Demo: Remote Experimentation with Open-Access Full-Duplex Wireless in the COSMOS Testbed

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ABSTRACT

To support experimentation with full-duplex (FD) wireless, we recently integrated two FlexICoN Gen-2 wideband FD radios in the open-access, city-scale NSF PAWR COSMOS testbed. Each integrated FD radio consists of an antenna, a customized Gen-2 RF self-interference (SI) canceller box, a USRP software-defined radio, and a remotely accessible compute node. The RF SI canceller box includes an RF canceller printed circuit board which emulates an integrated circuit implementation based on the technique of frequency-domain equalization. The Gen-2 canceller box can achieve up to 50 dB RF SI cancellation across 20 MHz bandwidth. In this demo, we present the design and implementation of the open-acccess, remotely accessible FD radios that are integrated in the indoor COSMOS Sandbox 2 at Columbia University. We also demonstrate example experiments that are available to researchers, where demo participants can observe the visualized performance of the open-access FD radios.

CCS CONCEPTS

• **Networks** → **Network architectures**; *Wireless access networks*; *Network experimentation*; • **Hardware** → **Wireless devices**; Printed circuit boards.

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1 INTRODUCTION

Full-duplex (FD) wireless has drawn significant attention [1–5] due to its potential to double the data rate at the physical layer as well as to provide benefits at all other layers in the networking stack. One of the main challenges associated with FD wireless is the self-interference (SI) experienced by a radio as it simultaneously transmits and receives on the same frequency. Therefore, at least 90 dB of SI cancellation (SIC) over the desired bandwidth is required, across the antenna interface, and RF and digital domains.

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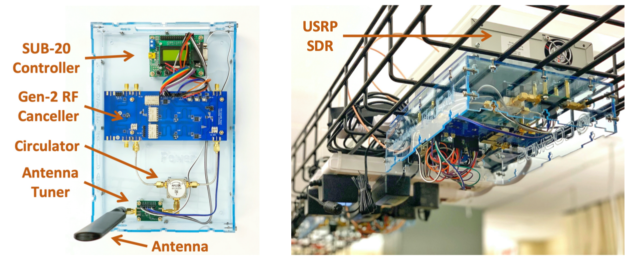

(a) (b)

Figure 1: **(a) The Gen-2 RF canceller box consisting of an antenna tuner, a circulator, a Gen-2 RF canceller PCB, and a SUB-20 controller; (b) The Gen-2 canceller box connected to the USRP SDR and compute node (not shown in the figure), which are integrated in the COSMOS Sandbox 2.**

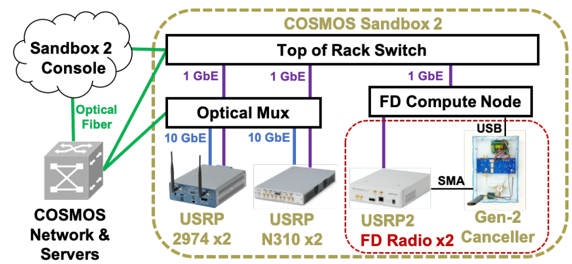

Figure 2: **COSMOS Sandbox 2 architecture, which includes (i) the remotely accessible console and two FD radios, each consisting of a USRP2 SDR and the Gen-2 canceller box, connected to the FD compute node; (ii) other remotely accessible SDRs used for experimentation with various technologies.**

Within the Columbia FlexICoN project [6], we have been focusing on the design and experimentation of FD radios and systems grounded in integrated circuit (IC) implementations, which are suitable for hand-held and form-factor-constrained devices [7–10]. To facilitate research in this area and allow remote experimentation, we previously integrated a FlexICoN 1st-generation (Gen-1) *narrowband* RF canceller box with a software-defined radio (SDR) in the open-access ORBIT testbed [11–13]. The Gen-1 canceller box consists of a printed circuit board (PCB) canceller emulating the original IC implementation [8], which provides an easy interface to the SDR platform. This Gen-1 canceller box can achieve 40 dB RF SIC across 5 MHz bandwidth [11].

More recently, we presented the FlexICoN 2nd-generation (Gen-2) *wideband* RF canceller in [14]. This canceller is based on the technique of frequency-domain equalization (FDE), and achieves up to 50 dB RF SIC across 20 MHz bandwidth. In this demo, we present the integration of the Gen-2 canceller box in the open-access NSF PAWR COSMOS testbed, which is being deployed in West Harlem, New York City [11, 15, 16]. We also present example experiments that can be run and modified by other experimenters. A full tutorial on how to access the FD radios and run experiments

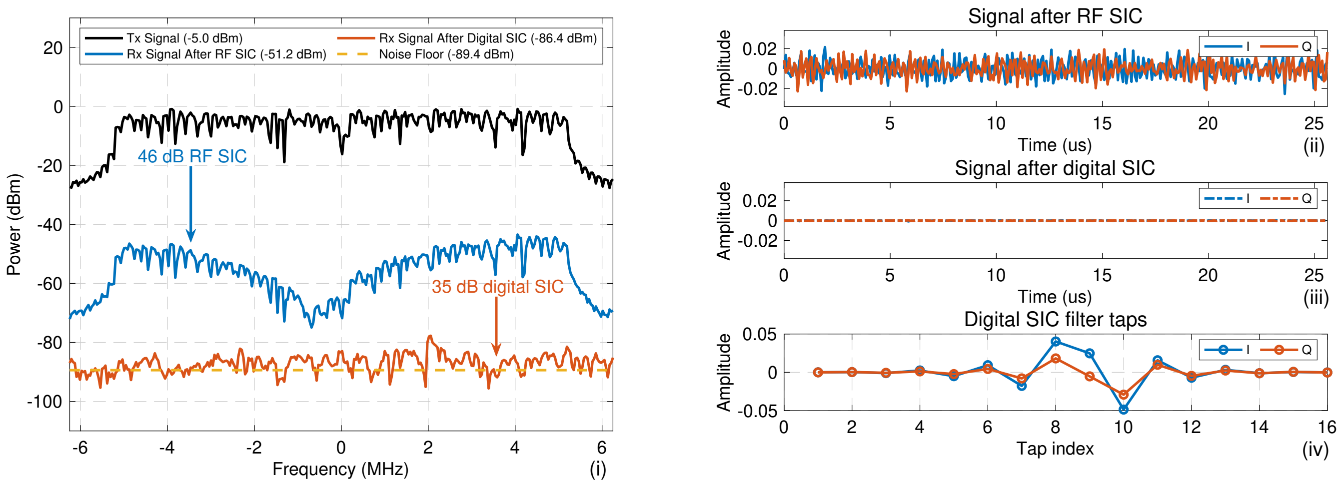

Figure 3: **Node-level self-interference cancellation (SIC) performance: (i) power spectrum of the received signal after SIC in the RF and digital domains, with -5 dBm average Tx power and -89 dBm receiver noise floor; (ii), (iii) time domain signals after RF and after digital SIC; (iv) digital SIC filter taps (the estimated SI channel). The carrier frequency used is the 915 MHz ISM band and the bandwidth is 12.5 MHz, currently limited by the USRP model and available compute resources.**

is available [17], alongside the open-source hardware and software [18]. A detailed discussion of the Gen-2 canceller integration in COSMOS can be found at [11]. We believe that the integrated FD radios and example experiments can facilitate further research in the area of FD wireless.

2 THE GEN-2 WIDEBAND FD RADIO

The Gen-2 canceller box integrated in COSMOS Sandbox 2 (see Fig. 1(a)) consists of several components: an antenna tuner, a circulator, the Gen-2 FDE-based RF canceller, and a SUB-20 controller. It is connected to a USRP SDR (model USRP2) as shown in Fig. 1(b). Fig. 2 shows the architecture of COSMOS Sandbox 2, where both the canceller box and SDR are connected to a remotely accessible compute node through the COSMOS network.

Gen-2 RF Canceller. The circulator provides 15–25 dB of isolation between the USRP Tx and Rx. This means that the received SI can be very strong, and thus cause the LNA and ADC of the Rx chain to operate in a nonlinear regime. As nonlinearity and clipping would negatively impact digital SIC, it is crucial to achieve sufficient SIC in the RF domain. Details and tradeoffs for the circuit implementation of the Gen-2 RF canceller can be found in [14]. In particular, the Gen-2 RF canceller PCB operates around the 915 MHz carrier frequency, and has 11 tunable components that are programmed over SPI via the SUB-20 controller [19].

Compute Node. The Gen-2 FD radios are connected to a remotely accessible compute node which runs Ubuntu 16.04, GNU Radio 3.7, and UHD 3.14 [20, 21]. Other more powerful COSMOS servers with heterogenous computing resources will be used in the future.

3 REMOTE-ACCESSED REAL-TIME DEMO

Below, we present three example real-time experiments that are available to the community.

Experiment 1: Real-Time Digital SIC. This real-time demonstration shows the level of achievable SIC for one FD radio transmitting OFDM-like packets [22]. Experimenters are able to generate different RF SIC profiles for the Gen-2 RF canceller through the GNU Radio graphical user interface (GUI). Demo participants will be able to observe the visualized SIC achieved in the RF and digital domains. Real-time performance is achieved by customized GNU Radio out-of-tree (OOT) blocks implemented in C++ for controlling the SUB-20 and performing digital SIC. Digital SIC is performed by a time-domain least-squares estimation of the SI channel using pilot symbols [14], and Fig. 3 shows that an overall SIC of over 80 dB is achieved across 12.5 MHz bandwidth. In the future, we will replace the USRP2s with the higher performance USRP 2974s [23], which are expected to improve the overall SIC to at least 90 dB.

Experiment 2: Real-Time OFDM Link. The two integrated Gen-2 wideband FD radios are synchronized over a MIMO cable, and can be used by the experimenter in an FD link. By using the GNU Radio OFDM blocks [20], this experiment implements real-time, packet-level SIC for both radios and allows for a real-time FD link. Demo participants will observe: (i) the successfully decoded OFDM packets, (ii) the digital SIC filter taps, and (iii) the power spectrum of the received signal after each SIC stage.

Experiment 3: Real-Time Packet Reception Ratio (PRR). The real-time OFDM link also allows the experimenter to measure the link-level packet reception ratio (PRR), which is calculated as the percentage of transmitted packets that are successfully decoded at each radio. Demo participants will be able to observe key measurements visualized, including: (i) the packet-level signal-to-noise ratio (SNR), (ii) the real-time PRR, and (iii, iv) the constellations and error vector magnitude (EVM) of the received signal.

The GNU Radio implementation of these experiments is available at [18] and can be easily modified to support experiments in different scenarios. As an example, our customized digital SIC block could be replaced with a block implementing a different algorithm. We anticipate that these experiments can provide a basis for further remote experimentation by the research community.

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REFERENCES

[1] Ashutosh Sabharwal, Philip Schniter, Dongning Guo, Daniel W Bliss, Sampath Rangarajan, and Risto Wichman. In-band full-duplex wireless: Challenges and opportunities. *IEEE J. Sel. Areas Commun.*, 32(9):1637–1652, 2014.

[2] Kenneth E. Kolodziej, Bradley T. Perry, and Jeffrey S. Herd. In-band full-duplex technology: Techniques and systems survey. *IEEE Trans. Microw. Theory Techn.*, 67(7):3025–3041, 2019.

[3] Dinesh Bharadia, Emily McMilin, and Sachin Katti. Full duplex radios. In *Proc. ACM SIGCOMM'13*, 2013.

[4] Liang Zhang and Nirwan Ansari. A Framework for 5G Networks with In-Band Full-Duplex Enabled Drone-Mounted Base-Stations. *IEEE Wireless Commun.*, 26 (5):121–127, 2019.

[5] MinKeun Chung, Min Soo Sim, Jaeweon Kim, Dong Ku Kim, and Chan-Byoung Chae. Prototyping real-time full duplex radios. *IEEE Commun. Mag.*, 53(9):56–63, 2015.

[6] The Columbia FlexICoN project. http://flexicon.ee.columbia.edu/.

[7] Jin Zhou, Negar Reiskarimian, Jelena Diakonikolas, Tolga Dinc, Tingjun Chen, Gil Zussman, and Harish Krishnaswamy. Integrated full duplex radios. *IEEE Commun. Mag.*, 55(4):142–151, 2017.

[8] Jin Zhou, Anandaroop Chakrabarti, Peter Kinget, and Harish Krishnaswamy. Low-Noise Active Cancellation of Transmitter Leakage and Transmitter Noise in Broadband Wireless Receivers for FDD/Co-Existence. *IEEE J. Solid-State Circuits*, 49(12):1–17, 2014.

[9] Bjorn Debaillie, Dirk-Jan van den Broek, Cristina Lavin, Barend van Liempd, Eric AM Klumperink, Carmen Palacios, Jan Craninckx, Bram Nauta, and Aarno Parssinen. Analog/RF solutions enabling compact full-duplex radios. *IEEE Sel. Areas Commun.*, 32(9):1662–1673, 2014.

[10] Dani Korpi, Joose Tamminen, Matias Turunen, Timo Huusari, Yang-Seok Choi, Lauri Anttila, Shilpa Talwar, and Mikko Valkama. Full-duplex mobile device: Pushing the limits. *IEEE Commun, Mag.*, 54(9):80–87, 2016.

[11] Manav Kohli, Tingjun Chen, Mahmood Baarani Dastjerdi, Jackson Welles, Ivan Seskar, Harish Krishnaswamy, and Gil Zussman. Open-Access Full-Duplex Wireless in the ORBIT and COSMOS Testbeds. In *Proc. ACM MobiCom'20 Workshop on Wireless Network Testbeds, Experimental evaluation & CHaracterization (WiNTECH'20)*, 2020.

[12] Open-access research testbed for next-generation wireless networks (ORBIT). http://www.orbit-lab.org/.

[13] Tingjun Chen, Mahmood Baraani Dastjerdi, Guy Farkash, Jin Zhou, Harish Krishnaswamy, and Gil Zussman. Open-access full-duplex wireless in the ORBIT testbed. *arXiv preprint arXiv:1801.03069v2*, 2018.

[14] Tingjun Chen, Mahmood Baraani Dastjerdi, Jin Zhou, Harish Krishnaswamy, and Gil Zussman. Wideband full-duplex wireless via frequency-domain equalization: Design and experimentation. In *Proc. ACM MobiCom'19*, 2019.

[15] Dipankar Raychaudhuri, Ivan Seskar, Gil Zussman, Thanasis Korakis, Dan Kilper, Tingjun Chen, Jakub Kolodziejski, Michael Sherman, Zoran Kostic, Xiaoxiong Gu, Harish Krishnaswamy, Sumit Maheshwari, Panagiotis Skrimponis, and Craig Gutterman. Challenge: COSMOS: A City-Scale Programmable Testbed for Experimentation with Advanced Wireless. In *Proc. ACM MobiCom'20*, 2020.

[16] Cloud Enhanced Open Software Defined Mobile Wireless Testbed for City-Scale Deployment (COSMOS). https://cosmos-lab.org/, 2020.

[17] Tutorial: Full-duplex wireless in the ORBIT and COSMOS testbeds. https://wiki.cosmos-lab.org/wiki/Tutorials/Wireless/FullDuplex, 2020.

[18] The Columbia FlexICoN project: Instructions and Code. https://github.com/Wimnet/flexicon_orbit, 2020.

[19] DIMAX SUB-20 user manual. http://www.xdimax.com/sub20/doc/sub20-man.pdf.

[20] GNU Radio. http://gnuradio.org/.

[21] USRP Hardware Driver (UHD) software. https://github.com/EttusResearch/uhd.

[22] Bastian Bloessl, Michele Segata, Christoph Sommer, and Falko Dressler. An IEEE 802.11a/g/p OFDM Receiver for GNU Radio. In *Proc. SRIF'13*, Aug. 2013.

[23] Ettus Research/NI USRP-2974 datasheet. https://www.ettus.com/wp-content/uploads/2019/01/377417a.pdf.