Open-Access Full-Duplex Wireless in the ORBIT Testbed

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Abstract—In order to support experimentation with full-duplex (FD) wireless, we recently integrated an open-access FD transceiver in the ORBIT testbed [1]. In this report, we present the design and implementation of the FD transceiver and interfaces, and provide examples and guidelines for experimentation. In particular, an ORBIT node with a National Instruments (NI)/Ettus Research Universal Software Radio Peripheral (USRP) N210 software-defined radio (SDR) was equipped with the Columbia FlexICoN Gen-1 customized RF self-interference (SI) canceller box. The RF canceller box includes an RF SI canceller that is implemented using discrete components on a printed circuit board (PCB) and achieves 40 dB RF SI cancellation across 5 MHz bandwidth. We provide an FD transceiver baseline program and present an example FD experiment, achieving 90 dB overall SI cancellation across both the RF and digital domains, demonstrating the FD capability in the ORBIT testbed. We also discuss potential FD wireless experiments that can be conducted based on the implemented open-access FD transceiver and baseline program.

I. INTRODUCTION

Due to its potential to double network capacity at the physical (PHY) layer and to provide many other benefits at higher layers, full-duplex (FD) wireless has drawn significant attention [2]–[4]. The major challenge associated with FD is the extremely strong self-interference (SI) on top of the desired signal, requiring more than 90 dB of self-interference cancellation (SIC) across both the RF and digital domains.

Our work on FD transceivers/systems within the Columbia FlexICoN project [5] focuses on integrated circuit (IC) implementations that are appropriate for mobile and small-form-factor devices [4], [6], [7]. In [8], we presented the FlexICoN Gen-1 FD transceiver and an FD wireless link, featuring 40 dB RF SIC across 5 MHz. The implemented Gen-1 RF SI canceller emulates its RFIC counterpart that we presented in [6] and modeled and analyzed in [9].

However, there is no existing open-access wireless testbed with FD-capable nodes, which is crucial for experimental evaluations of FD-related algorithms at the higher layers. Therefore, to facilitate research in this area and to allow the broader community to experiment with FD wireless, we integrated an improved version of the Gen-1 RF canceller presented in [8] with a National Instruments (NI)/Ettus Research USRP N210 SDR in the open-access ORBIT wireless testbed [1]. Since interfacing an RFIC canceller with an SDR presents numerous technical challenges, we implemented the RF canceller on a printed circuit board (PCB) to facilitate the cross-layered experiments with an SDR platform.

In this technical report, we present our cross-layered (hardware and software) implementation of an open-access FD transceiver integrated with the ORBIT testbed, including the design and implementation of the customized Gen-1 RF canceller box and an FD transceiver baseline program. We also present an example FD experiment that runs remotely in the ORBIT testbed, achieving 90 dB overall SIC across both RF and digital domains. The code for the baseline program and a tutorial for the FD transceiver are available at [10], [11]. The implemented FD transceiver and the baseline program, which can be further extended to more complicated communication networking scenarios, can allow the broader community to experiment with FD wireless.

II. THE FLEXICON GEN-1 RF CANCELLER BOX

Fig. 1 shows the block diagram of the implemented FD transceiver, in which a Gen-1 RF canceller box (as depicted in Fig. 2(a)) is connected to an Apex II multi-band antenna (at the ANT port) and a USRP (at the TX IN and RX OUT ports). Fig. 2(b) shows the FD transceiver installed
The amplitude- and phase-based RF canceller is implemented using discrete components on a PCB and is optimized around 900 MHz operating frequency. The RF canceller taps a reference signal from the output of the power amplifier (PA) at the TX side (through a 6 dB Mini-Circuits ADC-6-13+ directional coupler) and adjusts its amplitude and phase. Then, SIC is performed at the input of the low-noise amplifier (LNA) at the RX side.

For amplitude adjustment, a 7-bit SKY12343-364LF digital attenuator is used, in which the attenuation can be adjusted within a 31.75 dB range with a resolution of 0.25 dB. As a result, the RF canceller has an amplitude tuning range between −48 dB and −17 dB. For phase adjustment, a Mini-Circuits passive SPHSA-152+ phase-shifter is used, which covers full 360 deg and is controlled by an 8-bit TI-DAC081S101 digital-to-analog converter (DAC). Both the attenuator and phase shifter are programmed through the SUB-20 controller serial-to-parallel interface (SPI) with code values $\text{ATT}$ (ATTuation) and $\text{PS}$ (Phase Shift), respectively, and the parameter configuration ranges are $\text{ATT} \in \{0, 1, \ldots, 127\}$, $\text{PS} \in \{0, 1, \ldots, 255\}$.

The attenuator and DAC have 3 V supply voltage and the phase shifter has a reference voltage of 12 V.

An RF-CI RFCR3204 coaxial circulator is used, whose operating frequency is between 860-960 MHz.

### C. The Programmable Antenna Tuner

In order for the circulator to better match with varying impedance of the antenna due to environmental changes (around 900 MHz operating frequency), we also designed and implemented a programmable antenna tuner. Fig. 5 shows the circuit diagram and the PCB implementation of the antenna tuner. In particular, a $\pi$-network with lossless inductor ($L$) and digitally tunable capacitors ($C_i$) is used for impedance transformation. In our implementation, we use a fixed chip inductor with inductance $L_{\text{fixed}} = 5.1 \text{nH}$ and the Peregrine Semiconductor 5-bit PE64909 digitally tunable capacitors for $C_i$ ($i = 1, 2, 3$). By programming the capacitors with code values $\text{CAP}_i$ ($i = 1, 2, 3$), different antenna interface impedance matching can be achieved. The corresponding configuration ranges of the tunable capacitors are $\text{CAP}_i \in \{0, 1, \ldots, 31\}$, $\forall i = 1, 2, 3$.

### D. The SUB-20 Controller

As Fig. 1 shows, a DIMAX SUB-20 multi-interface USB adapter is connected to the host PC is used to program the attenuator and DAC (on the RF SI canceller) and the
capacitors (on the antenna tuner) through SPI. The SUB-20 SPI is configured to operate at the maximal master clock of 8 MHz. At this clock rate, programming one ATT or PS value (a 2-byte word including the address fields, etc.) takes 2 µs, and programming one CAPi value (a 1-byte word) takes 1 µs. We note that other controller platforms with higher SPI clock rates can also be used to improve the performance.

III. INTEGRATION WITH THE ORBIT TESTBED AND AN FD TRANSCEIVER BASELINE PROGRAM

Fig. 5 depicts an ORBIT node equipped with the Gen-1 RF canceller box. We use node11-10 in the ORBIT main grid with a USRP N210 SDR. In particular, the RF canceller box TX IN/RX OUT ports are connected to the USRP TX/RX ports, respectively, and the RF canceller box ANT port is connected to an Apex II multi-band antenna (see Figs. 1 and 2). We developed an FD transceiver baseline program, which contains two parts running on the host PC (i.e., the yellow box in Fig. 5): (i) a UHD program for the main SDR application, and (ii) a C-based SUB-20 program for configuring the RF canceller box.

Different from regular UHD programs that are designed for half-duplex applications, the FD UHD program includes three parallel threads for performance optimization (see Fig. 1): the TX/RX streaming threads running on the same frequency channel and a third thread for executing the digital SIC algorithm. In particular, the digital SIC algorithm is based on Volterra series and a least-square problem and is similar to that presented in [3], [7]. Moreover, the Eigen C++ library is included for computations in the digital SIC algorithm (e.g., matrix operations and FFT). The code for the FD transceiver baseline program is available at https://github.com/Wimnet/flexicon_orbit.

To facilitate the experiments with the RF canceller box and FD wireless, a customized OS image named flexicon-orbit-v1.ndz with the required software was created and stored in the ORBIT testbed. The steps for running the FD transceiver baseline program are as follows:

1. Load image flexicon-orbit-v1.ndz to node11-10.
   Then, ssh into node11-10 in the ORBIT main grid;
2. Check the configuration of the interface between the USRP N210 and the host PC using commands ifconfig and uhd_find_devices;
3. Run the FD transceiver baseline program by executing the UHD program and SUB-20 program using commands
   $ ./fd_transceiver_simple --args
   $ ./rf_canc_gen1_config --args
   in two separate terminal windows, such that the RF canceller box can be configured in parallel with the main UHD program. The corresponding input arguments are represented by args.
4. Observe the output log of the FD transceiver baseline program, such as the amount of achieved SIC in both RF and digital domains.

IV. AN EXAMPLE FD EXPERIMENT

In this section, we present an example FD experiment using the FD transceiver and the baseline program, where the FD transceiver transmits and receives simultaneously at 900 MHz carrier frequency with 5 MHz sampling rate.

In the example experiment, the FD transceiver (node11-10) sends a single tone with frequency offset 200 kHz at 0 dBm TX power level. Fig. 6 shows an example output of the FD transceiver SUB-20 program, where the RF SI canceller is configured with ATT = 30 and PS = 110, and the antenna tuner is configured with CAP1 = 16, CAP2 = 6, and CAP3 = 6.
Fig. [5] shows the TX/RX isolation of the RF canceller box under this configuration. Fig. [7] shows an example output of the FD transceiver UHD program where 90 dB overall SIC is achieved, where 45 dB is from the RF domain and 45 dB is from the digital SIC algorithm, and the SI signal is canceled to the receiver noise floor. Fig. [8] shows the power spectrum of the residual SI after RF and digital SIC through an offline MATLAB script, respectively.

In addition, another ORBIT node (node13-8) serves as a second radio that sends a single tone with frequency offset 400 kHz using the UHD tx_waveforms program [17], i.e.,

$ ./tx_waveforms --rate 5e6 --freq 900e6
--wave-type SINE --wave-freq 400e3$

Fig. [8] presents the power spectrum of the signal received at the FD node after RF and digital SIC. As Fig. [5] shows, the SI at the FD node (with frequency offset 200 kHz) is canceled to the receiver noise floor after SIC in both the RF and digital domains, and the digital SIC algorithm introduces minimal SNR loss to the desired signal (with frequency offset 400 kHz).

V. OTHER POTENTIAL FD WIRELESS EXPERIMENTS

Some potential FD experiments that can be conducted using the presented FD transceiver are listed below:
- Hands-on experiments with FD wireless on an SDR platform in a teaching/lab course;
- Studying different RF SIC performance and its relation to the antenna interface response by tuning the RF canceller box (the SUB-20 program);
- Studying the performance of the digital SIC algorithm by tuning its parameters (digital SIC thread of the UHD program);
- Development and evaluation of different digital SIC algorithms (digital SIC thread of the UHD program);
- Incorporation of modulated signals, such as QPSK and OFDM, with different bandwidth (the UHD program);
- Experimentation and evaluation of medium access control (MAC) algorithms in a heterogeneous network with an FD access point/client (e.g., modifying the UHD program and adding a MAC layer).

VI. CONCLUSION

In this report, we presented our cross-layered (hardware and software) design and implementation of the first open-access remotely-accessible FD transceiver which is integrated with the ORBIT wireless testbed. An FD transceiver baseline program and an example FD experiment were provided to facilitate the experimentation with the FD transceiver. We discussed other potential FD experiments that can be developed and conducted using the FD transceiver.

Our future work includes the integration of the Gen-2 canceller box with the ORBIT testbed. In particular, we presented the Gen-2 RF canceller in [18], which can achieve wideband RF SIC via the technique of frequency-domain equalization. The Gen-2 RF SI canceller implemented on a PCB emulates its RFIC counterpart we presented in [19]. We plan to install more FD transceivers in the ORBIT testbed with both Gen-1 and Gen-2 RF canceller boxes. Our future work also includes developing more advanced FD-related software and application programs.

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