COSMOS Tutorial: Experimentation with Compact Full-Duplex Wireless

Manav Kohli

Electrical Engineering, Columbia University

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Joint work with Tingjun Chen, Mahmood Baraani Dastjerdi, Guy Farkash, Prof. Harish Krishnaswamy, Prof. Gil Zussman

COSMOS Experimental Research – Example

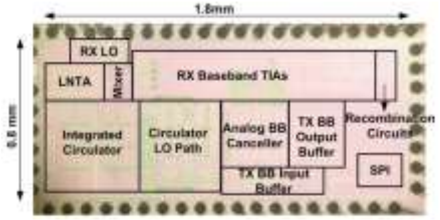
- Internal "Test Experiments" to help drive design requirements

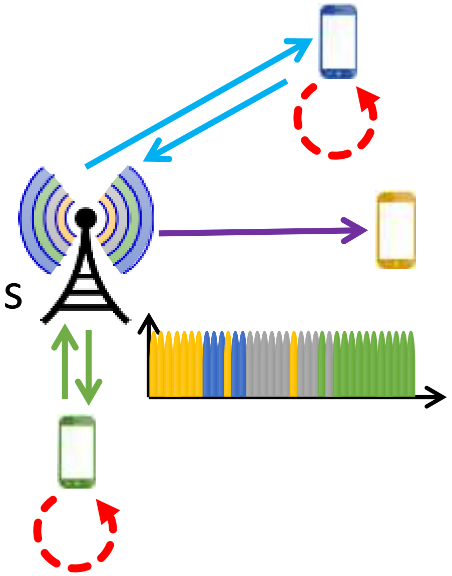
- Experiment on **Full-Duplex Wireless**:

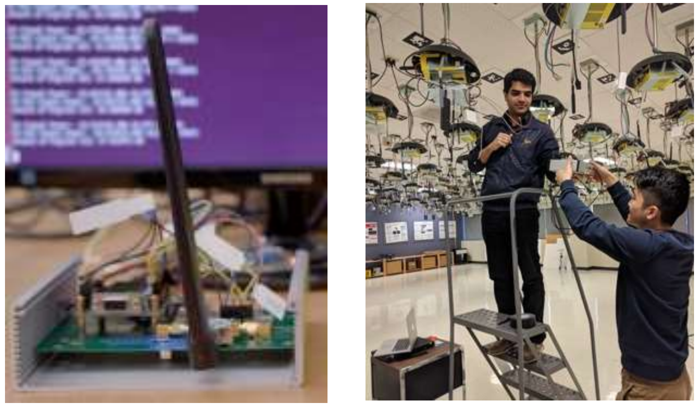
FlexICoN

(Columbia)

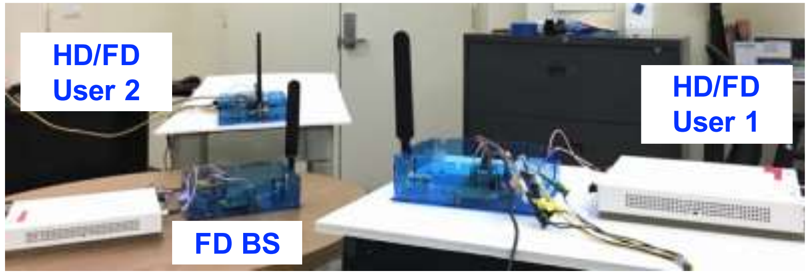
- ***Goal***: design and evaluate algorithms and protocols across various layers of the network stack (PHY, Link, MAC and above) for **IC-based full-duplex nodes**







Programmable Gen-1 full-duplex node installed in ORBIT



Gen-2 wideband full-duplex testbed

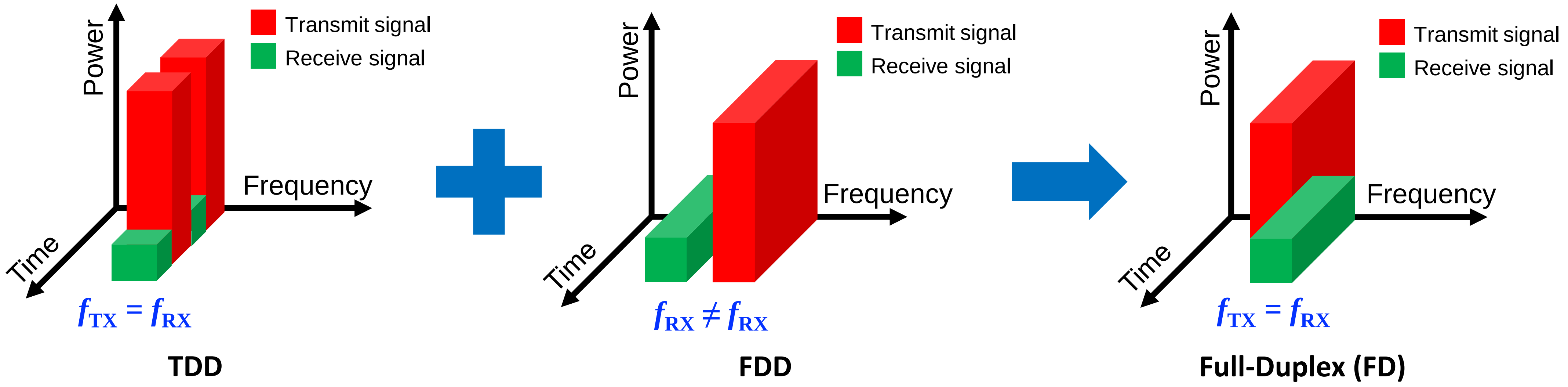
Outline

- Background on full-duplex wireless and the Columbia FlexICoN project
- Tutorial: Open-access full-duplex wireless in the ORBIT testbed [*IEEE INFOCOM’18 Demo*] [*arXiv’18*]
- Future integration in the COSMOS testbed [*ACM MobiCom’19*]

Full-Duplex Wireless

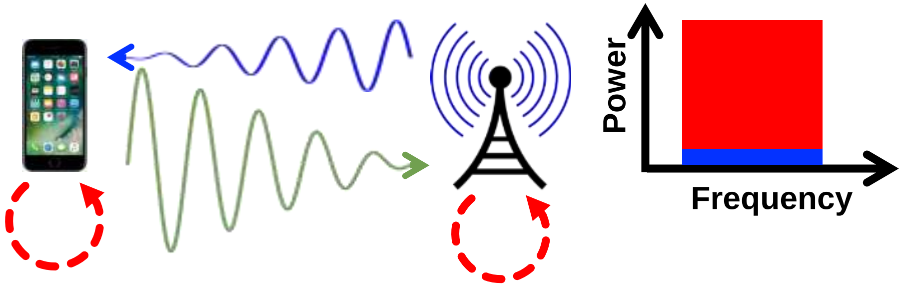
- Legacy half-duplex wireless systems separate transmission and reception in either:
  - Time: Time Division Duplex (TDD)
  - Frequency: Frequency Division Duplex (FDD)

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

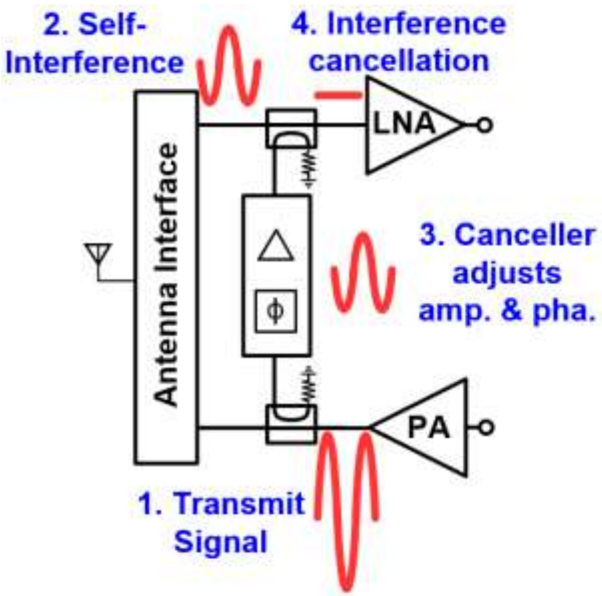


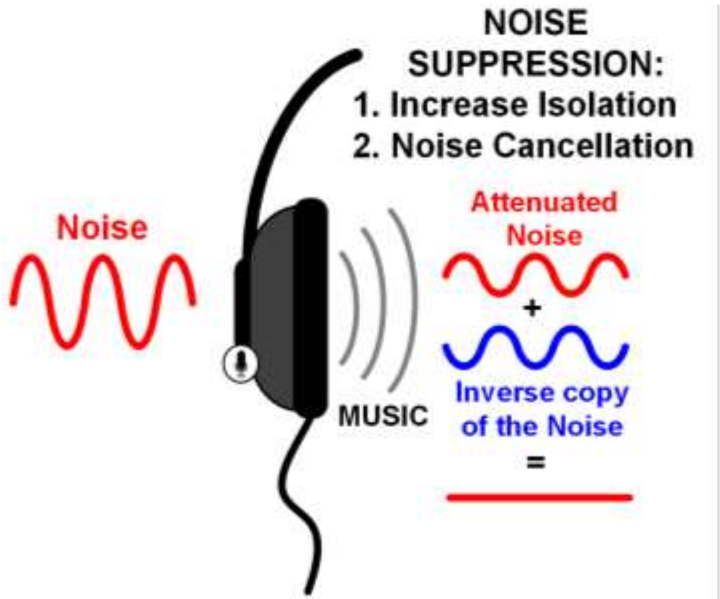
Full-Duplex Wireless

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



- 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





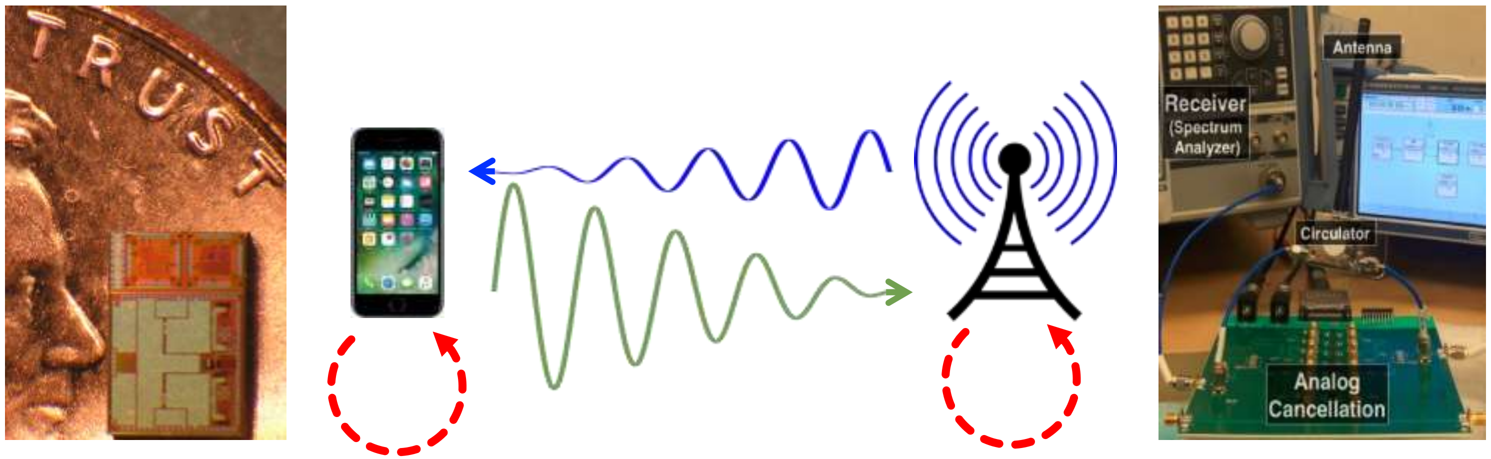
How much is 90dB?

Self-interference (SI)

Desired signal

The Columbia FlexICoN Project

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



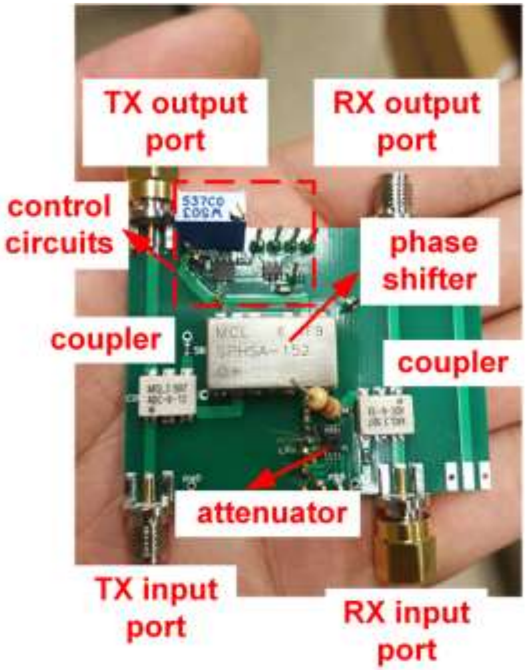
Full-duplex radios implemented in RFIC (Columbia)

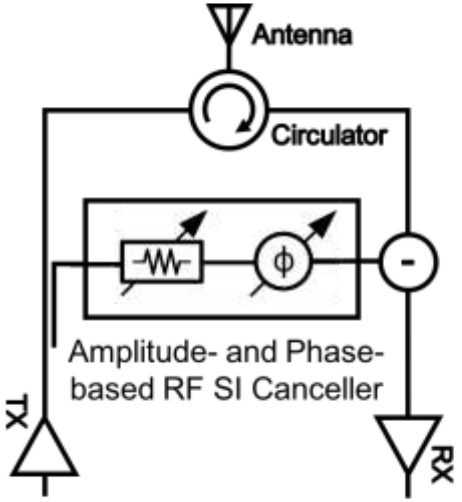
Full-duplex radios using off-the-shelf components (e.g., Stanford)

- 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.

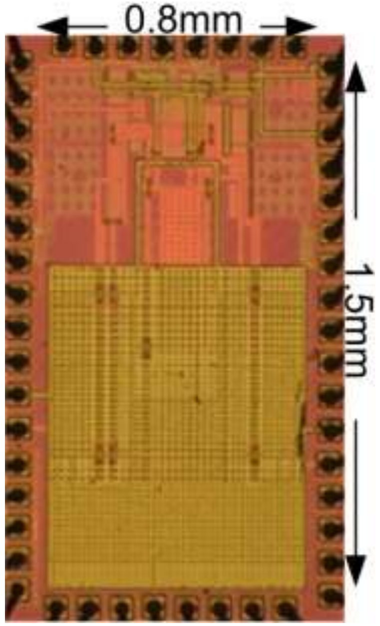
Gen-1 Compact RF SI Canceller

- A frequency-flat amplitude and phase-based analog self-interference (SI) canceller
  - Performance analysis of FD radios with imperfect SI cancellation
  - Integrated with an NI USRP software-defined radio (SDR) for experimental evaluation



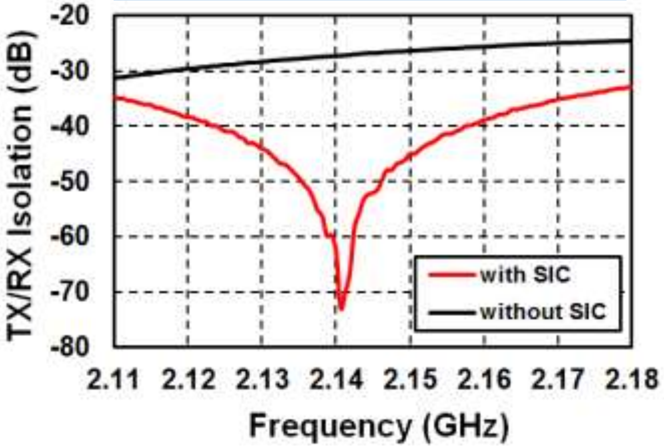


Emulating the RFIC SI canceller



Chip photo

20 dB RF SIC BW: 3 MHz

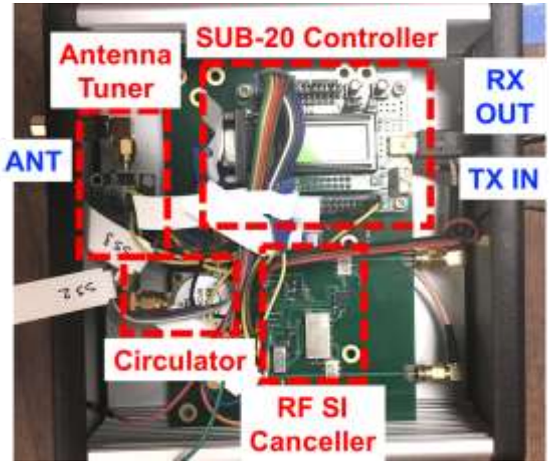


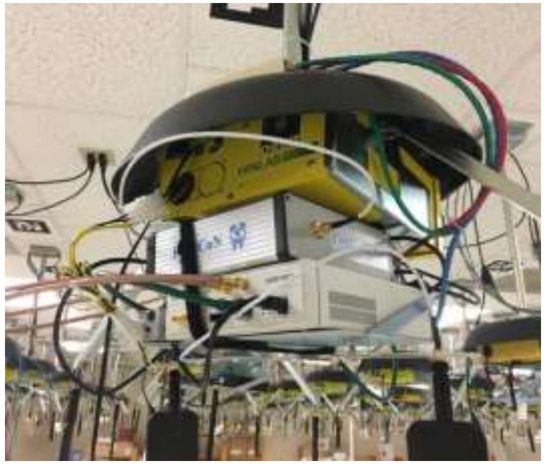
Self-Interference Cancellation (SIC) measurement

- 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.

Full-Duplex Wireless in the ORBIT Testbed

- **Goal**: Support **open-access** experiments with full-duplex wireless and facilitate research in the community
  - A programmable full-duplex node with a Gen-1 RF canceller deployed in ORBIT achieving 85 dB self-interference cancellation across 5 MHz bandwidth
  - Will be integrated in the COSMOS testbed





- T. Chen, M. Baraani Dastjerdi, G. Farkash, J. Zhou, H. Krishnaswamy, and G. Zussman,"Demo: Open-access full-duplex wireless in the ORBIT testbed," in *Proc. IEEE INFOCOM'18*, 2018.
- 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.
- "Tutorial: Full-duplex wireless in the ORBIT testbed," available at https://wiki.cosmos-lab.org/wiki/tutorials/full_duplex
- "Open-access full-duplex wireless in the ORBIT testbed: Instructions and code," available at https://github.com/Wimnet/flexicon_orbit

Tutorial

- We use the FD node integrated in ORBIT grid (`node11-10`) as an example
- FD experiments in COSMOS will follow a similar approach once the hardware is installed
- The detailed tutorial can be found on the ORBIT/COSMOS wiki

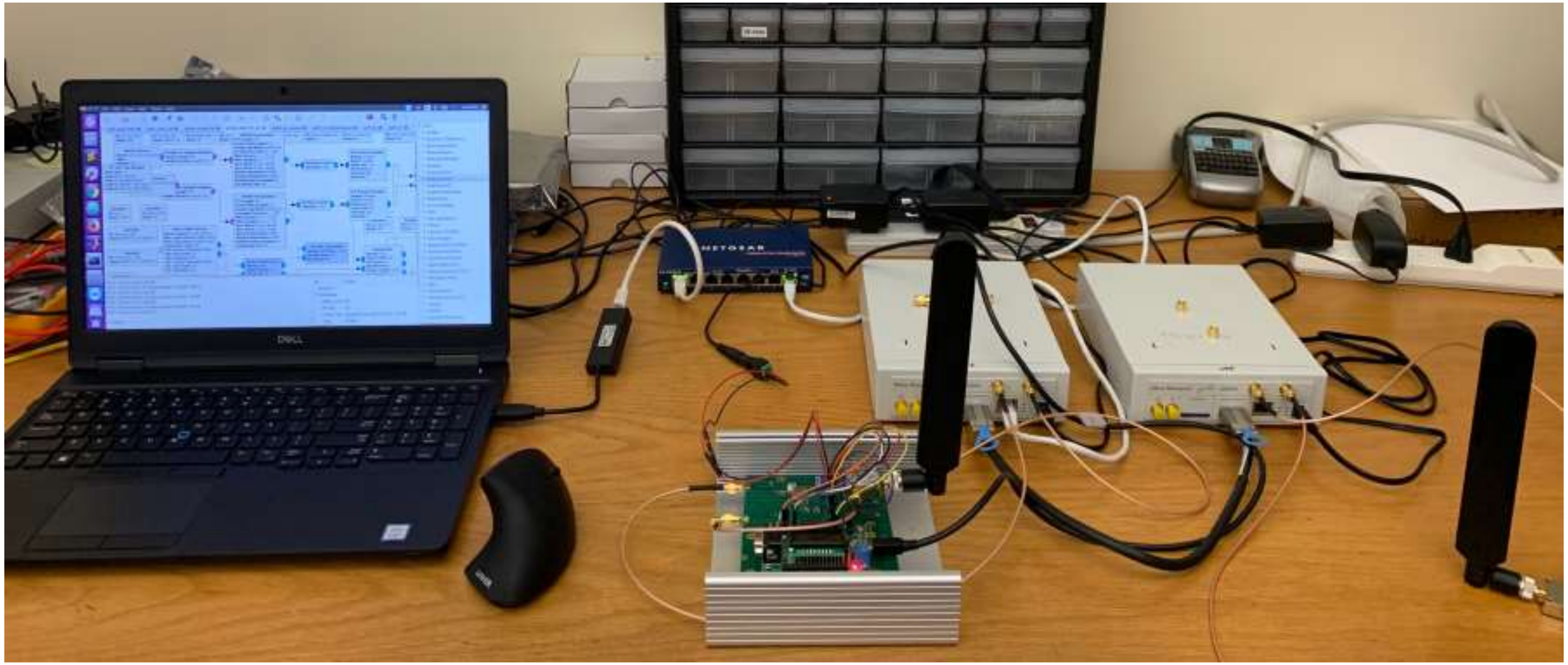
- Hardware
    - USRP N210
    - The FlexICoN Gen-1 RF canceller box

- Software (already included in the node image `flexicon-orbit-v3.ndz`) :
    - UHD and GNU Radio with customized out-of-tree (OOT) module (`C++`)
    - `libusb` and `libsub` (`C/C++`) for interfacing with the SUB-20 controller
    - The `Eigen C++` library for channel estimation and digital SIC

- Let's get started!

Tutorial

- Summer 2019
  - Integration of the Gen-1 RF canceller in COSMOS
  - Integration of the Gen-2 wideband RF canceller in COSMOS
  - More advanced example experiments (e.g., integration with gr-ieee802-11)



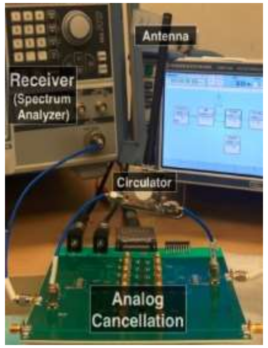
Tutorial

- Summer 2019
  - Integration of the Gen-1 RF canceller in COSMOS
  - Integration of the Gen-2 wideband RF canceller in COSMOS
  - More advanced example experiments (e.g., integration with gr-ieee802-11)

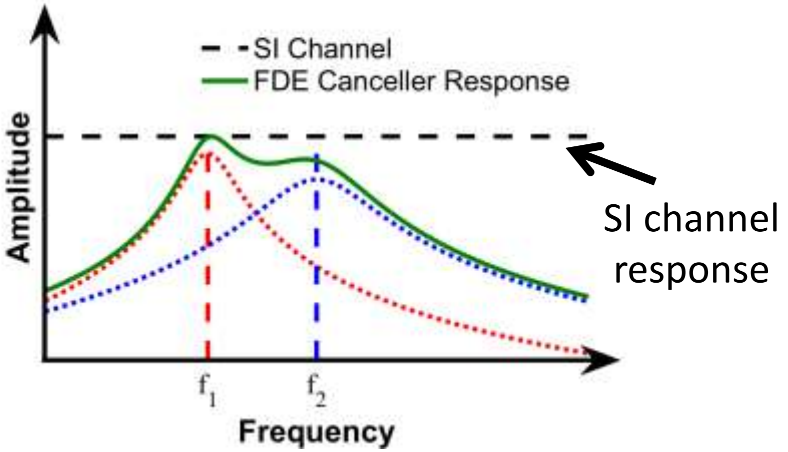
- Examples of supported research
  - Adaptive RF canceller configuration
  - Experimental evaluation of different digital SIC algorithms
  - Measurement- and trace-based evaluation of full-duplex rate gains
  - PHY layer security
  - Building blocks of MAC layer algorithms for full-duplex networks (design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

Compact Wideband Full-Duplex Wireless

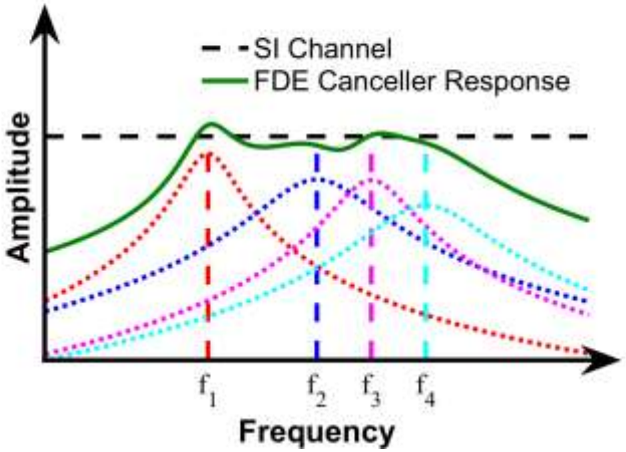
- In a *time-domain* delay line-based wideband RF canceller, each delay line w/ *fixed* delay is associated with
  - One amplitude control [*Bharadia et al. 2013*]
  - One amplitude control and one phase control [*Korpi et al. 2016*]
  - Multiple delay lines are combined to enhance performance



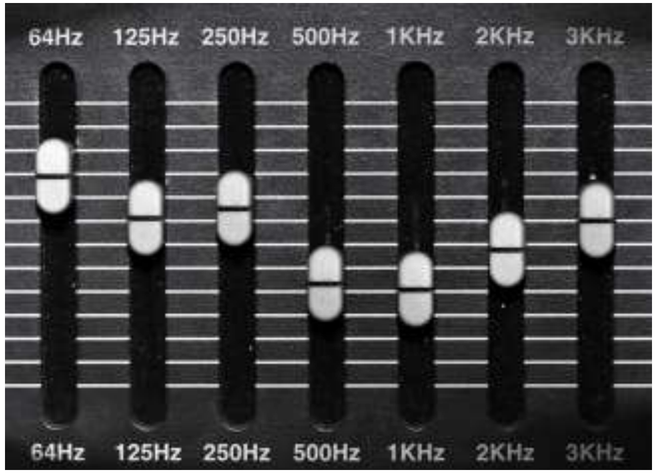
- **Main idea based on frequency-domain equalization (FDE)**: The self-interference (SI) channel can be emulated in the *frequency-domain* using parallel reconfigurable RF bandpass filters with amplitude and phase controls



2 FDE taps



4 FDE taps



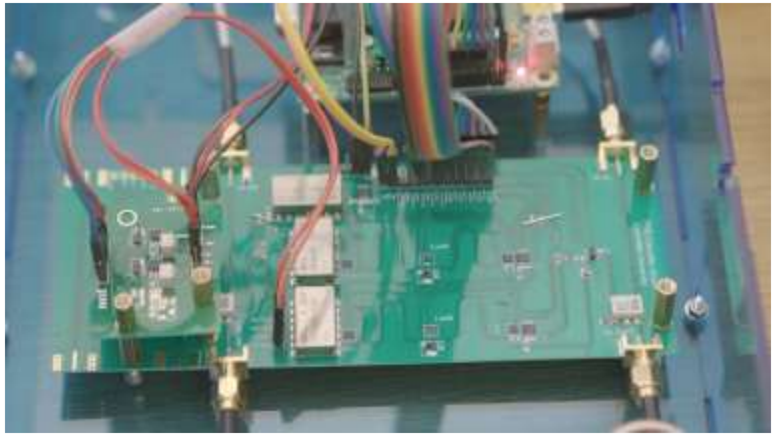
Audio Equalizer

- 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.

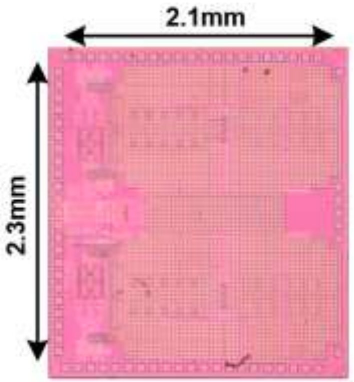
Gen-2 Wideband RF SI Canceller based on FDE

- A frequency-domain equalization- (FDE-) based wideband SI canceller implemented on a PCB
  - Two parallel FDE taps
  - Each FDE tap is implemented as an RF bandpass filter (BPF) with amplitude and phase controls

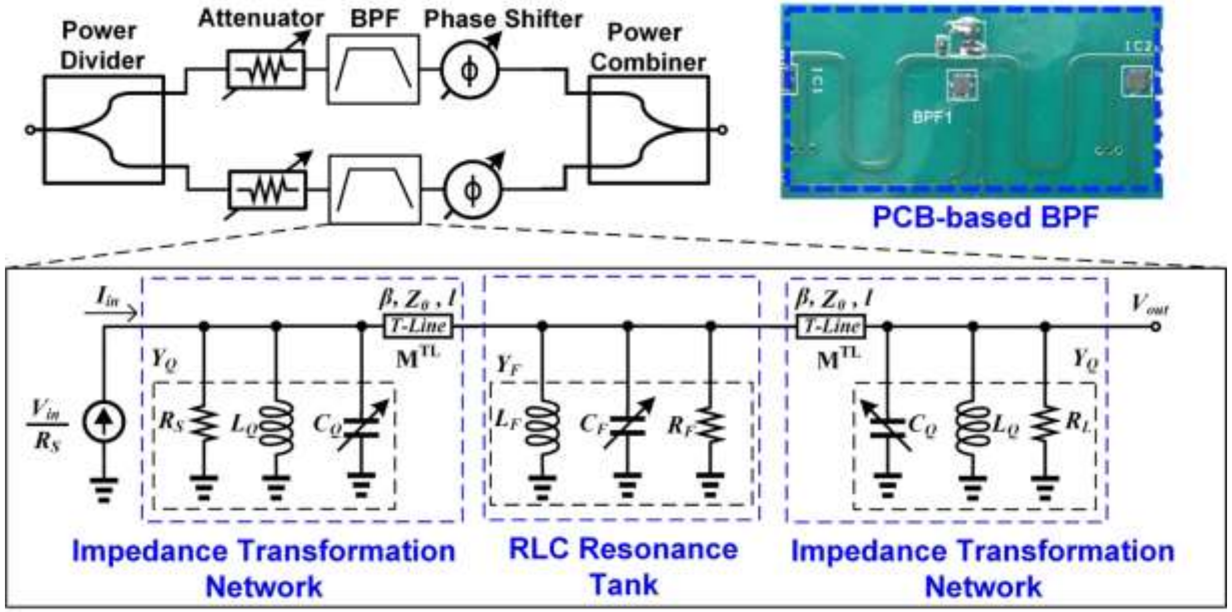
Gen-2 wideband FDE-based PCB canceller



Emulating the FDE-based RFIC canceller



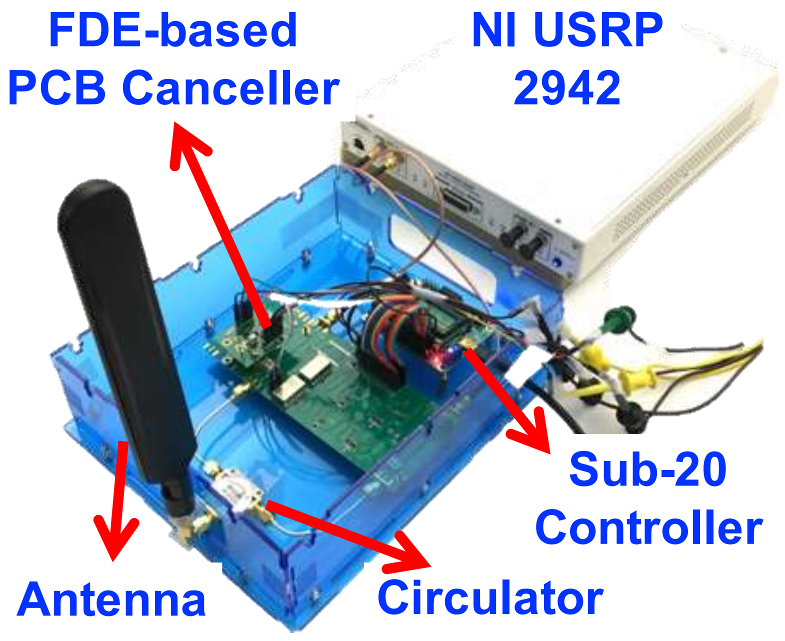
Chip photo

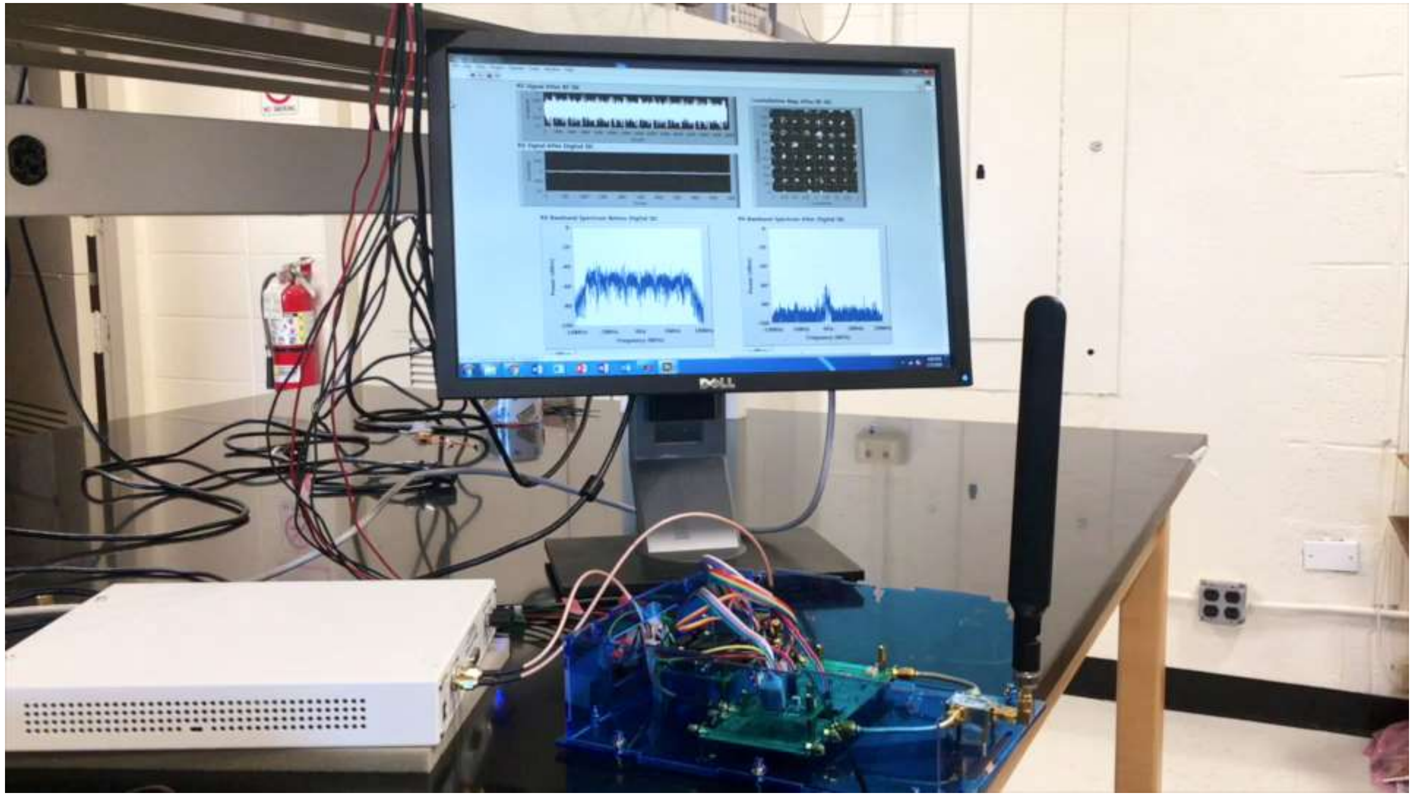


Design and implementation of the parallel FDE taps

Experimental Evaluation

- 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)
- Adaptive FDE-based canceller configuration

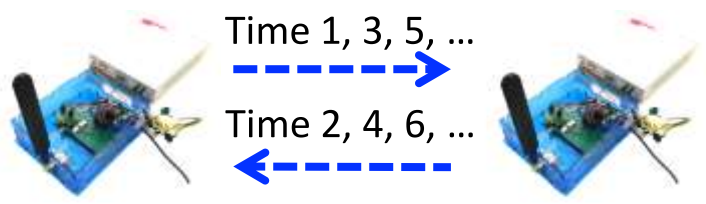




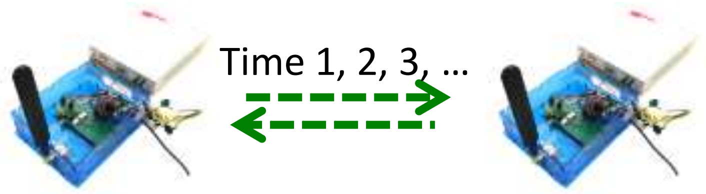
Experimental Evaluation

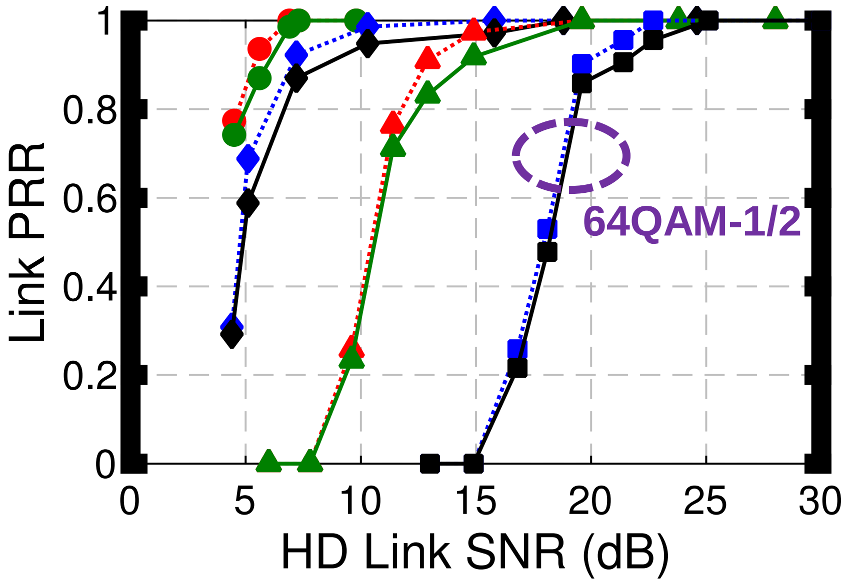
- SNR-PRR (packet reception ratio) relationship
  - 1,000 OFDM packets of length 800-Byte sent over the link
  - Measure average link PRR with varying link SNR (with a link distance of 5m and varying Tx gain)

HD Link: Alternate transmissions

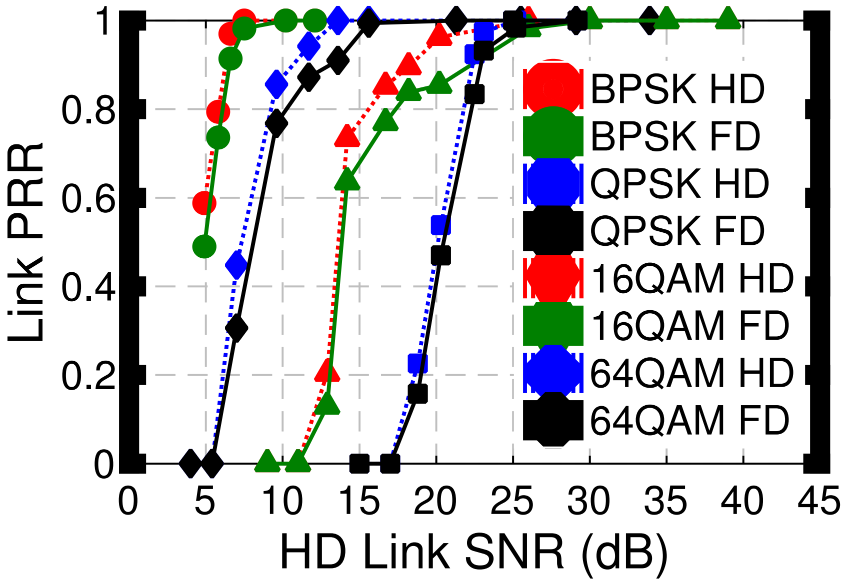


FD Link: Simultaneous transmissions





Coding rate 1/2



Coding rate 3/4

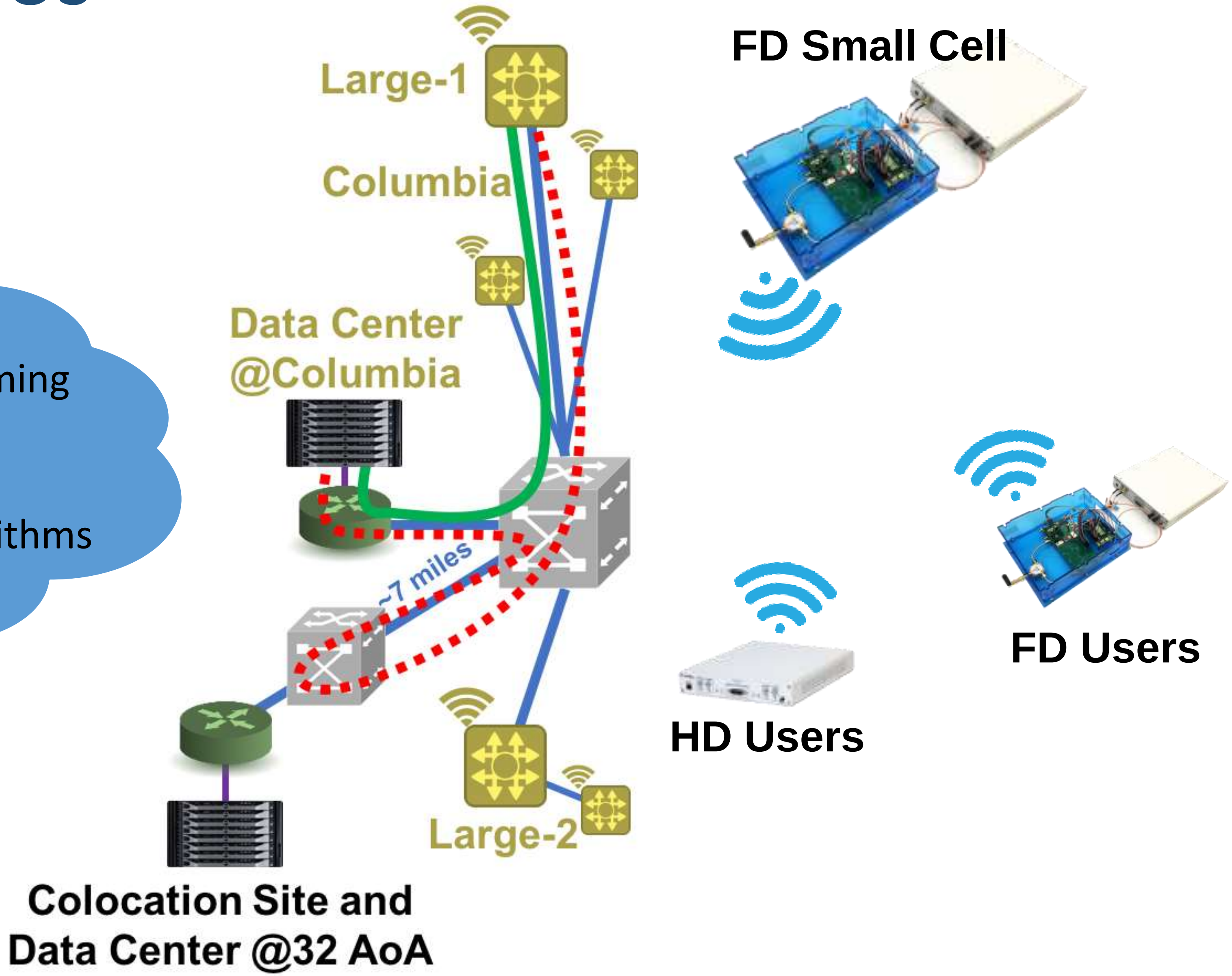
The average FD link PRR is **93.5%** of the average HD link PRR, resulting in an average FD link throughput gain of **1.87x**

Integration with COSMOS

FlexICoN Server

- Baseband complex (IQ) data streaming and processing
- Customized adaptive digital self-interference (SI) cancellation algorithms

Edge-Cloud



Summary

- Tutorial: Open-access wireless in the ORBIT testbed using the FlexICoN Gen-1 RF canceller box
- Summer 2019: Gen-1 and Gen-2 wideband RF cancellers to be integrated in the COSMOS testbed
- The testbed can be used for various research projects related to full-duplex wireless

Thank you!

tingjun@ee.columbia.edu

http://www.ee.columbia.edu/~tc2668