Enabling Practical Full-Duplex Wireless

From Circuits to Software

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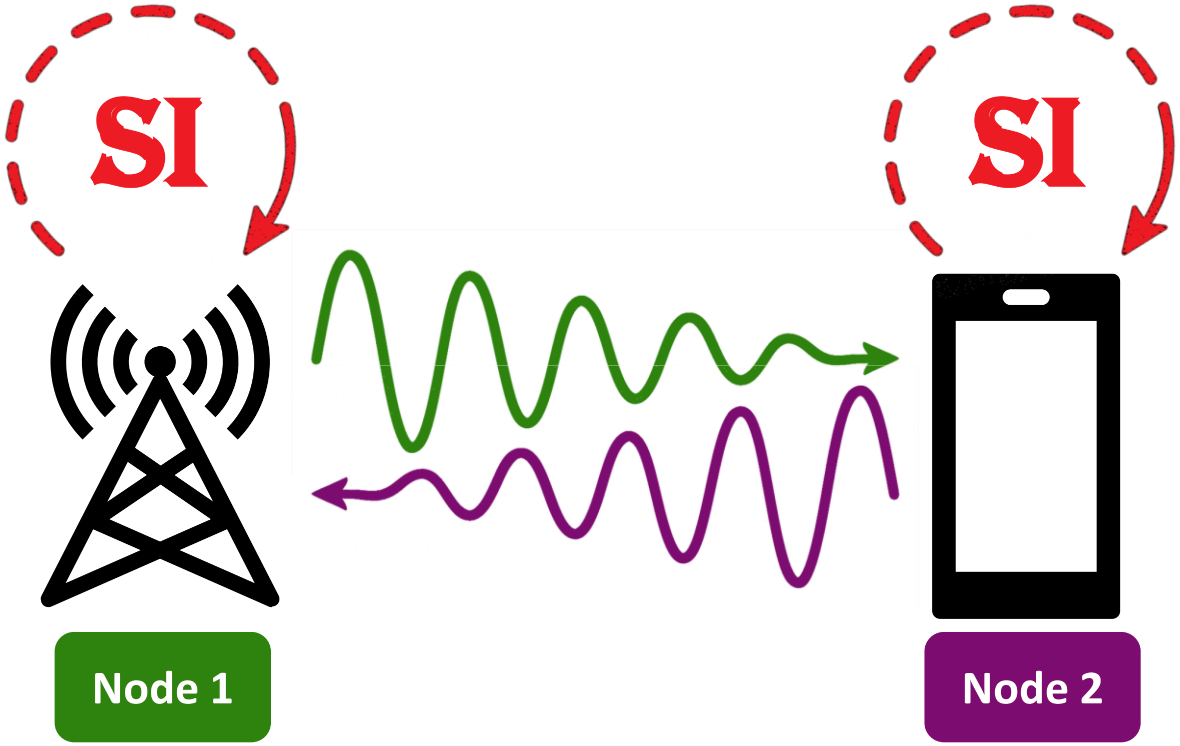
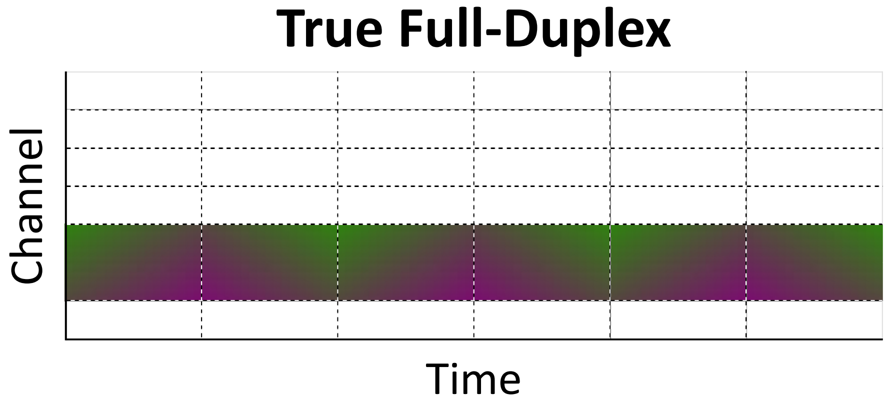
Rising Stars Forum, MobiSys'26, Cambridge, UK

Full-Duplex Communication

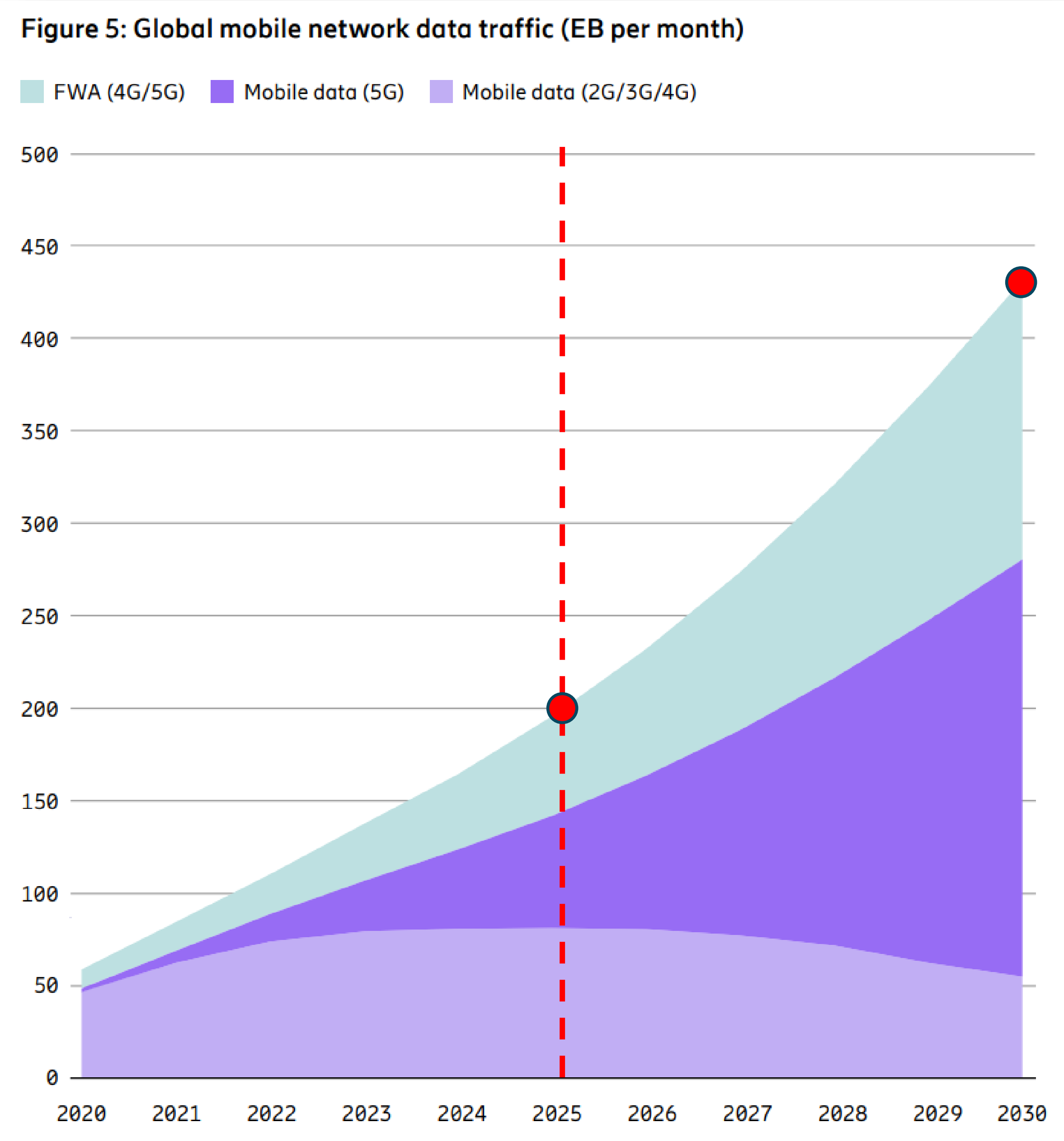


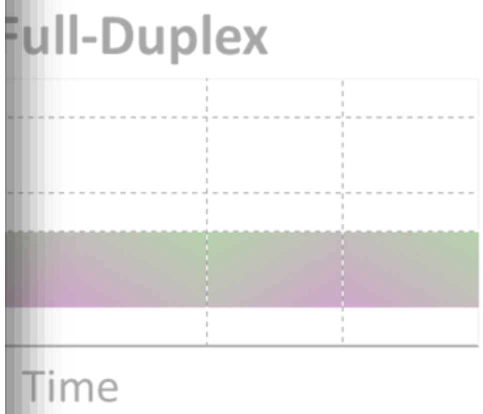


1. **Enhanced spectrum efficiency**
2. **Improved data rates**
3. **Reduced communication latency**

A. Nagulu, N. Reiskarimian, T. Chen, S. Garikapati, I. Kadota, T. Dinc, S. Garimella, M. Kohli, **A. S. Levin**, G. Zussman, H. Krishnaswamy. Doubling Down on Wireless Capacity: A Review of Integrated Circuits, Systems, and Networks for Full Duplex. *Proceedings of the IEEE*, 112(5):405–432, 2024.

Full-Dupl





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Two challenges stand between full-duplex and practical deployment: cancelling extremely strong, time-varying self-interference — and integrating that cancellation into a functional radio transceiver.

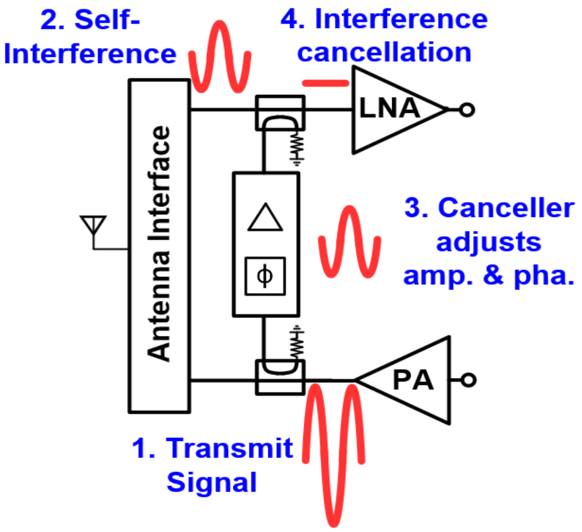
The Challenge of Self-Interference

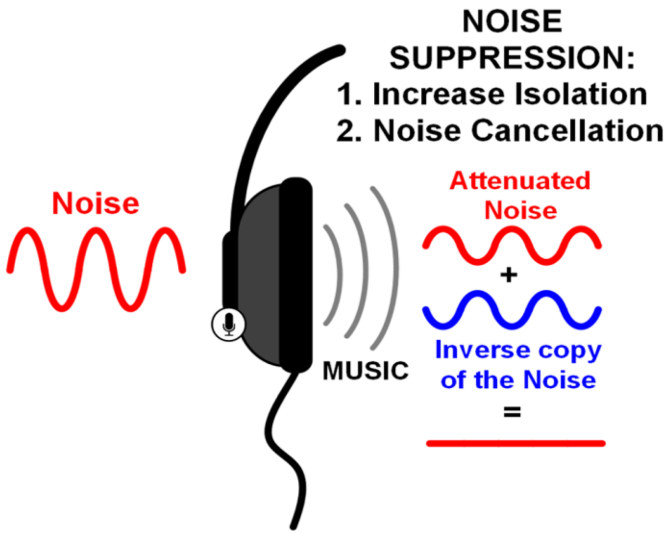
A device's own transmission leaks into its receiver as **self-interference (SI)**, typically **90-120dB** stronger than the desired incoming signal.

The **SI is highly dynamic**, changing constantly as the surrounding environment changes and electromagnetic conditions shift.

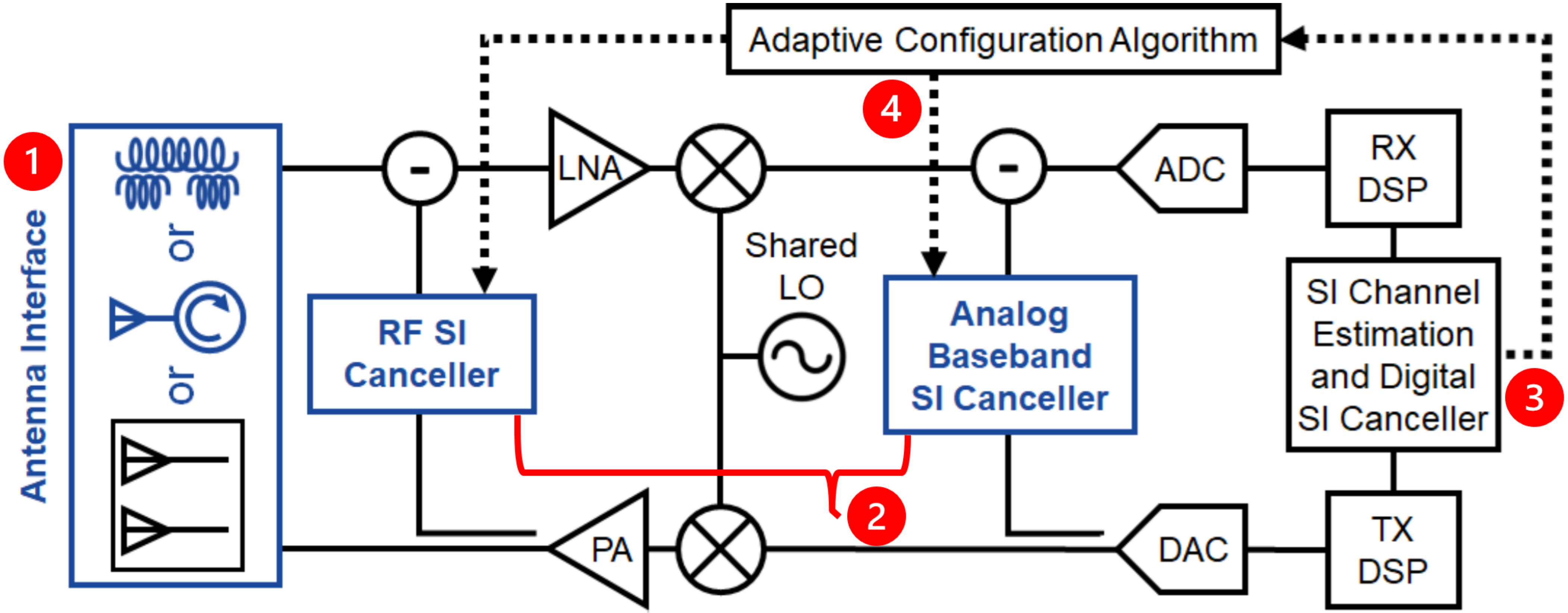
Cancelling SI well enough – and quickly enough – to recover the desired signal **requires a multi-stage adaptive cancellation pipeline**.

Recovering the desired signal from the SI is like finding a quarter in a hundred football fields!





Multi-Stage SI Cancellation Architecture



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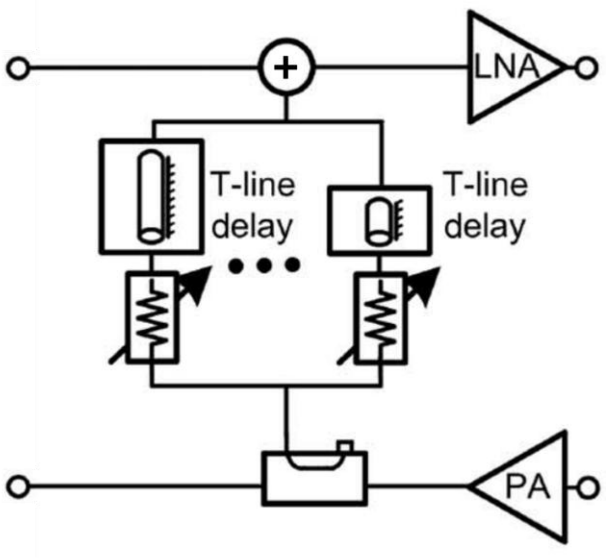
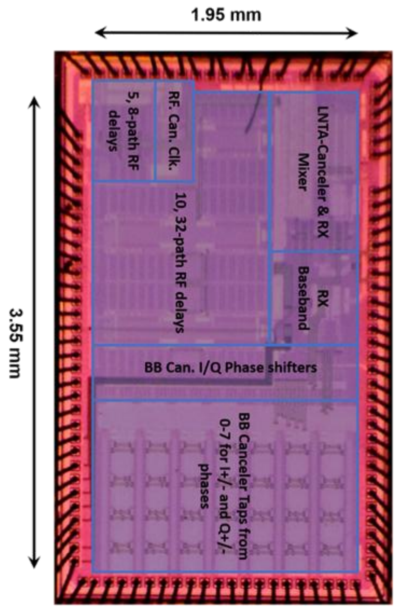
Adaptive Wideband SI Cancellation

In real-world deployments, we aim to achieve FD performance **across large bandwidths** using increasingly **complex programmable RFIC canceller designs**.





Determining an optimal configuration is ***hard***.

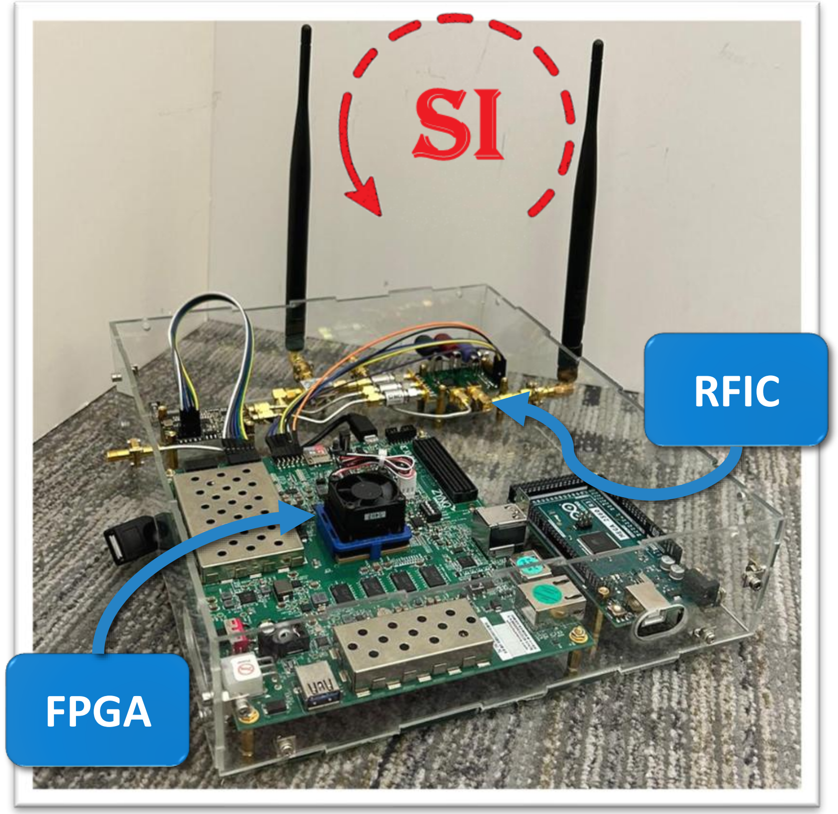
Just selecting taps and delays yields a configuration space on the order of

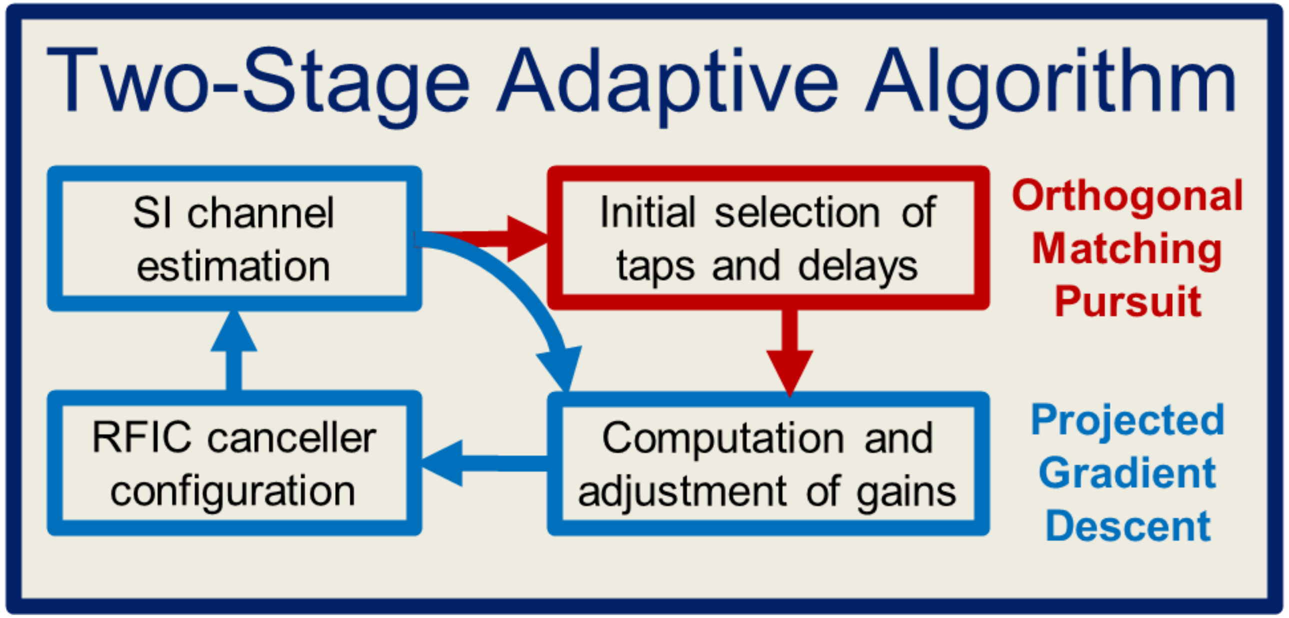
$$\mathbf{1^1 \times 8^5 \times 32^{10} \approx 10^{19}}$$

Table 1: RFIC Canceller Taps

Tap Class	Count	Parameter	Settings	Maximum
Zero-Delay	1	Gain	64 (6 bits)	−27 dB
		Delay	1 (0 bits)	–
Low-Delay	5	Gain	64 (6 bits)	−33 dB
		Delay	8 (3 bits)	2 ns
High-Delay	10	Gain	64 (6 bits)	−36 dB
		Delay	32 (5 bits)	8 ns

Adaptive Wideband FD Radio





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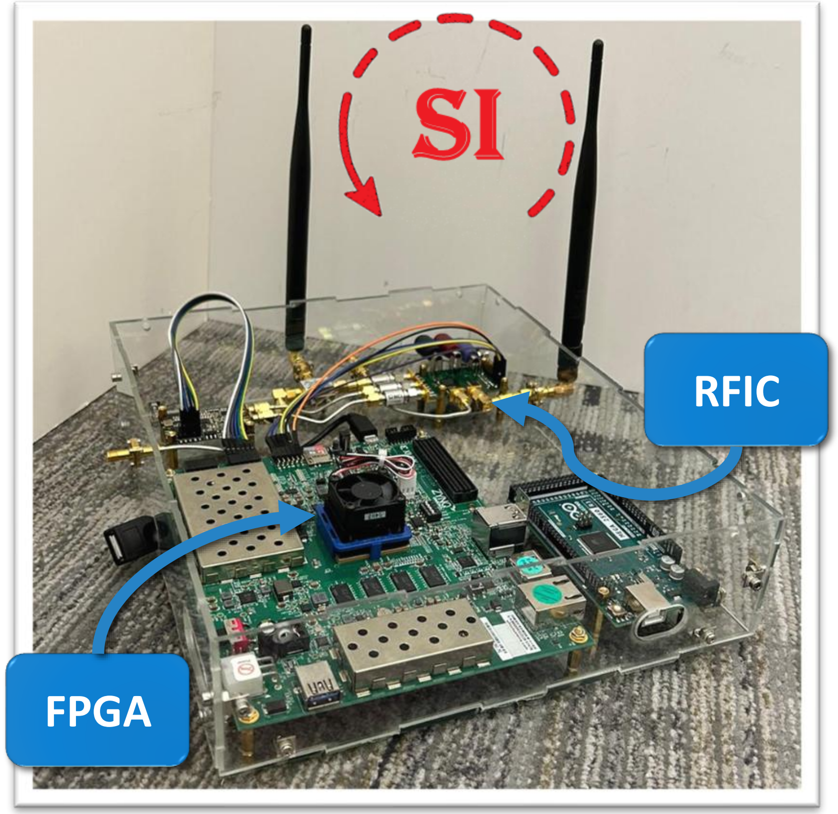

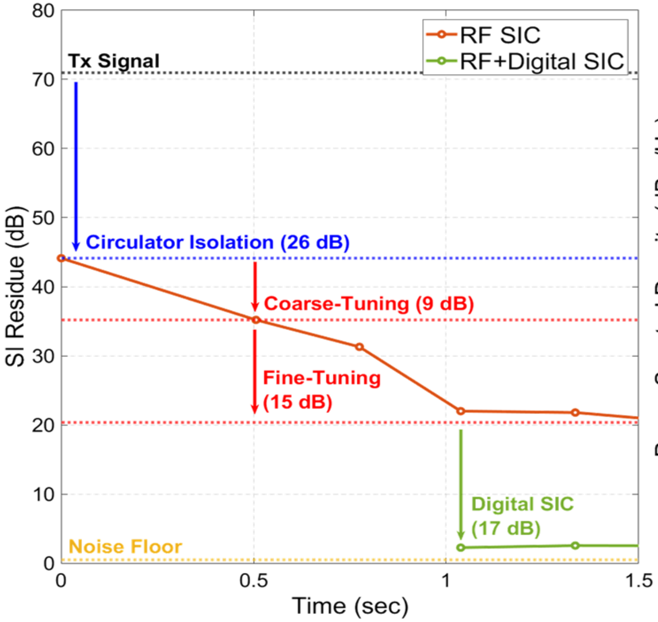

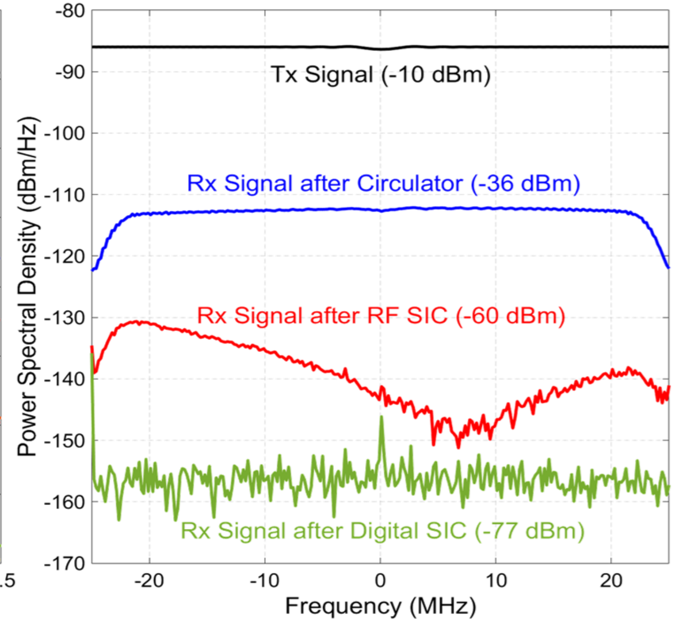

Noise-floor level cancellation >50MHz bandwidth!

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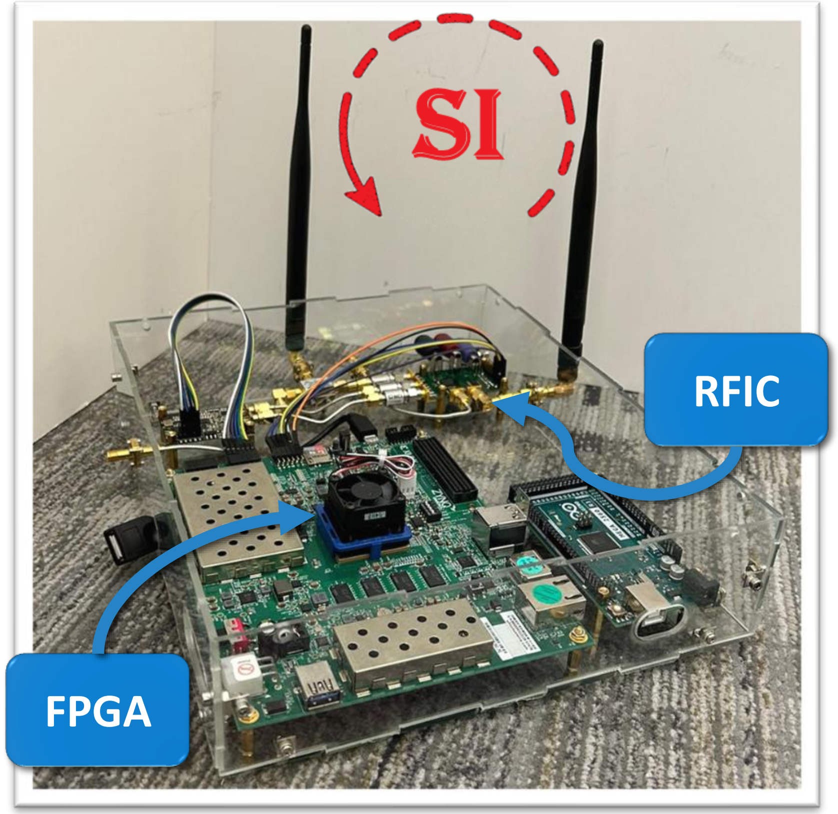

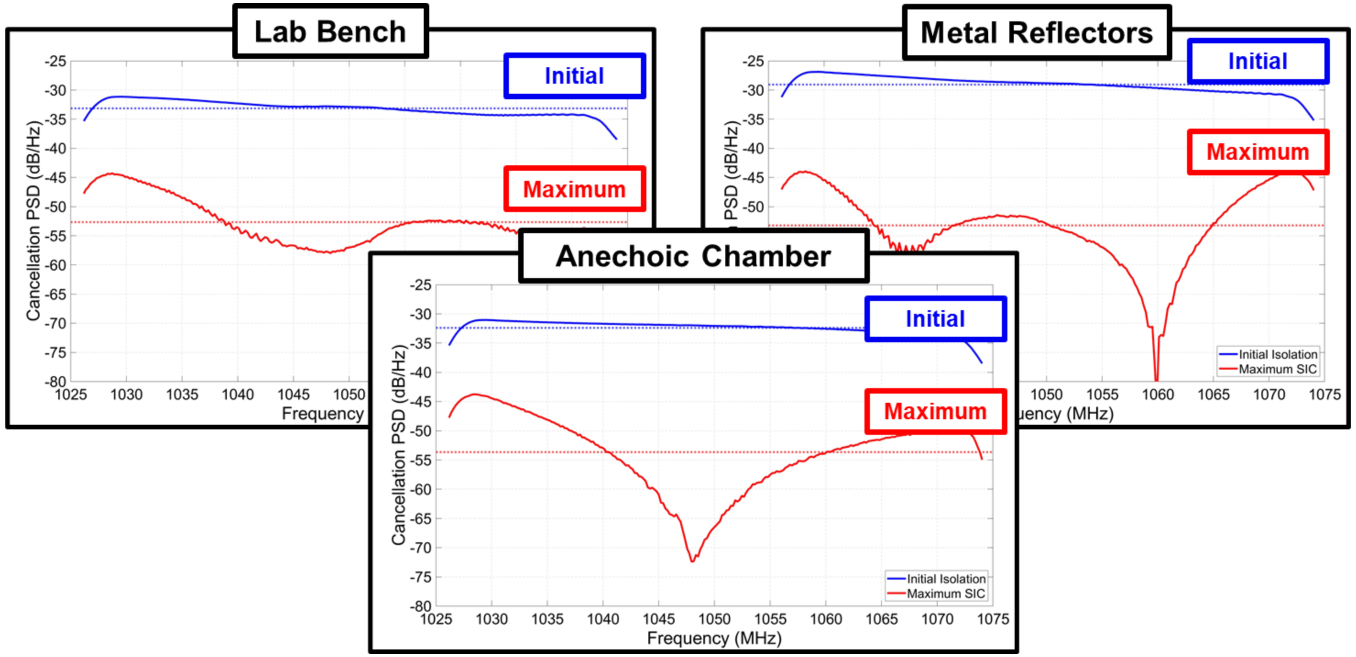

Adaptive analog SIC in various environments!

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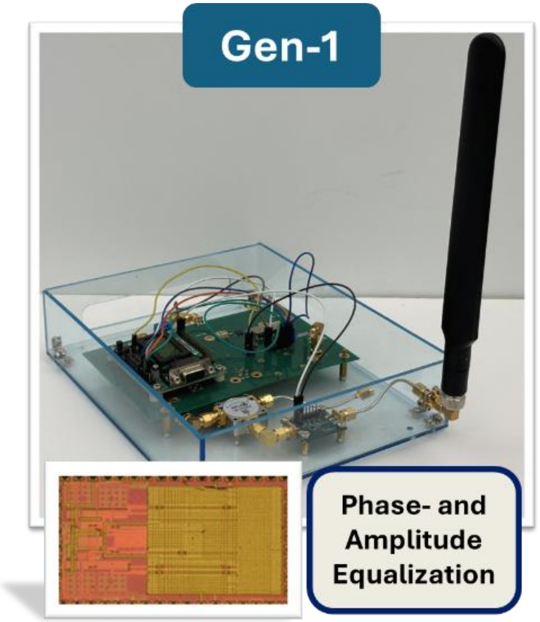
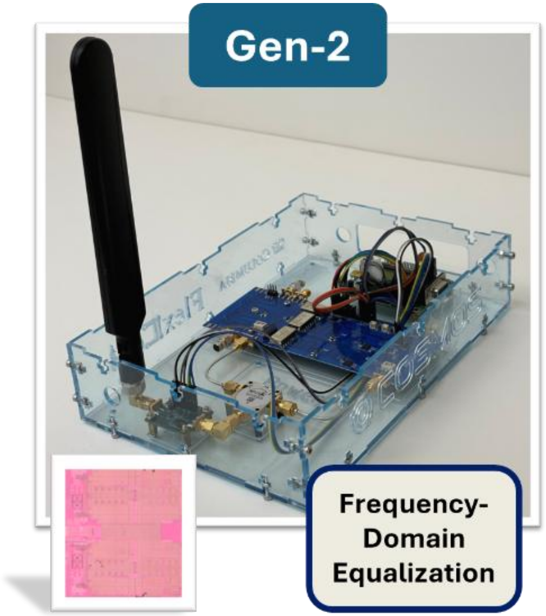
FlexICoN: Three Generations of FD Radios



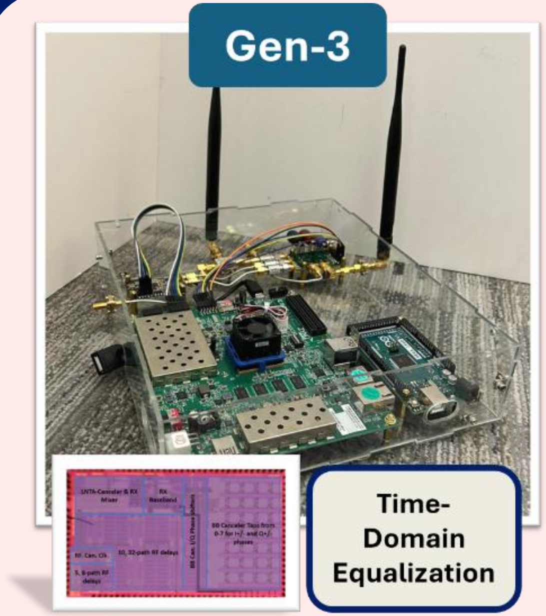
$$H_{P\&A}(f) = \alpha e^{-j\phi}$$

- 2 degrees of freedom
- 43dB of RF SIC
- 5MHz bandwidth



$$H_{FDE}(f) = \sum_{n=1}^{2} \frac{A_n e^{-j\phi_n}}{1 - jQ_n\left({}^{f_{c,n}}\!/_{f} - {}^{f}\!/_{f_{c,n}}\right)}$$

- 8 degrees of freedom
- 50dB of RF SIC
- 20MHz bandwidth



$$H_{TDE}(f) = \sum_{n=1}^{16} \alpha_n e^{-j2\pi f \tau_n}$$

- 32 degrees of freedom
- 50dB of RF SIC
- >50MHz bandwidth

A Unified Hardware/Software Framework

Hardware

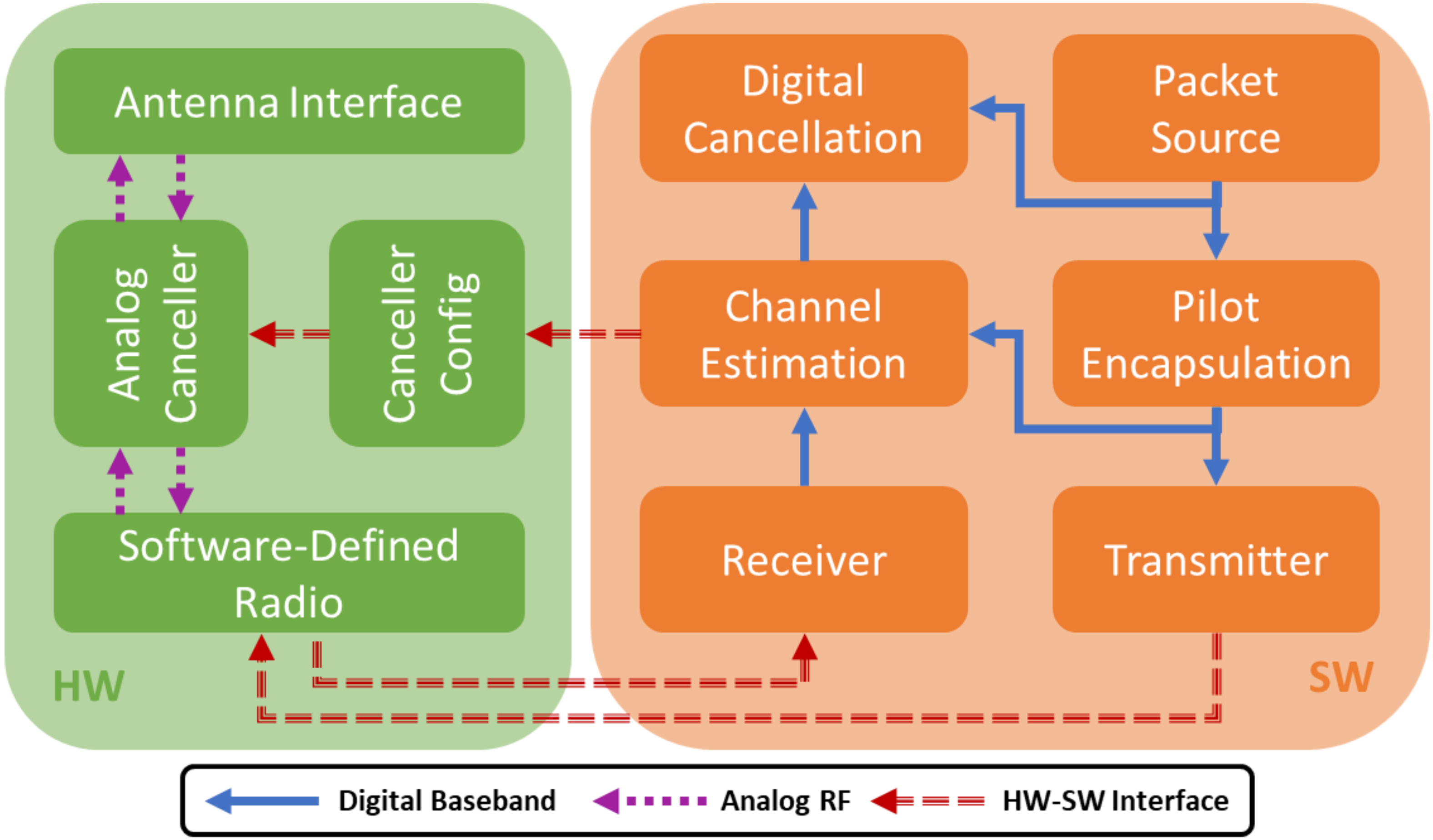
- Antenna interface providing passive isolation (e.g., circulator, split Tx-Rx)
- Tunable analog RFIC canceller with an interface for real-time configuration
- Software-defined radio for real-time packet transmission and reception

Software

- SI channel estimation to enable digital cancellation and canceller optimization
- Hardware-aware real-time adaptive canceller configuration algorithm
- Full PHY layer: packet encapsulation, demodulation, synchronization, etc.

Practical FD requires precise coordination between the various hardware and software components to operate properly.

A Unified Hardware/Software Framework



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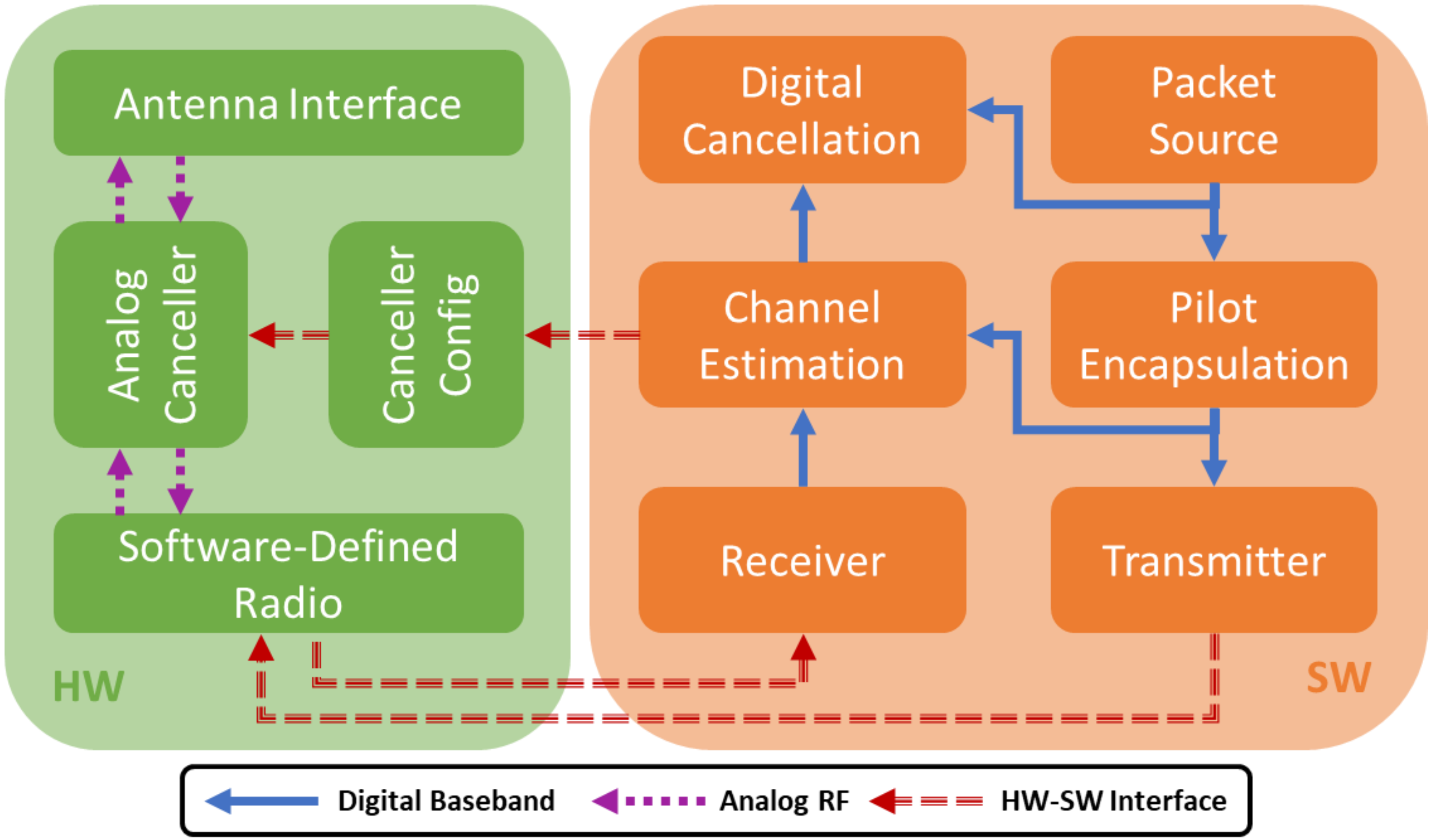

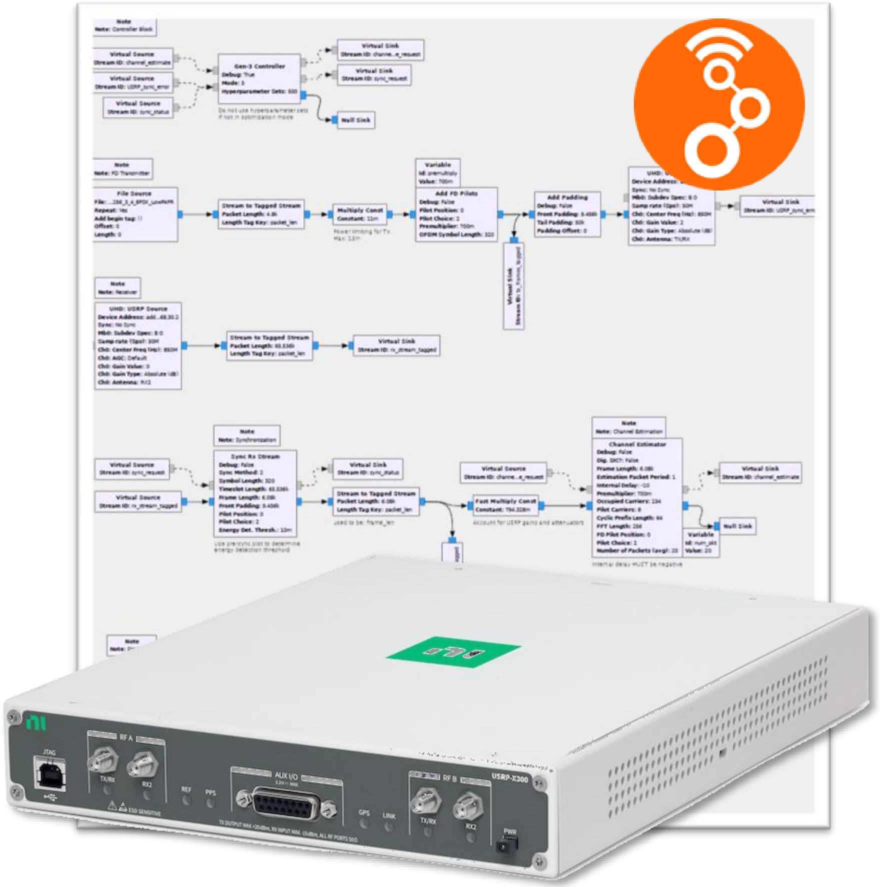

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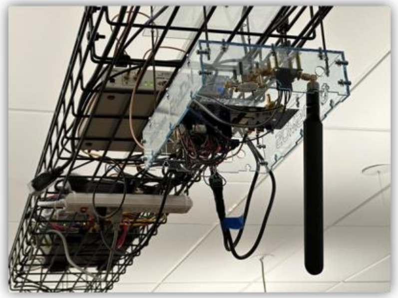
Open-Access FD Wireless on COSMOS

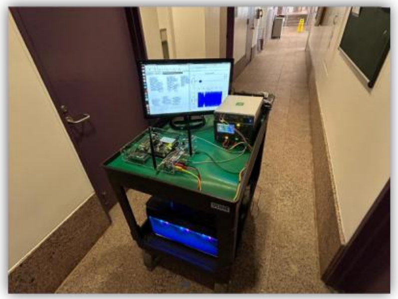
```
flexicon_dev/
|-- documentation/          : Additional docs, notes, and design info
|
|-- firmware/               : Microcontroller / control-board firmware
|   \-- ArduinoCode/        : Arduino source for analog canceller / RF control
|
|-- hardware/               : RF front-end and FPGA designs
|   |-- FPGA/               : FPGA projects, bitstreams, and helper scripts
|   |   |-- hw_files/       : Hardware configuration files
|   |   |-- matlab/         : MATLAB scripts for FPGA-related processing
|   |   |-- vitis_project/  : Vitis project files
|   |   \-- vivado_project/ : Vivado project files
|   \-- txboard/            : Tx/Rx board firmware and support code
|
|-- software/               : Host-side software and support libraries
|   |-- gr-fullduplex/      : GNU Radio OOT module with full-duplex blocks
|   |-- libsub20/           : SUB-20 control library (vendored)
```

A comprehensive GNU Radio toolkit for FD experimentation on the COSMOS testbed, compatible across all three generations of radios.

Mobile Gen-1 FD Radio
- USRP B205mini-I SDR
- Intel NUC 8i7BEH mini-PC
- Real-time FD operation at bandwidths up to 5MHz
- Full mobile setup with portable battery available

Gen-2 FD Radio Network
- Two USRP X310 SDRs
- Two Dell R740 servers
- Real-time FD operation at bandwidths up to 25MHz
- Four synchronized nodes in a fixed configuration





Mobile Gen-3 FD Radio
- USRP X310 SDR
- Custom Intel i9-based PC
- Real-time FD operation at bandwidths up to 100MHz
- First demonstration of true adaptive SIC in mobility

Thank You!

More information:

flexicon.ee.columbia.edu

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