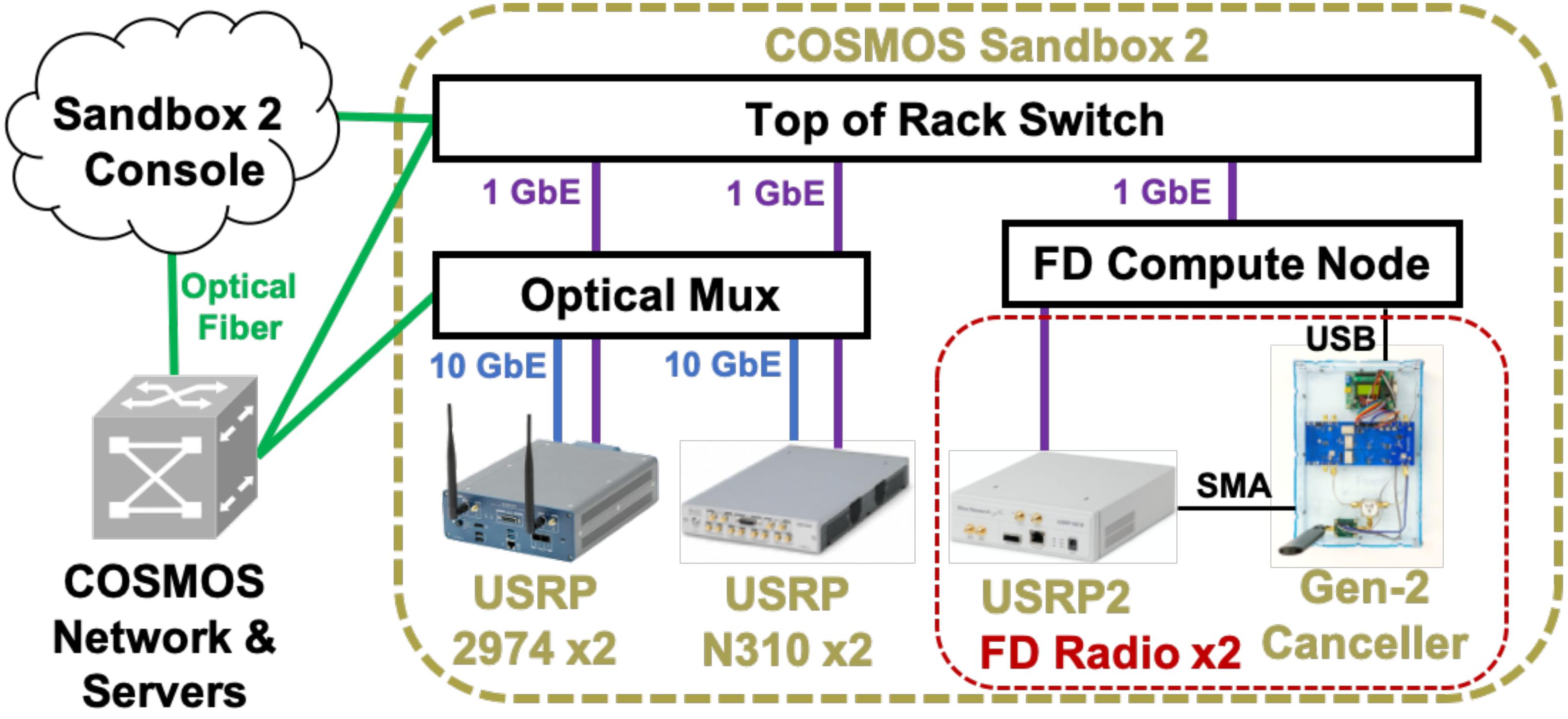

Gen-2 RF canceller box

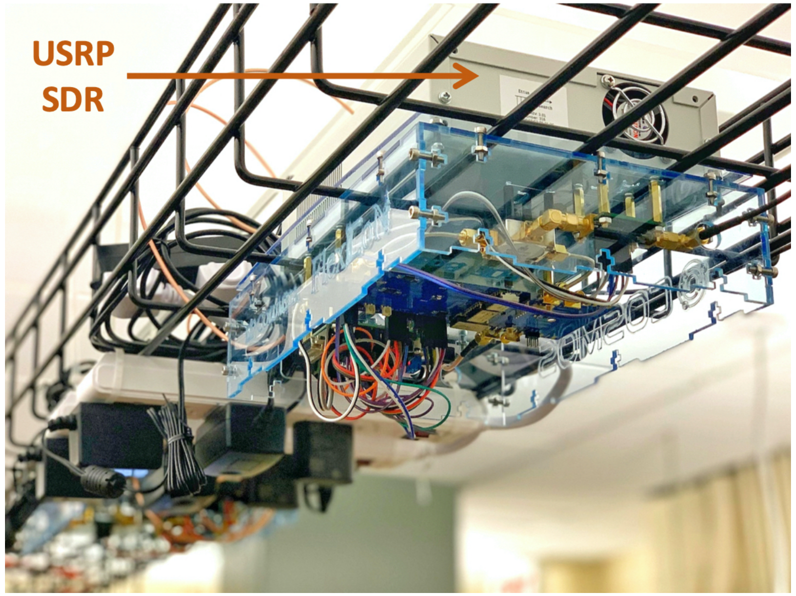



| Component | Values |
|---|---|
| Attenuator (ATT) | 0 – 127 (7-bit) |
| Phase Shifter (DAC) | 0 – 255 (8-bit) |
| Centre Frequency (CF) | 0 – 15 (4-bit) |
| Quality Factor (QF) | 0 – 31 (5-bit) |
| RF Switch (SW) | 0, 1 (1-bit) |

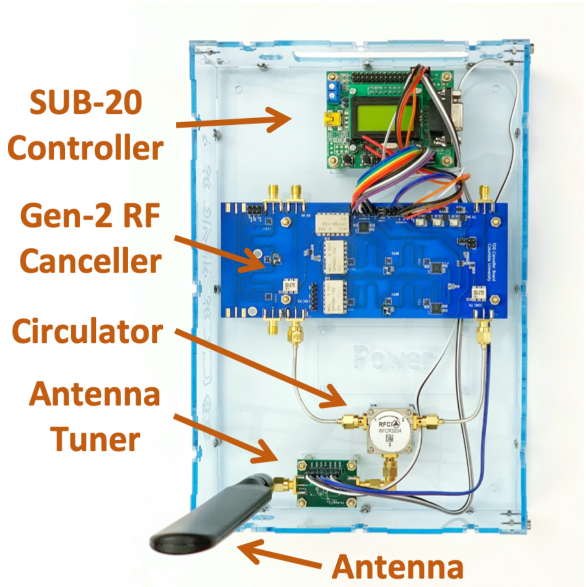
- T. Chen, M. Baraani Dastjerdi, J. Zhou, H. Krishnaswamy, and G. Zussman, “Wideband compact full-duplex wireless via frequency-domain equalization: Design and experimentation,” in *Proc. ACM MobiCom’19,* 2019.

# Integration with COSMOS




Gen-2 RF canceller box with USRP2 SDR integrated in COSMOS Sandbox 2




- The integrated Gen-2 FD radios are **remotely accessible** to experimenters through the COSMOS network and Sandbox 2 console

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# Logging into COSMOS and Accessing the FD Radios

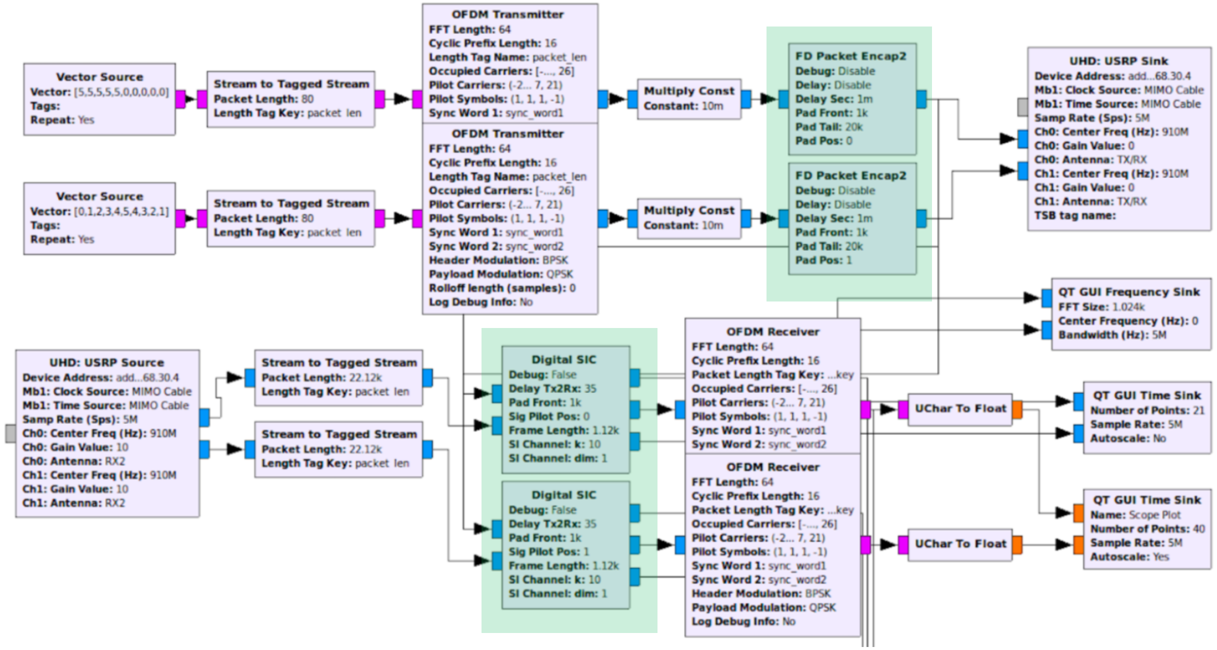
- Focus on COSMOS for the rest of presentation
  - Instructions for ORBIT are very similar and available at the link below
- Login to COSMOS Sandbox 2 over SSH
- Once logged into COSMOS Sandbox 2, SSH into the FD Compute Node
- GNU Radio experiments are run from the FD Compute Node

A full tutorial for using the integrated Gen-1 and Gen-2 FD radios can be found at this link:

https://wiki.cosmos-lab.org/wiki/Tutorials/Wireless/FullDuplex

# Experiments

- Developed a set of customized out-of-tree (OOT) blocks for GNU Radio
  - Designed to work with the built-in OFDM PHY layer blocks
- The OOT blocks are programmed in C++, allowing for **real-time performance**
- Developed OOT blocks include:
  - A block for performing digital SIC on the received signal
  - A block for configuring the canceller PCB via the SUB-20 controller
- Experiments are a baseline: researchers may use them for other experimentation scenarios




Example GNU Radio flowgraph with customized OOT blocks highlighted in green

# Conclusion

- Integrated a narrowband Gen-1 FD radio in the ORBIT testbed, and two wideband Gen-2 FD radios in the COSMOS testbed
- Provide example experiments, which may be used by others as a basis for further experimentation on FD
- Integration of FD radios serves as a blueprint for future integration of custom hardware in COSMOS
- In the near future, we will integrate the Gen-2 FD radios in COSMOS with higher performance USRP 2974s
- We will also integrate the Gen-2 FD radios with the COSMOS servers, allowing for a greater range of possible experiments

# Tutorial and open-source hardware and software

- The full tutorial for accessing the Gen-1 and Gen-2 FD radios and running these experiments: https://wiki.cosmos-lab.org/wiki/Tutorials/Wireless/FullDuplex
- The open-source hardware and software can be accessed at: https://github.com/Wimnet/flexicon_orbit
- Further details about the Gen-1 and Gen-2 FD radios may be found at:
  https://flexicon.ee.columbia.edu/gen-1-open-access
  https://flexicon.ee.columbia.edu/gen-2-open-access

# Thank you!

https://cosmos-lab.org

https://flexicon.ee.columbia.edu

mpk2138@columbia.edu

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