Wideband Full-Duplex Wireless via Frequency-Domain Equalization: Design and Experimentation

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ACM MobiCom 2019
Oct. 22, 2019

Columbia University in the City of New York

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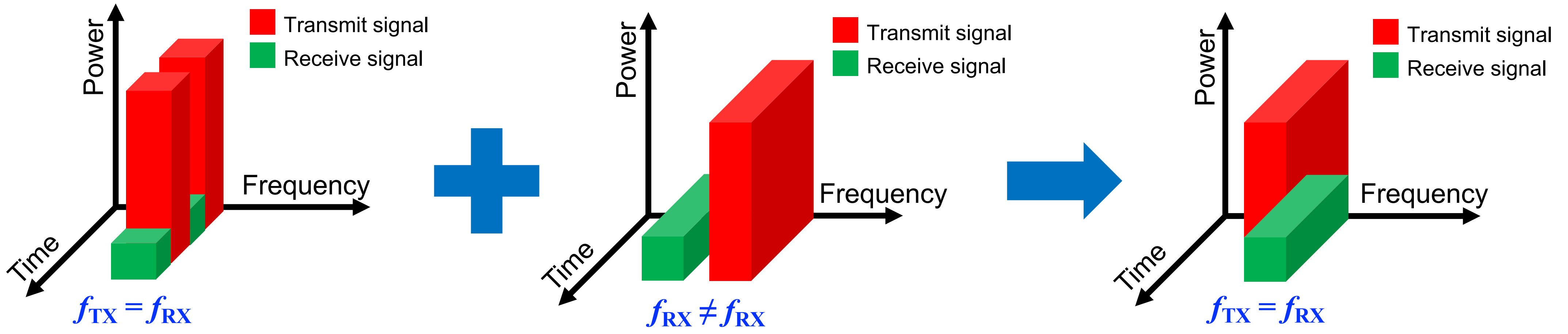
CoSMIC

Full-Duplex Wireless

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

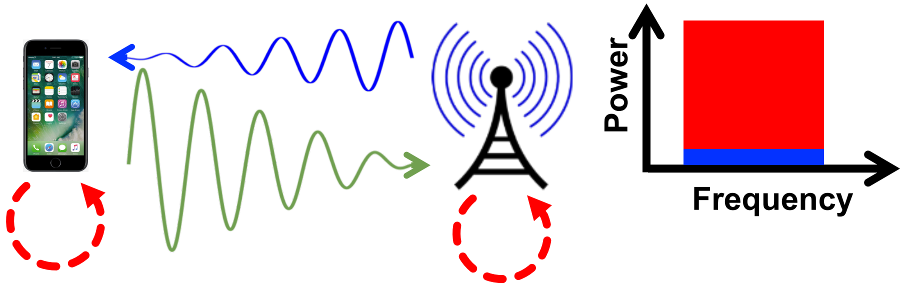
- (In-band) Full-duplex wireless: simultaneous transmission and reception on the same frequency channel



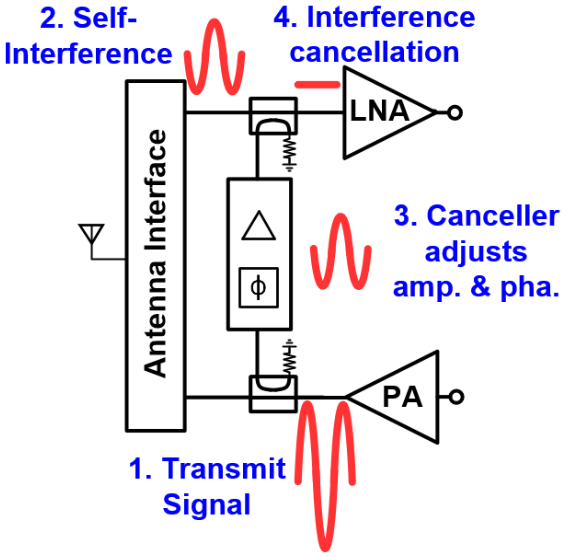
TDD **FDD** **Full-Duplex (FD)**

Full-Duplex Wireless

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



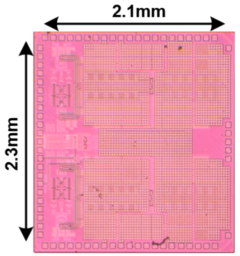
- Viability is limited by self-interference (SI)
  - Transmitted signal is **billions** of times (**10^9 or 90 dB**) stronger than the received signal
  - Requiring extremely powerful SI cancellation (SIC) across the ***antenna***, ***RF***, and ***digital*** domains



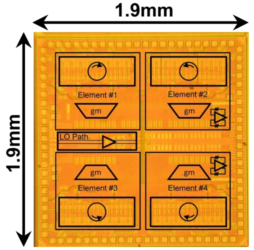
Self-interference (SI) Power

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/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



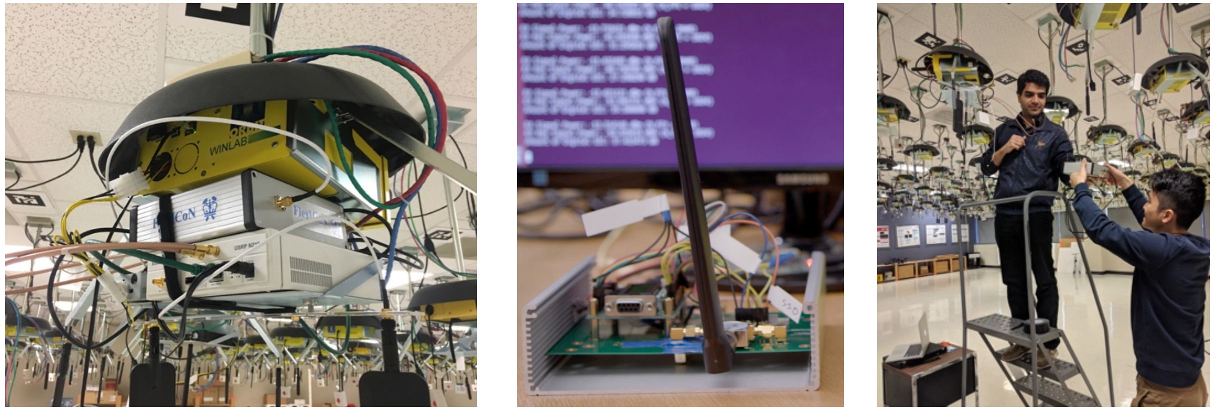
RFIC FD receiver



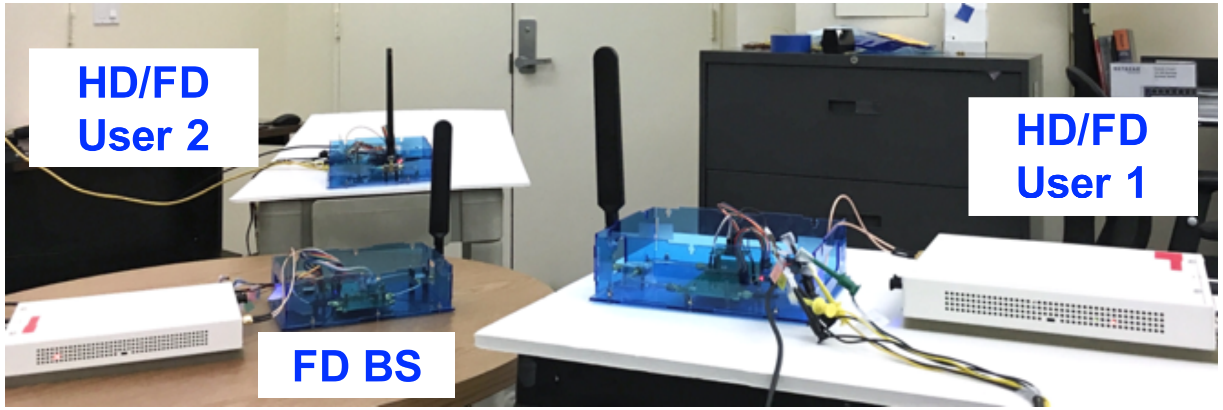
RFIC FD phased array

ORBIT

COSMOS



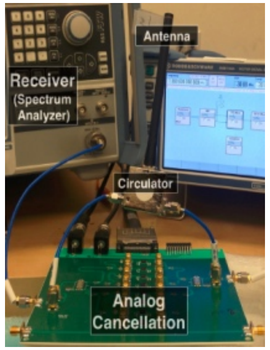
A programmable Gen-1 *narrowband* full-duplex node in ORBIT

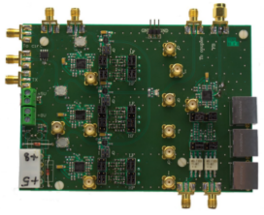


Gen-2 *wideband* full-duplex radios and testbed

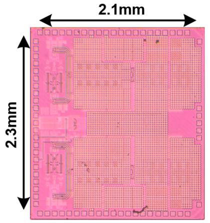
- **T. Chen**, M. Baraani Dastjerdi, H. Krishnaswamy, and G. Zussman, "Wideband full-duplex phased array with joint transmit and receive beamforming: Optimization and rate gains," in *Proc. ACM MobiHoc'19*, 2019. **Best Paper Finalist**
- **T. Chen**, J. Diakonikolas, J. Ghaderi, and G. Zussman, "Hybrid scheduling in heterogeneous half- and full-duplex wireless networks," in *Proc. IEEE INFOCOM'18*, 2018.
- M. Baraani Dastjerdi, N. Reiskarimian, **T. Chen**, G. Zussman, and H. Krishnaswamy, "Full duplex circulator-receiver phased array employing self-interference cancellation via beamforming," in *Proc. IEEE Radio Frequency Integrated Circuits (RFIC) Symposium*, 2018.
- 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

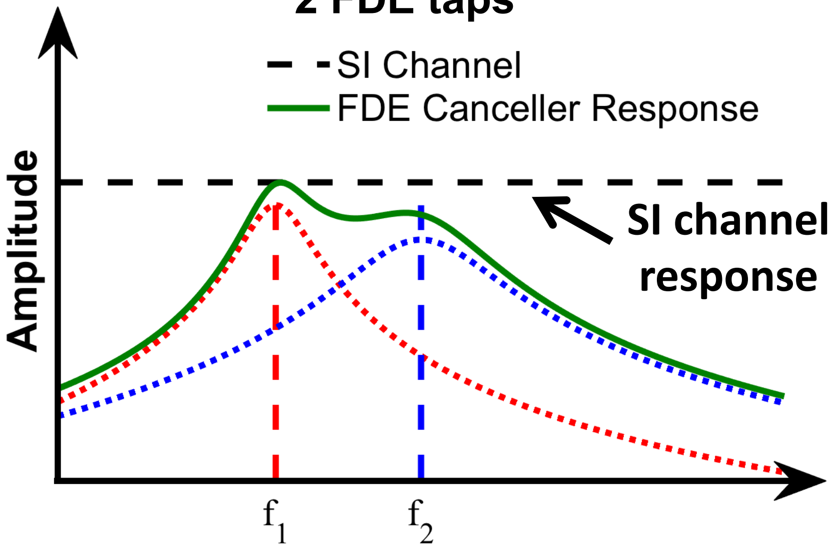


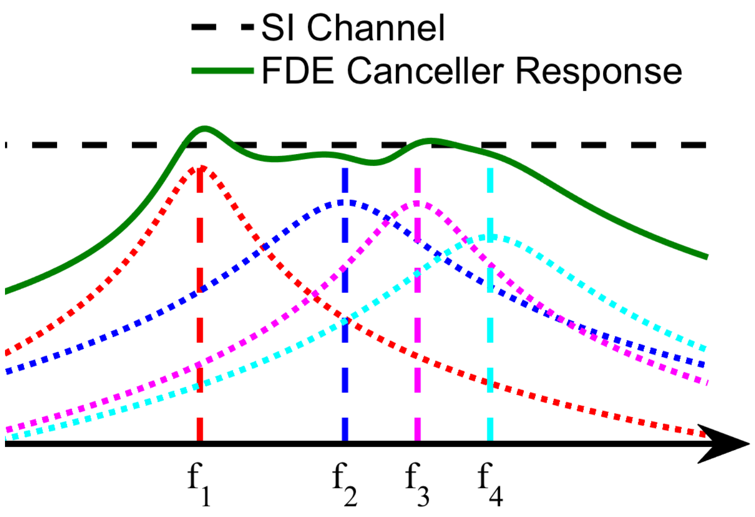


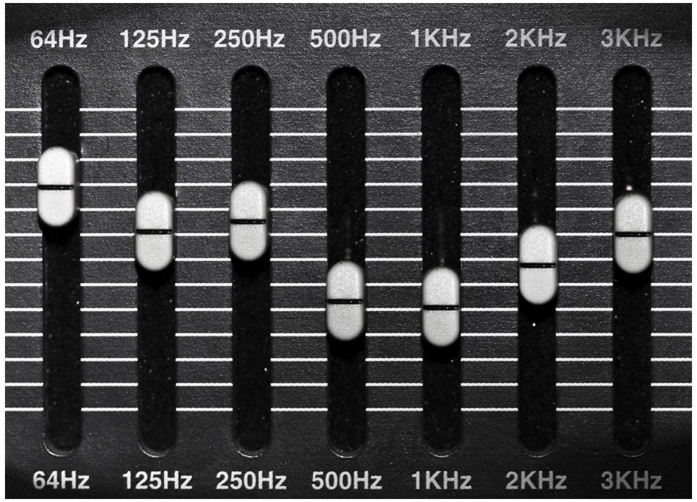
- Traditional RF SI cancellers using delay lines (i.e., ***time-domain equalization***) are more suitable for **large-form-factor** nodes (e.g., [*Bharadia et al. 2013*], [*Korpi et al. 2016*])
  - Multiple delay lines are combined to achieve wideband cancellation
  - Each delay line has a *pre-configured fixed* delay with amplitude and phase control
- **Main idea**: The SI channel can be emulated using parallel reconfigurable RF bandpass filters with amplitude and phase controls (i.e., ***frequency-domain equalization [FDE]***)
  - Leverage recent advances in the RFIC community on *N*-path filters grounded in **IC implementations**



Chip photo



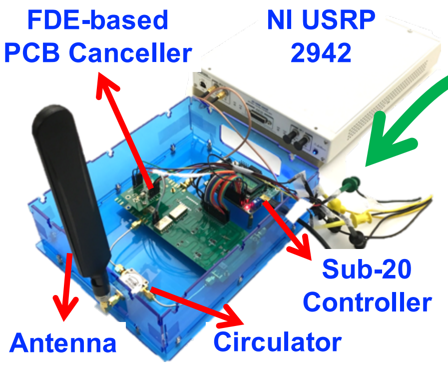




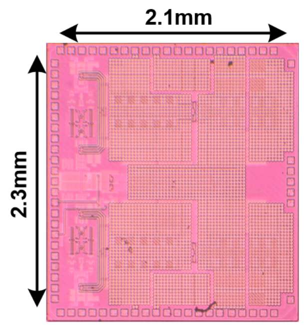
Audio Equalizer

FDE-based (Compact) Wideband RF SI Canceller

- An FDE-based SI canceller implemented on a PCB
  - Two parallel FDE taps, each consists of a reconfigurable RF bandpass filter with amplitude and phase controls
  - Each FDE tap features four degrees of freedom (DoF)

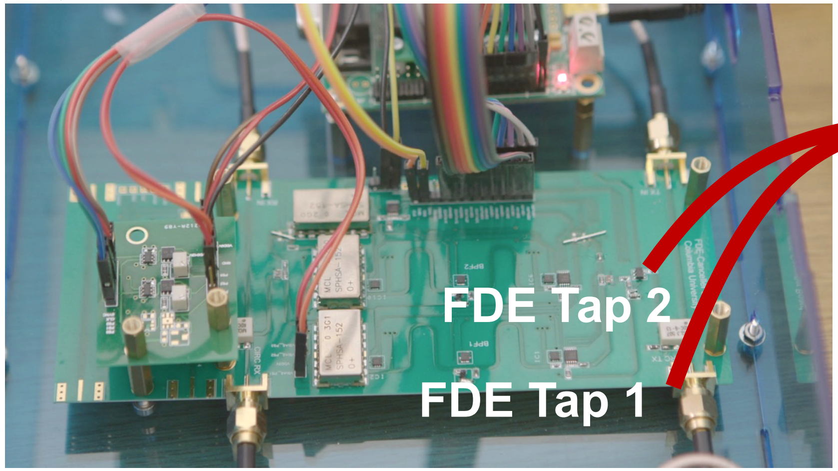


FD radio prototype

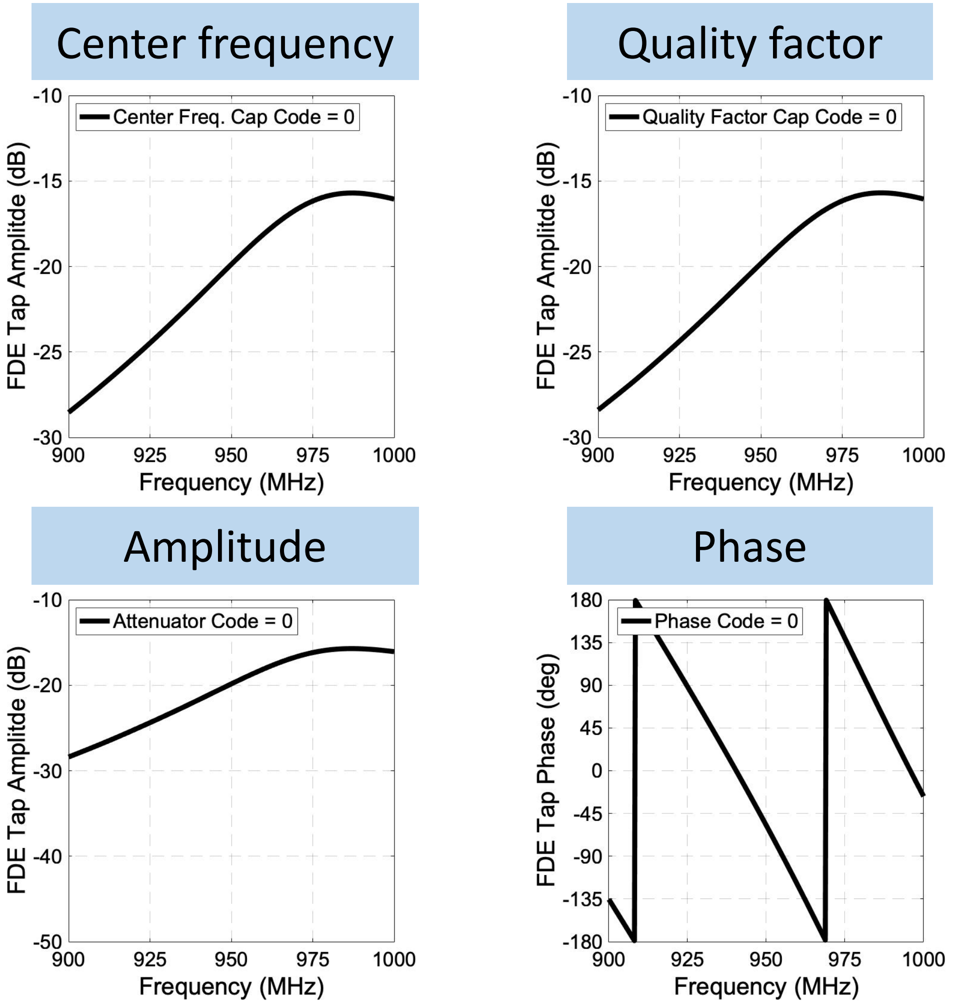


Chip photo

FDE-based PCB canceller



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

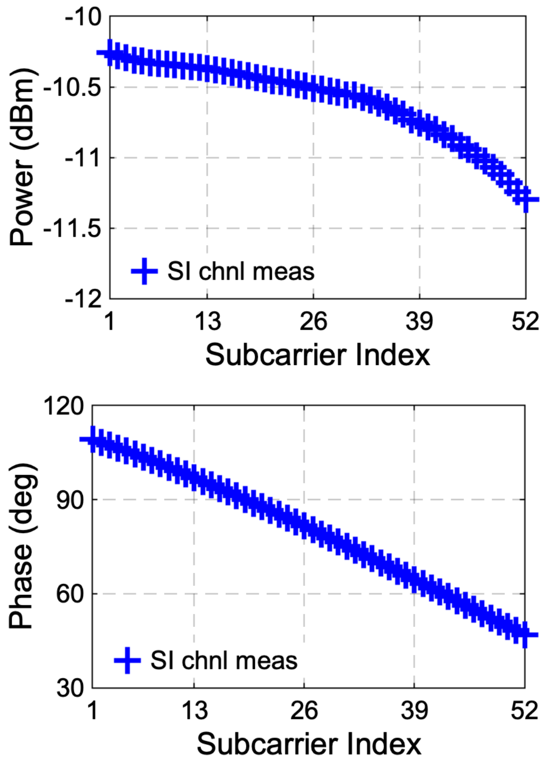


Programmable DoF of each FDE tap

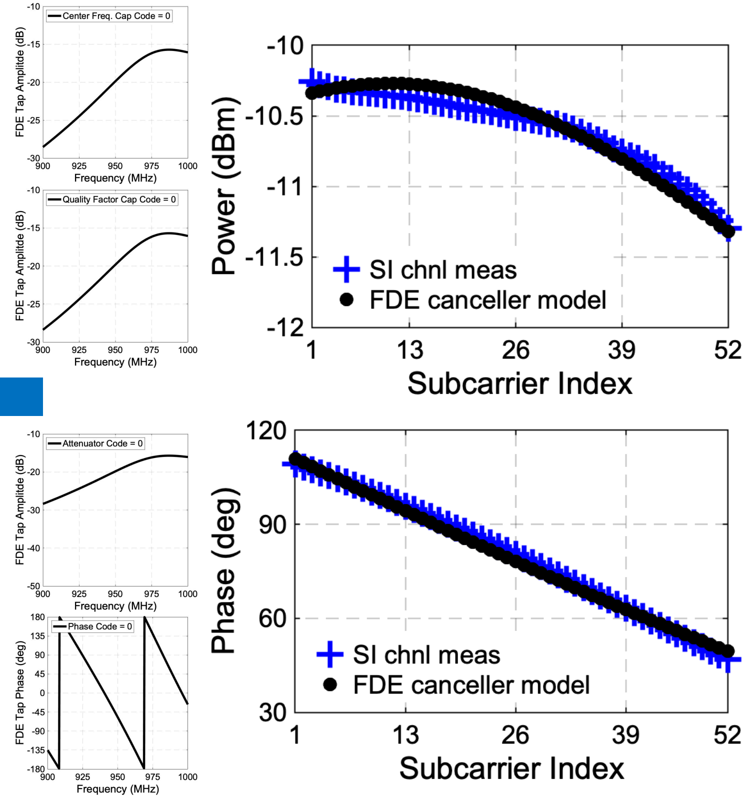
Optimized FDE-based Canceller Configuration

- Derive a mathematical SI canceller hardware model as a function of the four (programmable) degrees of freedom and validate model accuracy
- Implement an optimized canceller configuration scheme for achieving the best RF SIC performance

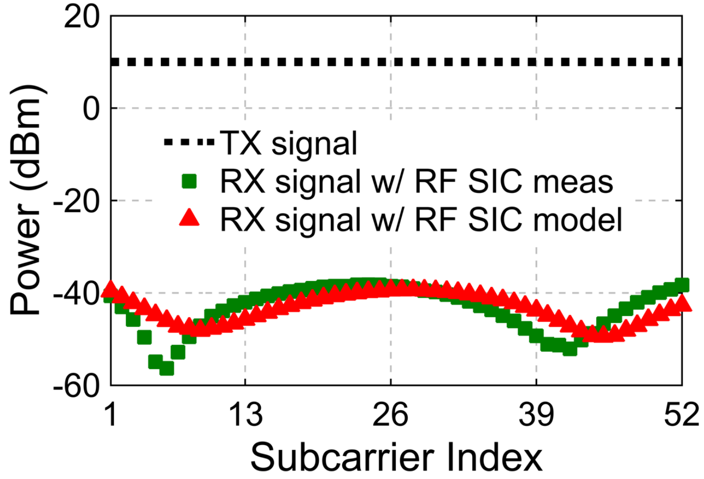
Step 1: Measure real-time SI channel using packet preamble



Step 2: Optimize FDE-based canceller parameters to match its response to the SI channel



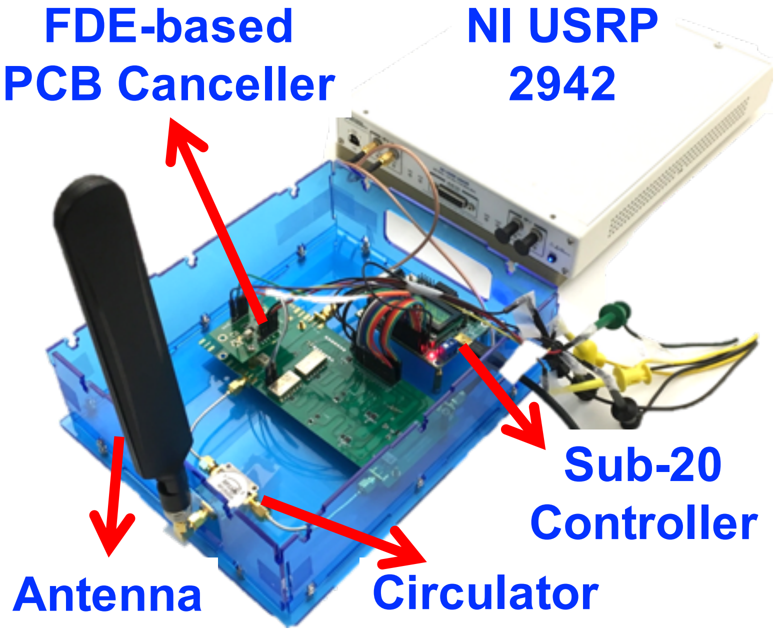
Step 3: RF SIC is performed at the Rx input



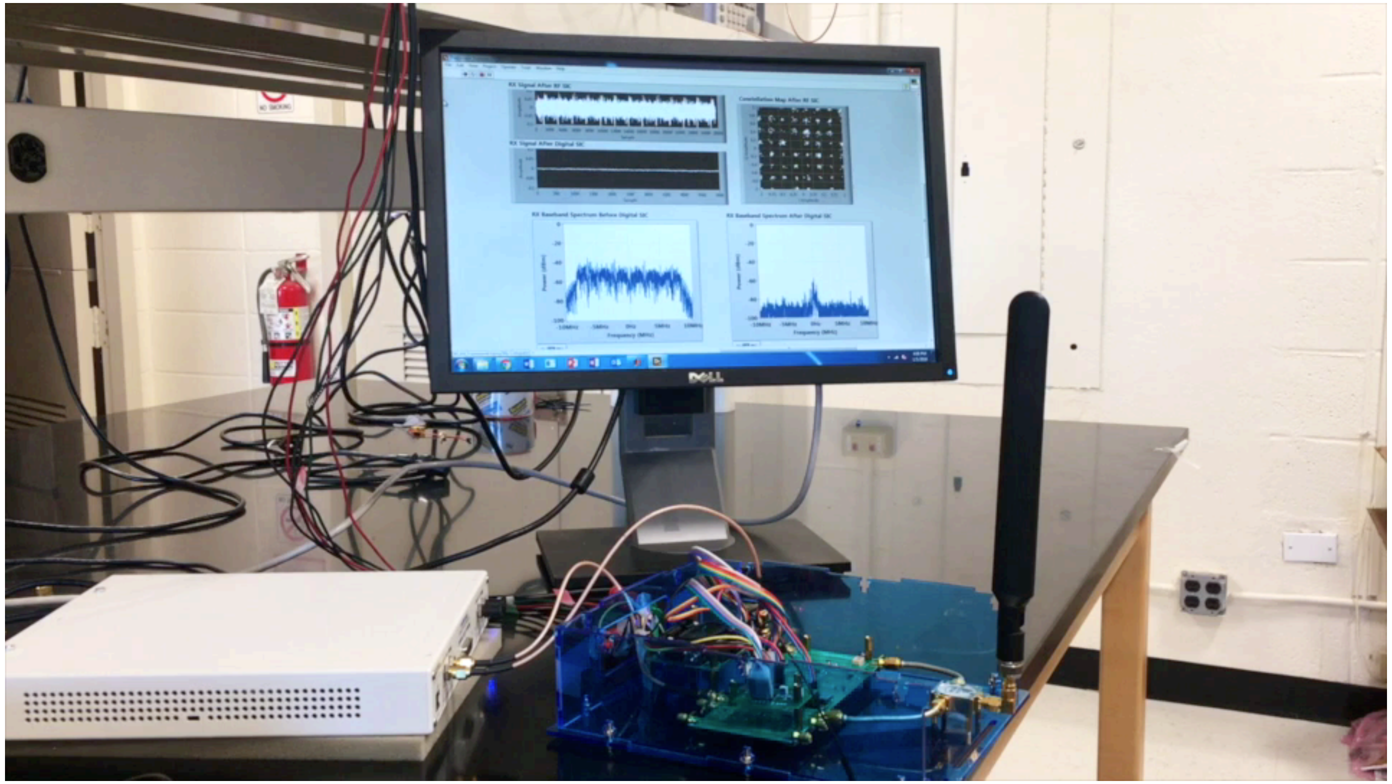
- TX power: +10 dBm average
- Modeled and measured RF SIC based on the accurate canceller model
- **~52 dB** RF SIC across **20 MHz** bandwidth

Experimental Evaluation – Node Level

- **20 MHz** OFDM PHY (BPSK-1/2 to 64QAM-3/4)
- TX power: **+10 dBm average**, RX noise floor: **-85 dBm**, overall SIC: **95 dB** (52/43 dB in the RF/digital domain)
- Adaptive optimized FDE-based canceller configuration

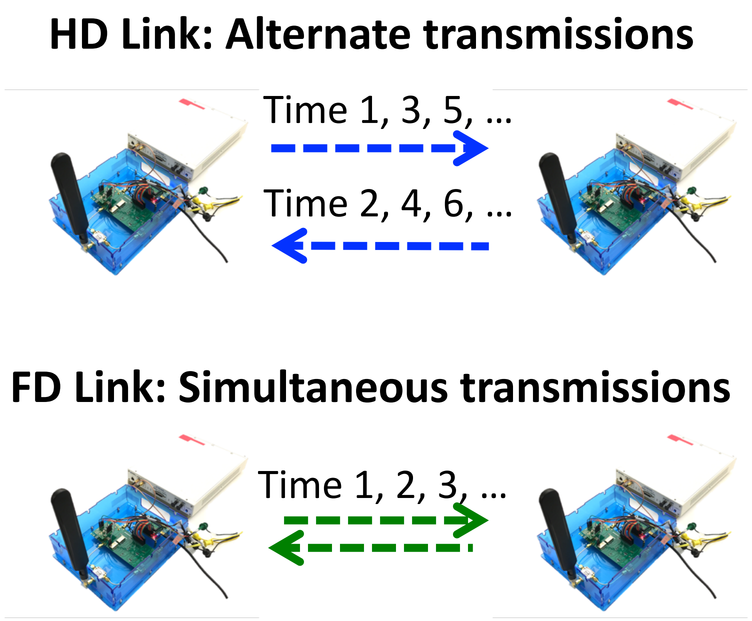


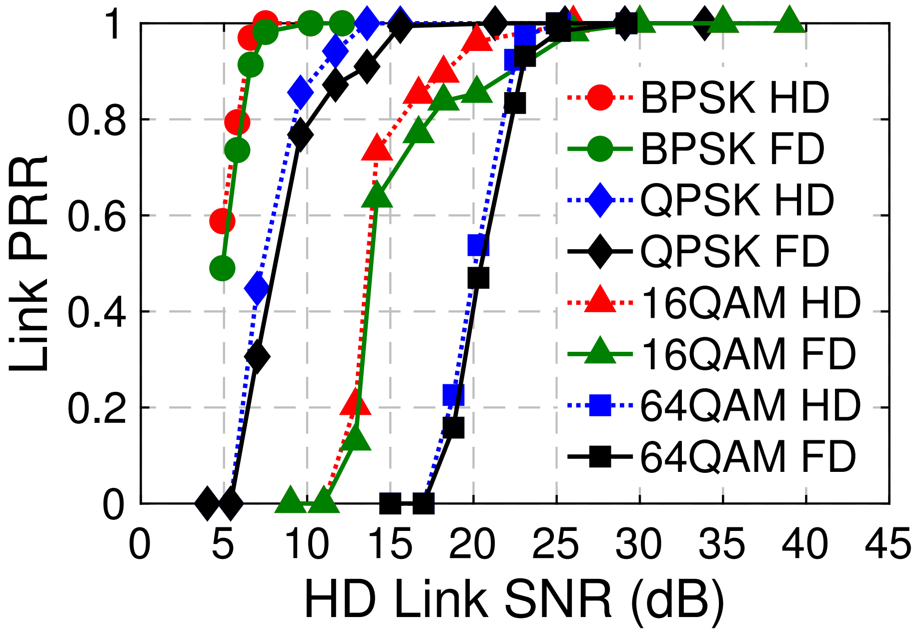
FDE-based FD radio prototype



Experimental Evaluation – Link Level

- 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)



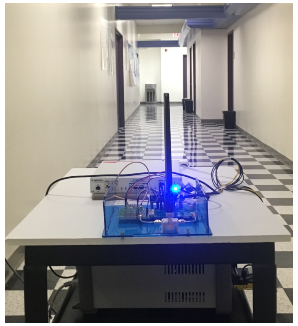


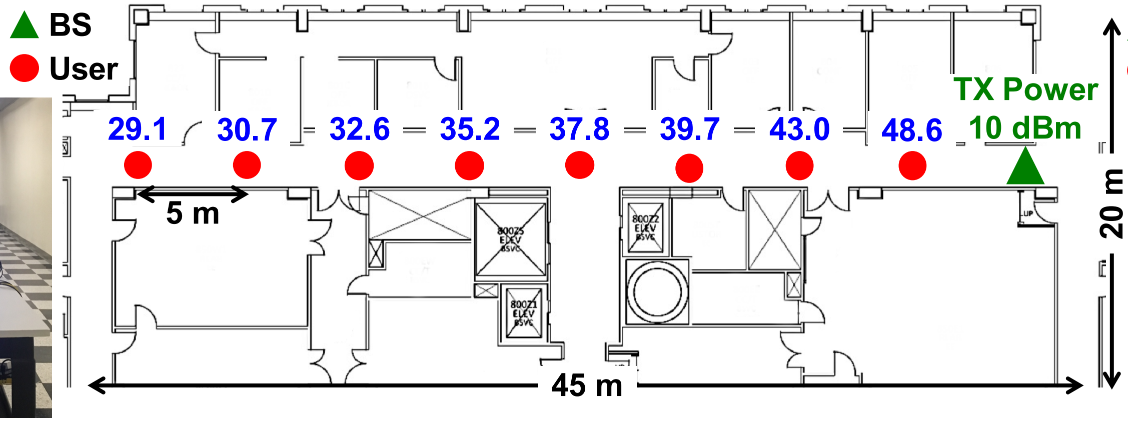
Coding rate 3/4

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**

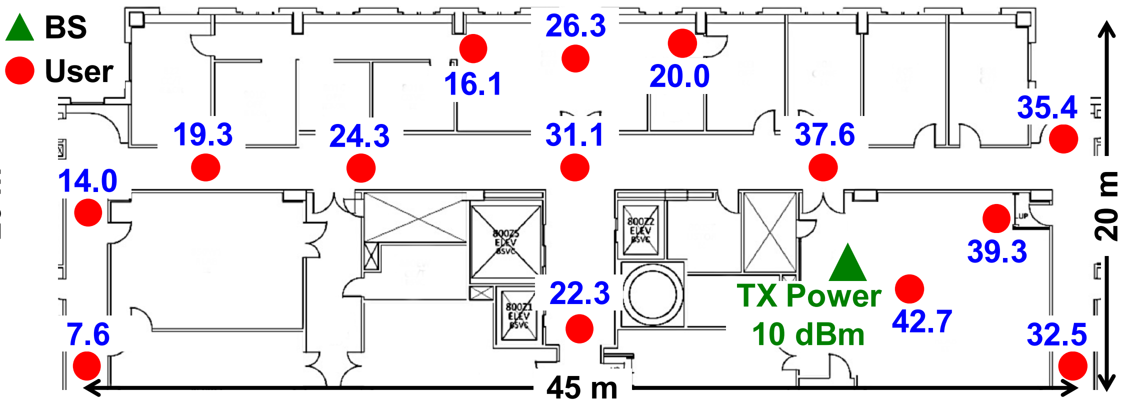
Experimental Evaluation – Link Level

- FD link with one base station (BS) and one user
  - 1,000 OFDM packets of length 800-Byte sent over the link
  - Measure link SNR with varying user location
- **Line-of-sight (LOS)** and **Non-line-of-sight (NLOS)** experiments
- Experimental setup and example measured **link SNR (in dB)**





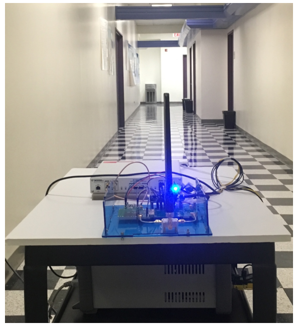
LOS deployment

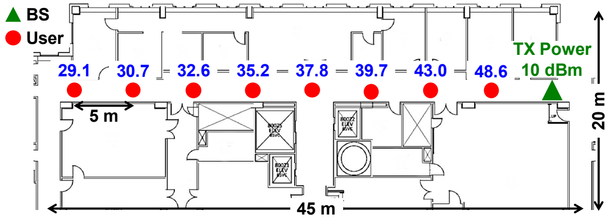


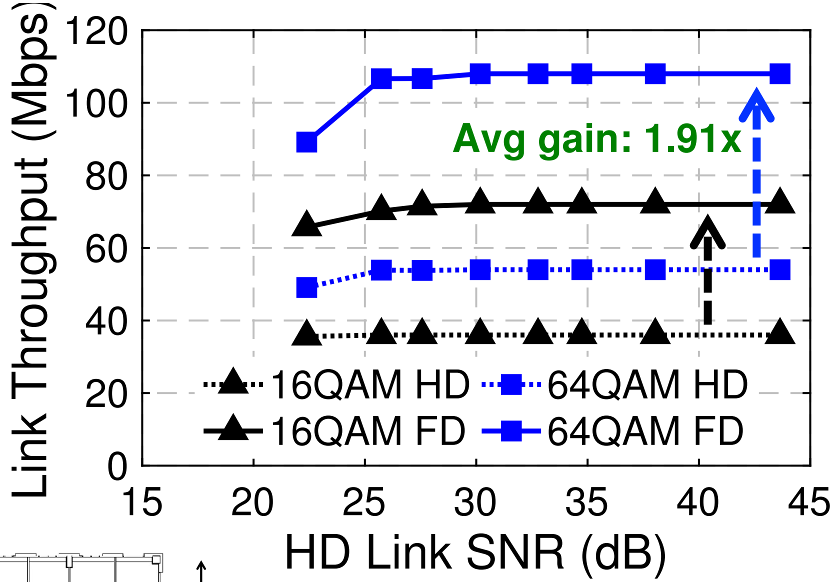
NLOS deployment

Experimental Evaluation – Link Level

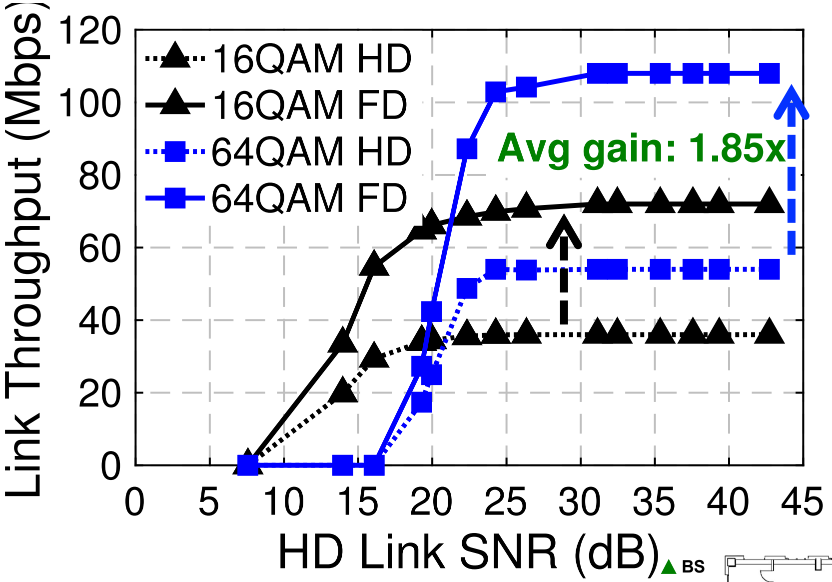
- FD and HD link throughput and gain



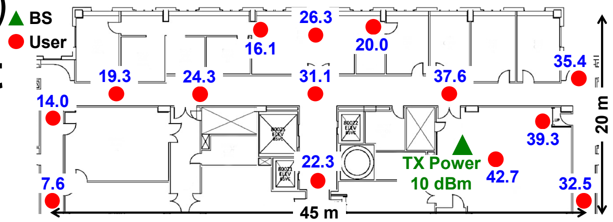




LOS deployment



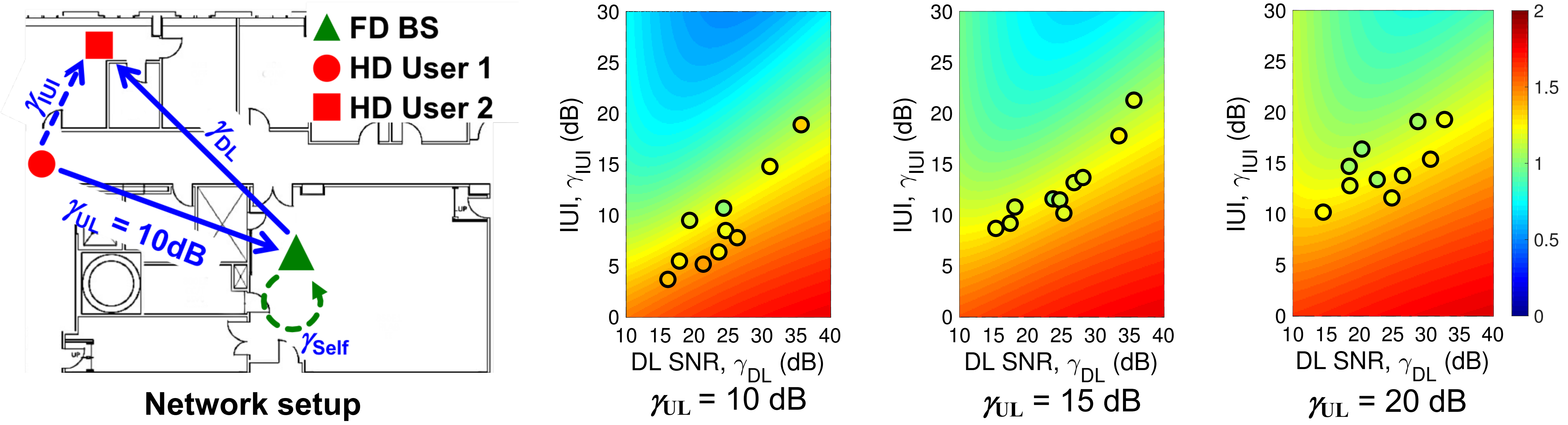
NLOS deployment



(i) Average link throughput gains are **1.91x** and **1.85x** for LOS and NLOS deployments, respectively
(ii) With sufficient link SNR, FD can provide a throughput gain of **exact 2x**

Experimental Evaluation – Network Level

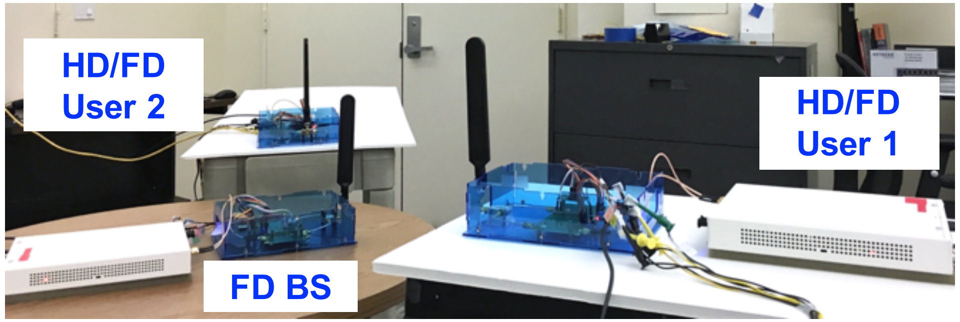
- 3-node networks (1 BS and 2 HD users) with inter-user interference (IUI)
  - Simultaneous uplink-downlink (UL-DL) transmissions with UL and DL SNR values γ_{UL} and γ_{DL}
- **Analytical** (colored surface) and **experimental** (filled circles) network-level FD throughput gain
  - 30 different pairs of user 1 and user 2 locations

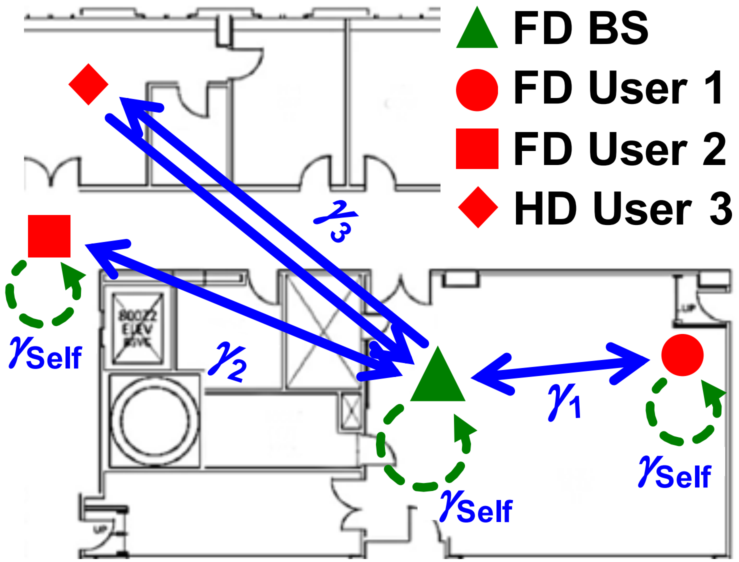


The experimental FD gain is on average 93% of the analytical FD gain

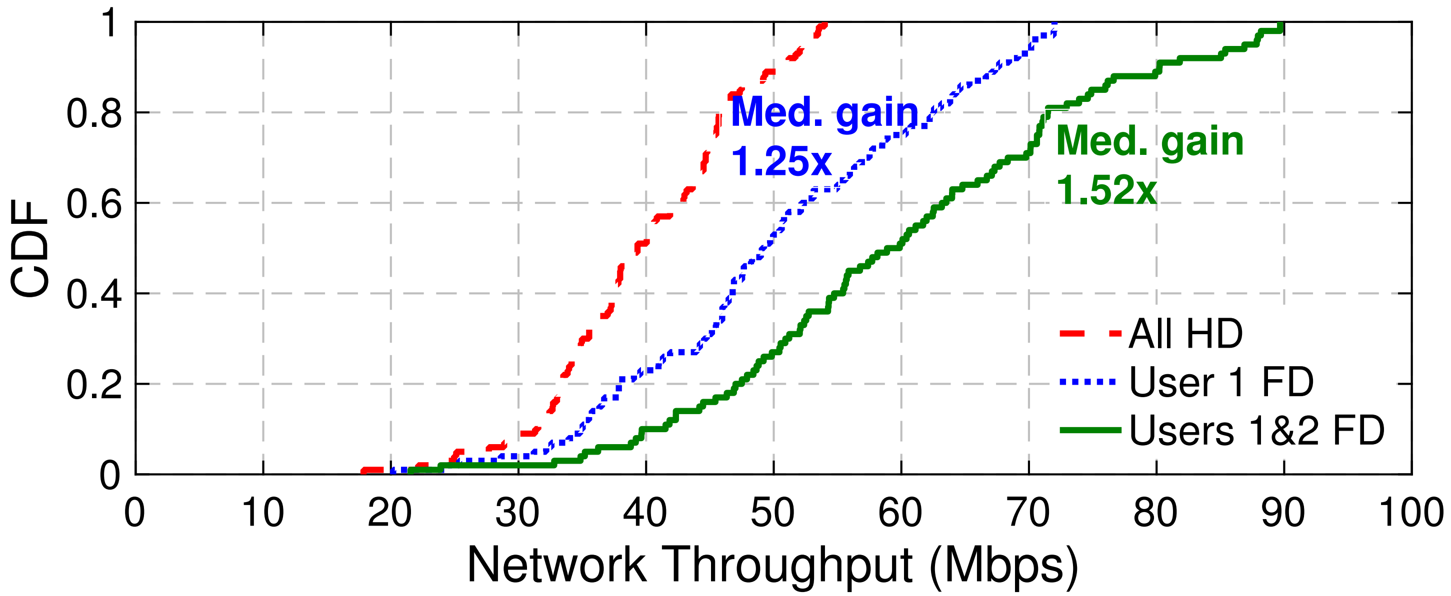
Experimental Evaluation – Network Level

- Networks with heterogeneous HD and FD users
- Example 4-node networks with 1 FD BS and 3 HD/FD users





Network setup

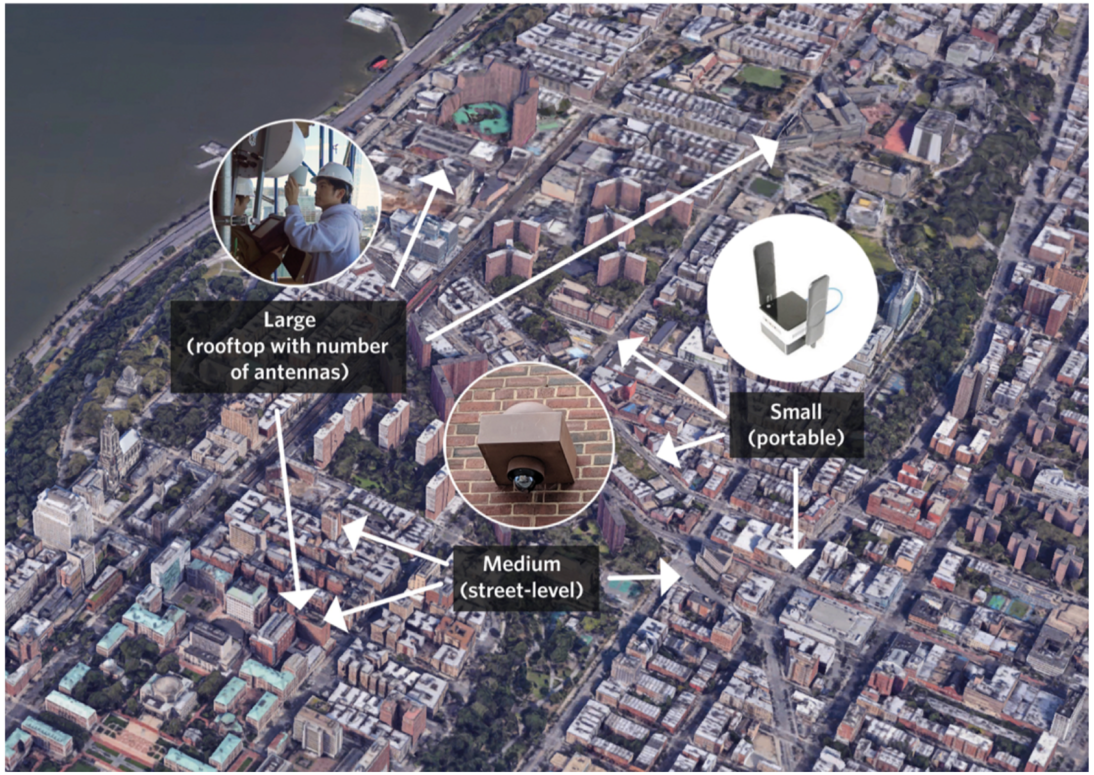


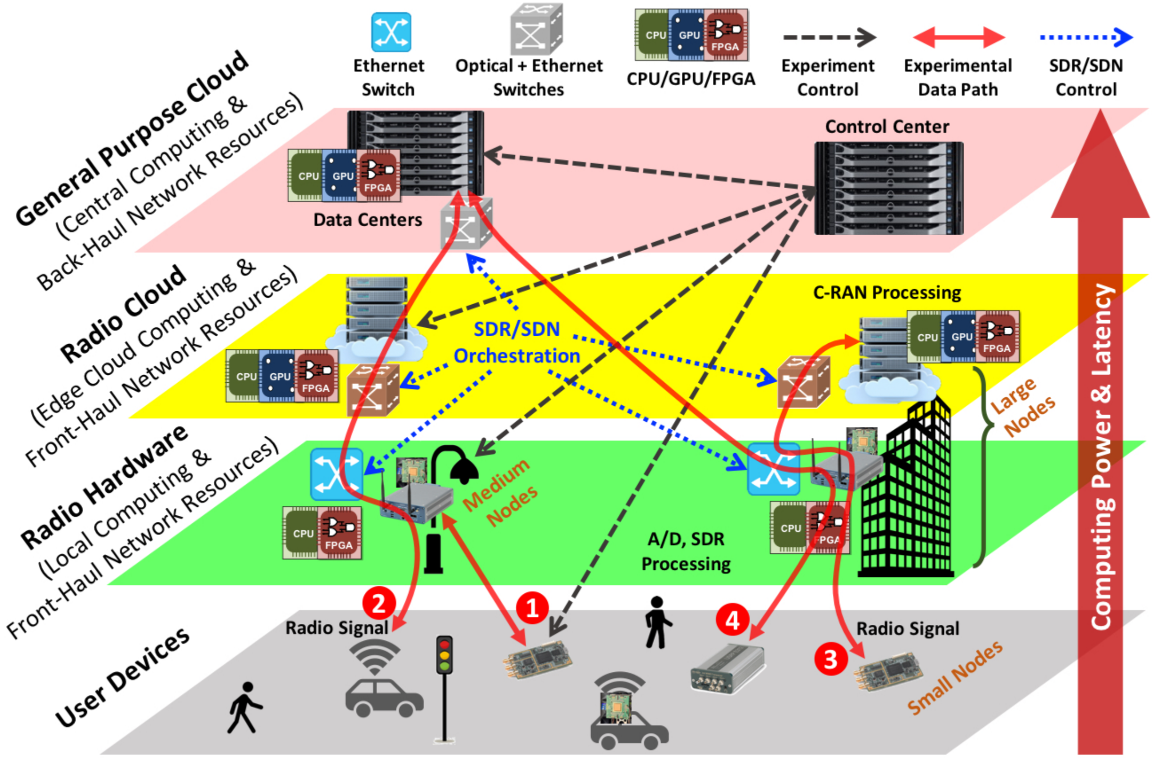
CDF of network throughput with zero, 1, and 2 FD users

The network-level FD gain increases as more users become FD-capable, especially for users with relatively high SNR values

Open-Access Full-Duplex Radios in the COSMOS Testbed

- ***C**loud enhanced **O**pen **S**oftware-defined **MO**bile wireless testbed for city-**S**cale deployment* (COSMOS) is a city-scale programmable testbed for advanced wireless technologies in West Harlem, New York City

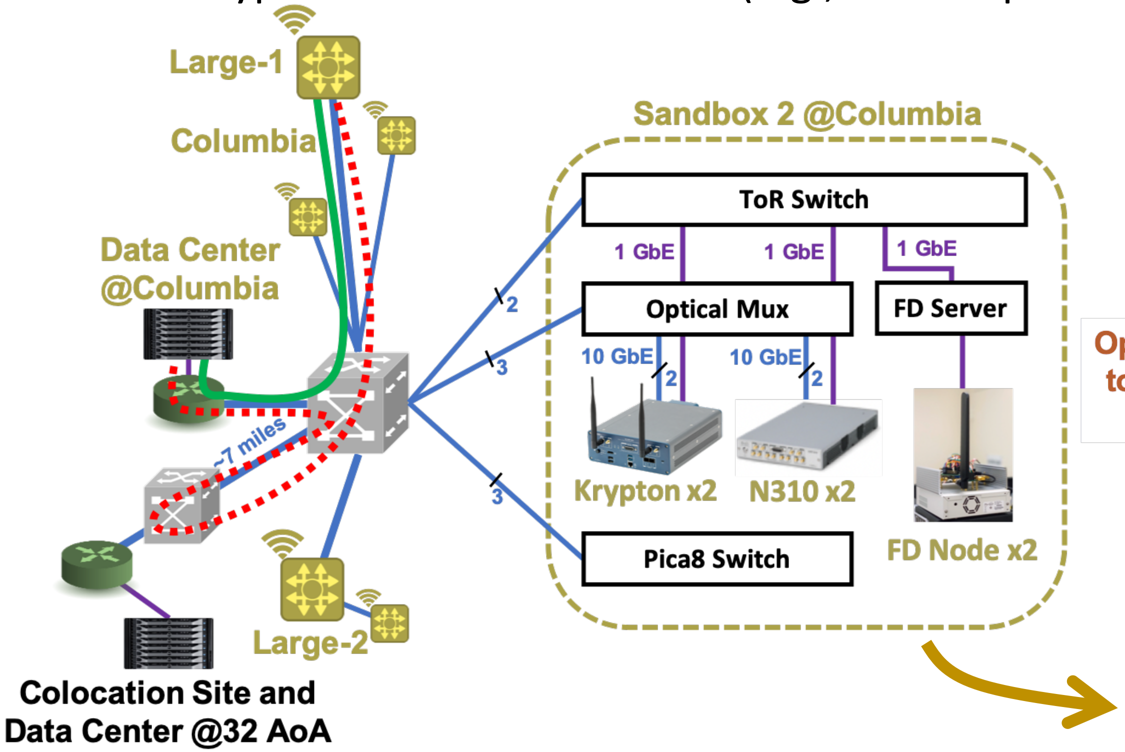


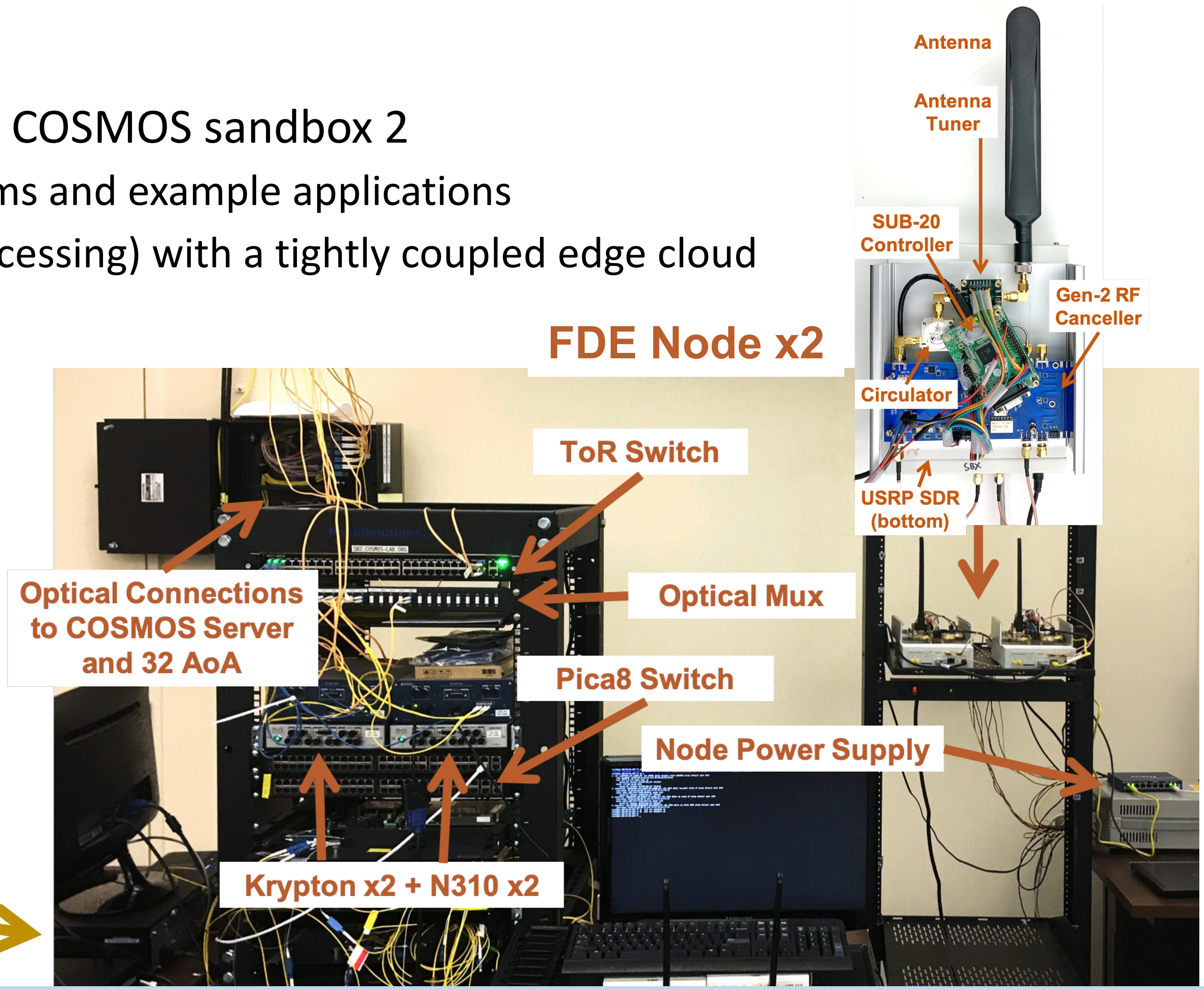


The COSMOS testbed deployment area and its multi-layered computing architecture

Open-Access Full-Duplex Radios in the COSMOS Testbed

- Integration of FDE-based full-duplex radios in the COSMOS sandbox 2
  - Provide customized open-source baseline programs and example applications
  - Prototype C-RAN functionalities (e.g., remote processing) with a tightly coupled edge cloud





- **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*.
- "Tutorial: Full-duplex wireless in the COSMOS testbed," available at https://wiki.cosmos-lab.org/wiki/tutorials/full_duplex

Summary

- Compact wideband full-duplex wireless
  - Design and implementation of FDE-based full-duplex radios, which are more suitable for small-form-factor nodes
  - Derive and validate a mathematical FDE-based canceller hardware model
  - Extensive experimental evaluation of the FDE-based full-duplex radios in a software-define radio testbed

- Ongoing work
  - Integration of more open-access FDE-based full-duplex radios in the programmable city-scale COSMOS advanced wireless testbed
  - Development of more example applications at the higher layers in full-duplex networks

Thank you!

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