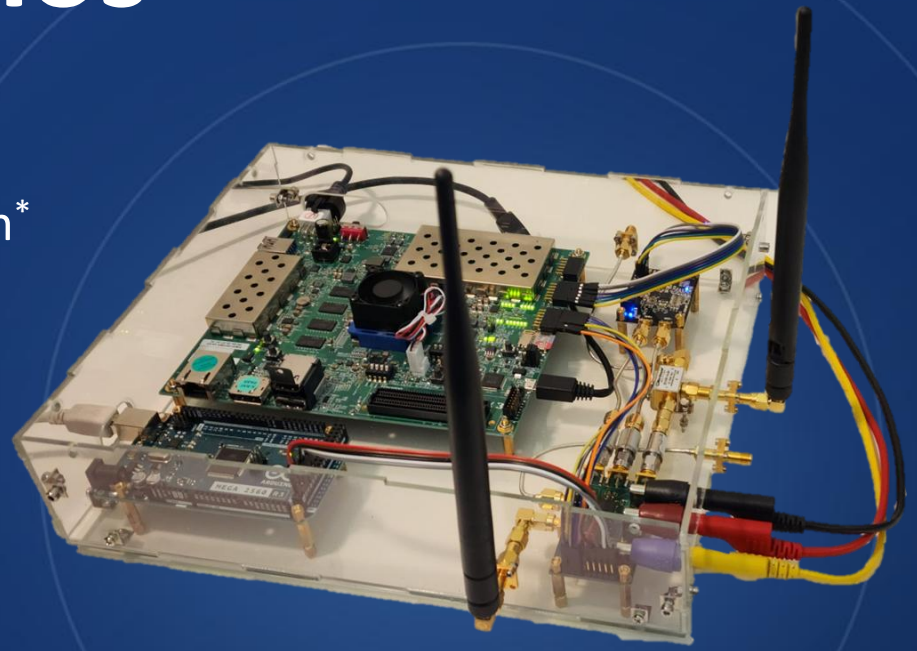
# Wideband Real-Time Adaptive Full-Duplex Radios

**Alon S. Levin**[*], Igor Kadota[†], Bo Zhang[*], Sasank Garikapati[*], Manav Kohli[*], Harish Krishnaswamy[*], Mingoo Seok[*], Gil Zussman[*]

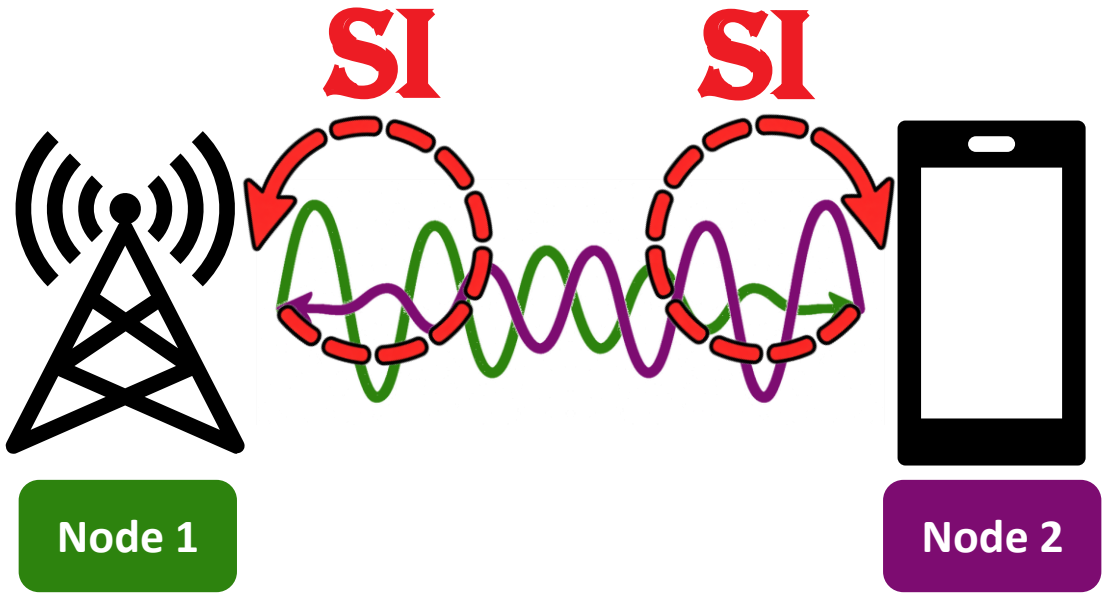
[*]Columbia University; [†]Northwestern University

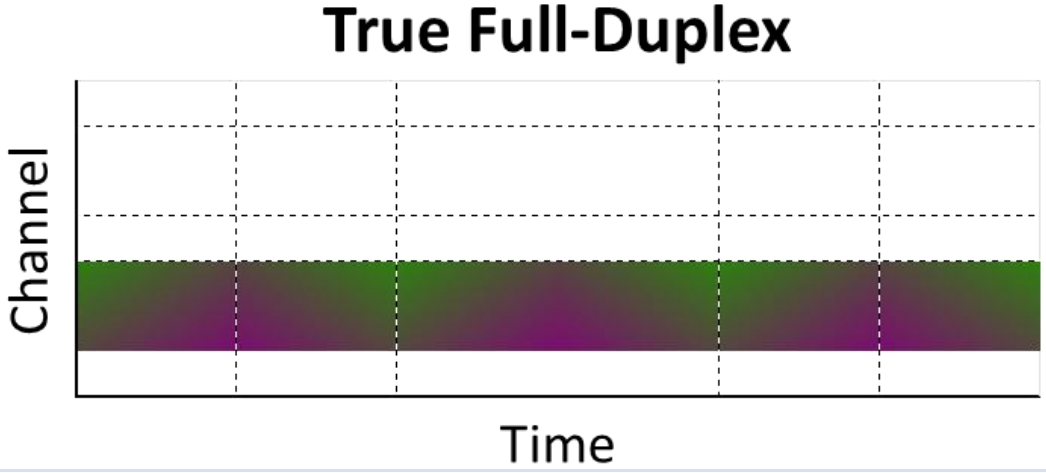
**MobiCom '26 | Austin, TX | October 28, 2026**



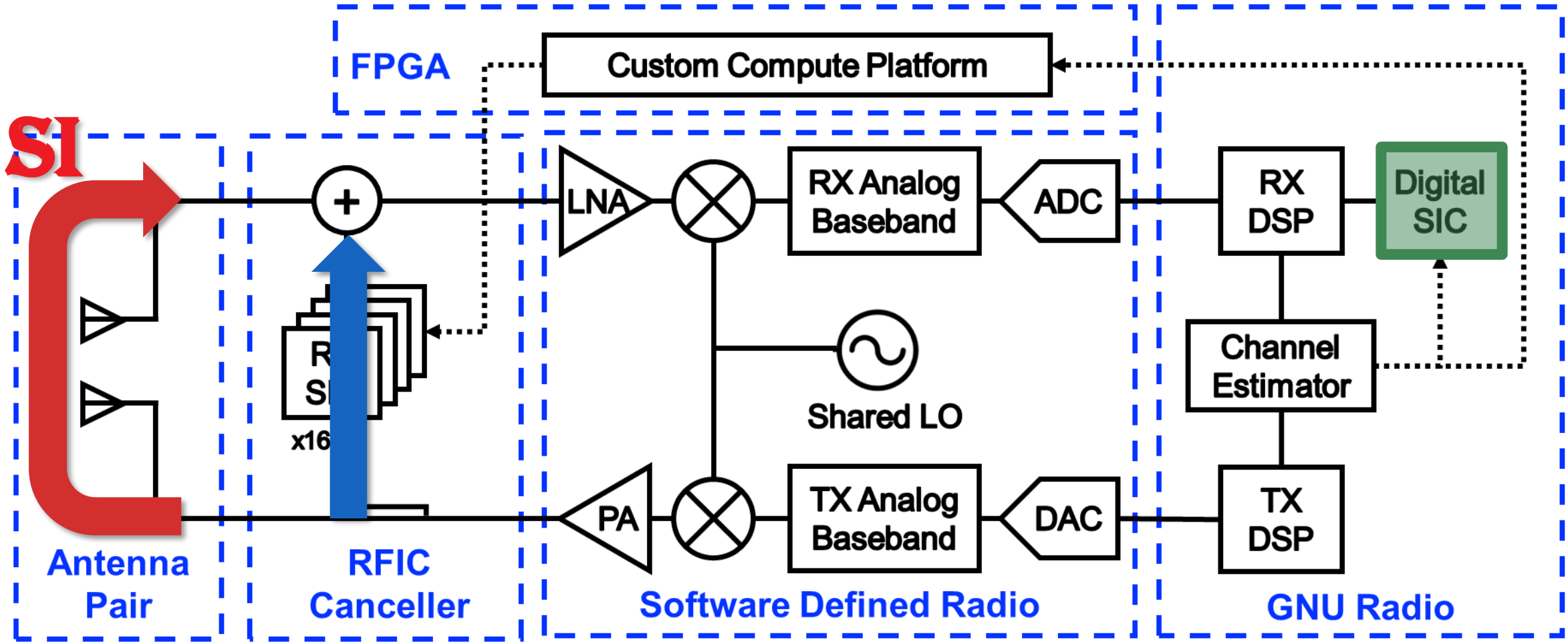
# Full-Duplex Wireless

- **Full-duplex (FD)** radios can simultaneously **transmit** and **receive** on the same frequency, potentially doubling the data rate of standard **half-duplex (HD)** systems.
- This comes at the cost of extremely strong **self-interference (SI)**.
  - ~**70–110 dB** of SI cancellation is needed to reach noise-floor-level suppression.
- SIC typically spans the **antenna interface**, **analog**, and **digital cancellation** domains.



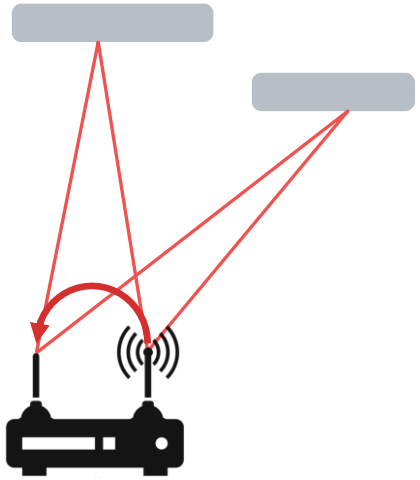



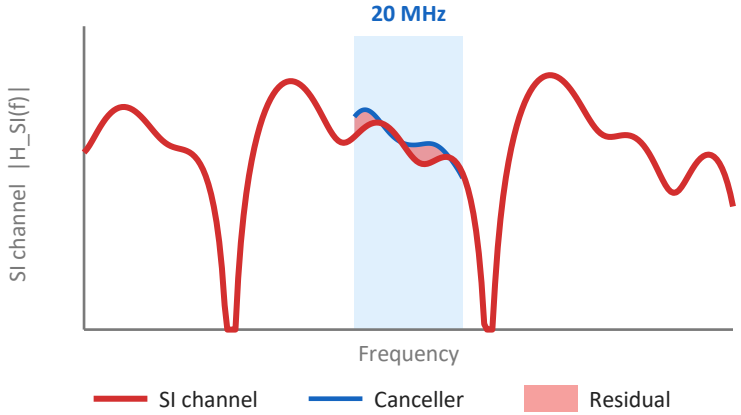
# Self-Interference Cancellation



# The Challenge of Self-Interference

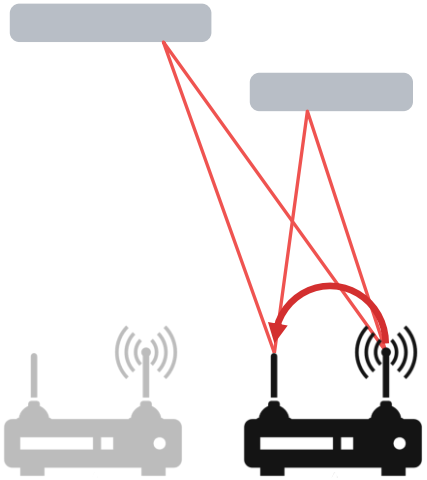
- The SI channel is **highly dynamic**, and particularly during **mobility**.

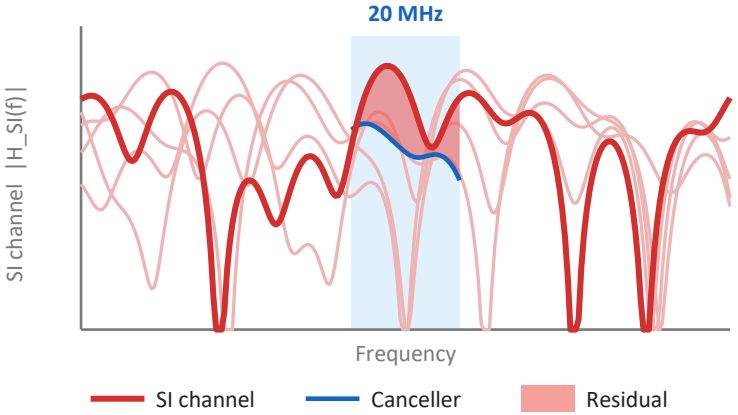


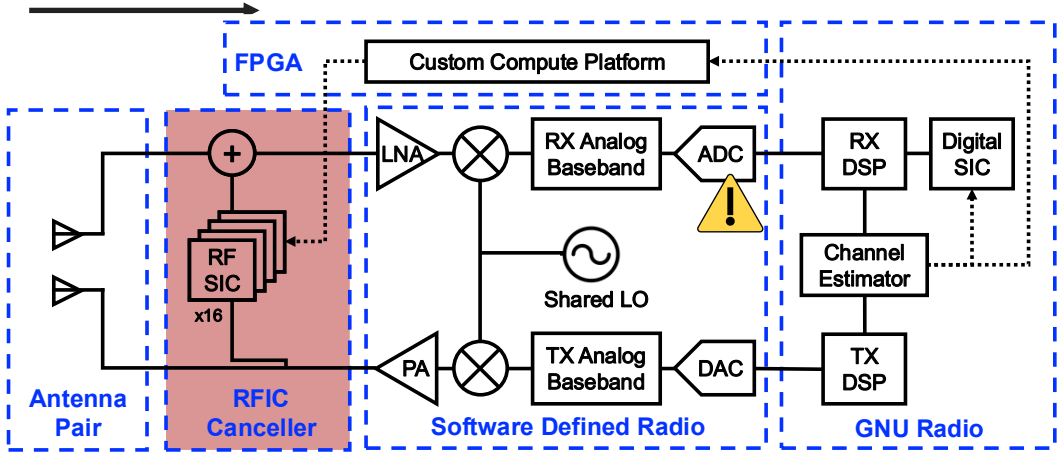


# The Challenge of Self-Interference

- The SI channel is **highly dynamic**, and particularly during **mobility**.
  - Analog cancellation must be capable of **tracking** and **adapting** to this evolution!
  - Misconfiguration of the analog SIC stage risks **saturating** the receiver frontend.

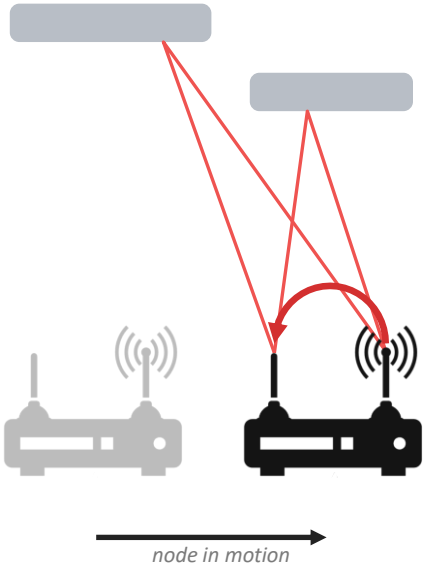


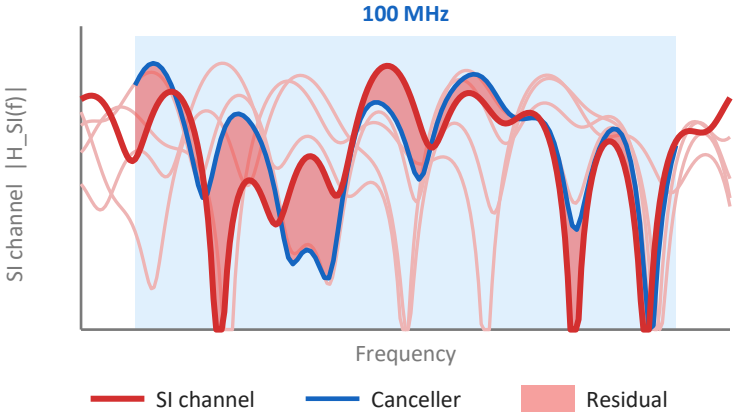


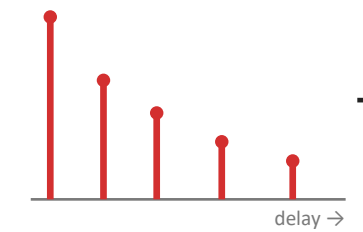



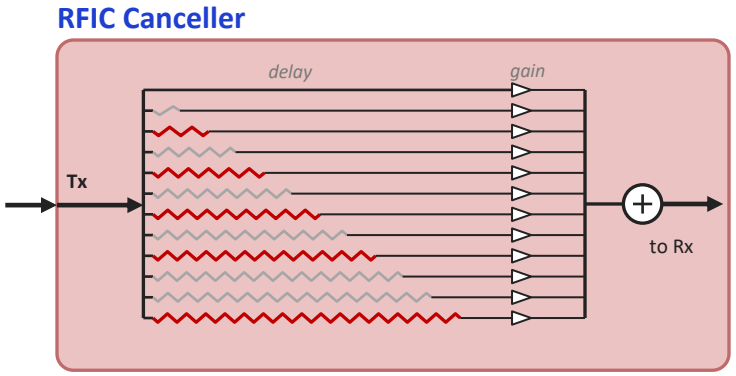
# The Challenge of Self-Interference

- The SI channel is **highly dynamic**, and particularly during **mobility**.
  - Analog cancellation must be capable of **tracking** and **adapting** to this evolution!
  - Misconfiguration of the analog SIC stage risks **saturating** the receiver frontend.
- The challenge **grows with bandwidth**.
  - Analog cancellation performance degrades sharply with increasing bandwidth.
  - To accurately model the SI channel's multipath structure, **more complex RFIC architectures** with **more independent parameters** are required!



# Our Contributions

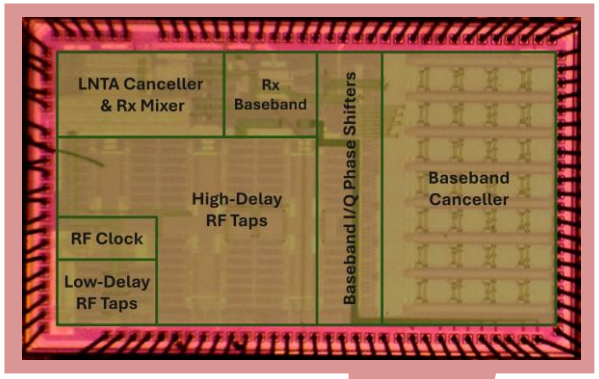
1. We integrate a highly configurable wideband TDE RFIC canceller as the frontend of an SDR-based FD radio.
2. We enable real-time adaptive RF SIC by means of a novel globally- and locally-sparse reconstruction-based configuration algorithm, implemented on an FPGA.
3. We evaluate the performance of the algorithm and the node in realistic scenarios, including mobility and an FD link.

$$\mathbf{A}^{\star} := \arg \min_{\mathbf{0} \leq \mathbf{A} \leq \mathbf{1}} \|H_{\mathrm{SI}}(f) - \mathbf{HA}\|^2$$

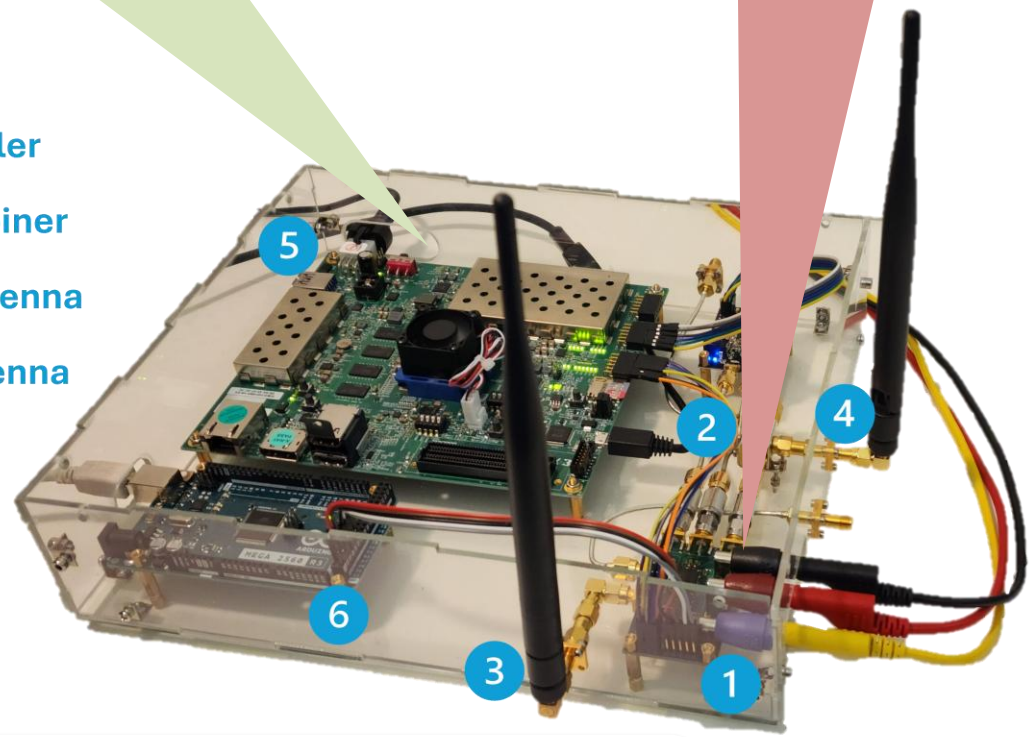
$$\text{s.t.} \quad \|\mathbf{A}\|_1 \leq K$$

$$\|\mathbf{A}\|_0 \leq M$$

$$\|\mathbf{A_n}\|_0 \leq 1, \ \forall n \in \{0, \ldots, 15\}$$

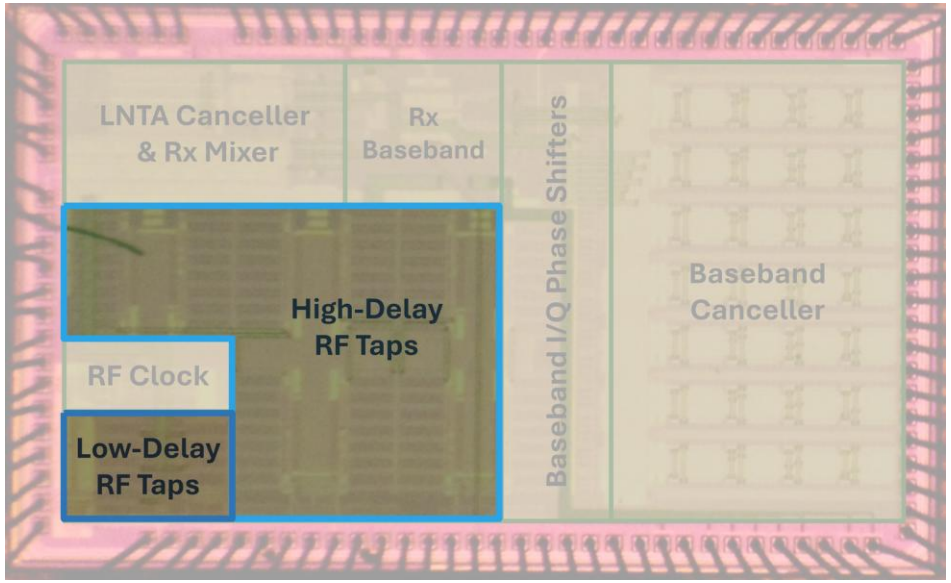



1. RFIC Canceller
2. Power Combiner
3. Transmit Antenna
4. Receive Antenna
5. FPGA
6. Arduino




*To the best of our knowledge, this is the first real-world implementation and experimental evaluation of a wideband FD radio design configured by a sparsity-employing algorithm, and the first optimization and evaluation of SIC under mobile conditions with a real FD radio.*

# Background: The RFIC Canceller




| 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 |

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

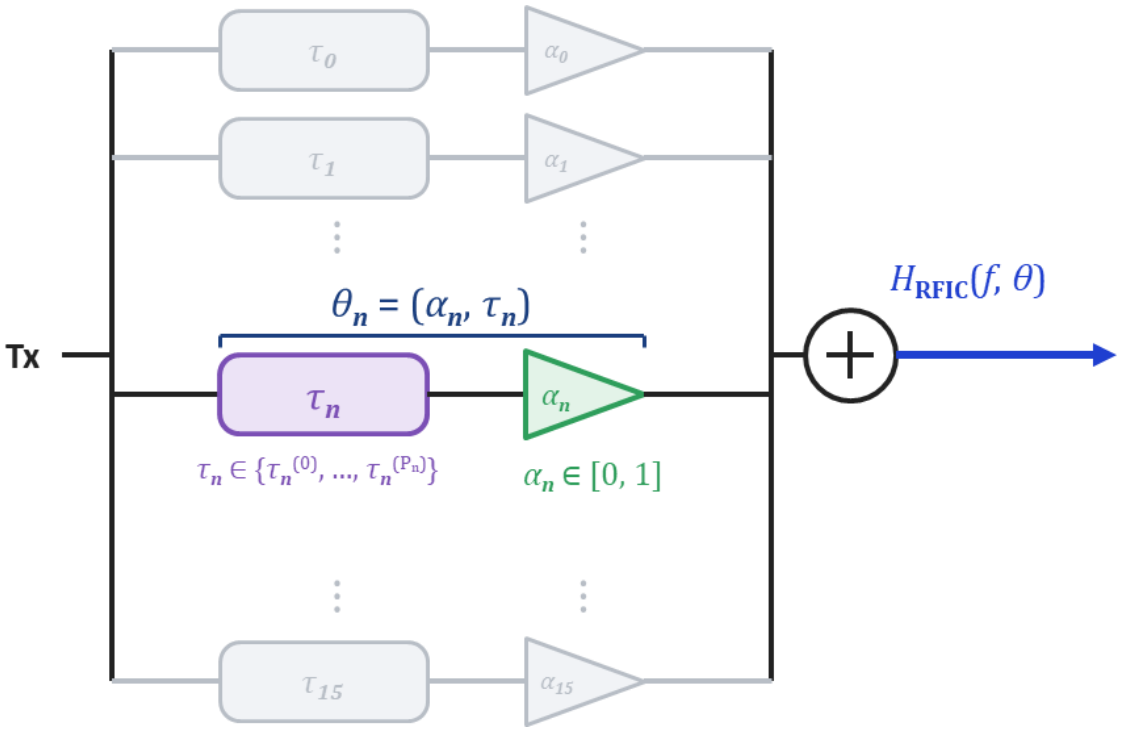
zero-delay low-delay high-delay possible configurations

**You have better odds at winning the Mega Millions Jackpot (1 in 290,472,336)!**

A. Nagulu, S. Garikapati, M. Essawy, I. Kadota, T. Chen, A. Natarajan, G. Zussman, H. Krishnaswamy. Full-Duplex Receiver with Wideband Multi-Domain FIR Cancellation Based on Stacked-Capacitor, N-Path Switched-Capacitor Delay Lines. Proc. IEEE ISSCC'21, 2021.
S. Garikapati, A. Nagulu, I. Kadota, M. Essawy, T. Chen, S. Wang, T. Pande, A. Natarajan, G. Zussman, H. Krishnaswamy. Full-Duplex Receiver With Wideband, High-Power RF Self-Interference Cancellation. *IEEE Journal of Solid-State Circuits*, 59(7).2105-2120, 2024.

# Basic Problem Formulation

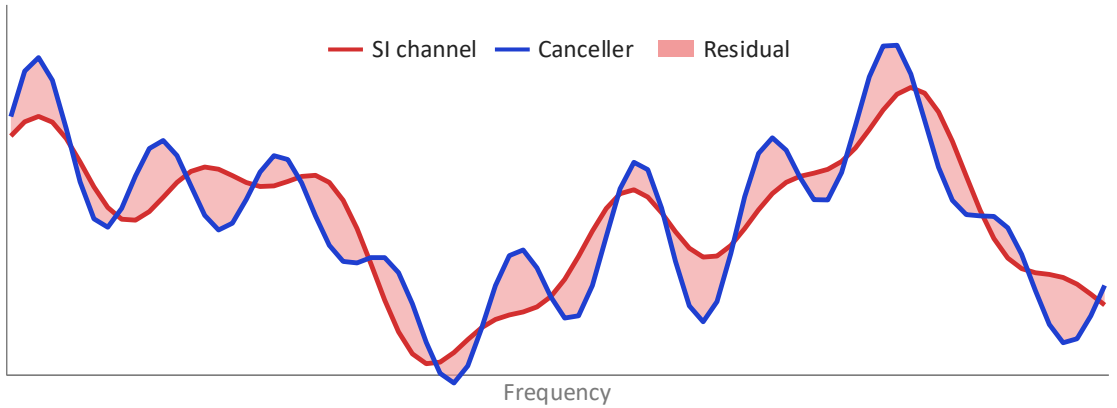
The RFIC canceller has 16 parallel taps, each with configurable gain $\alpha_n$ and delay $\tau_n$:



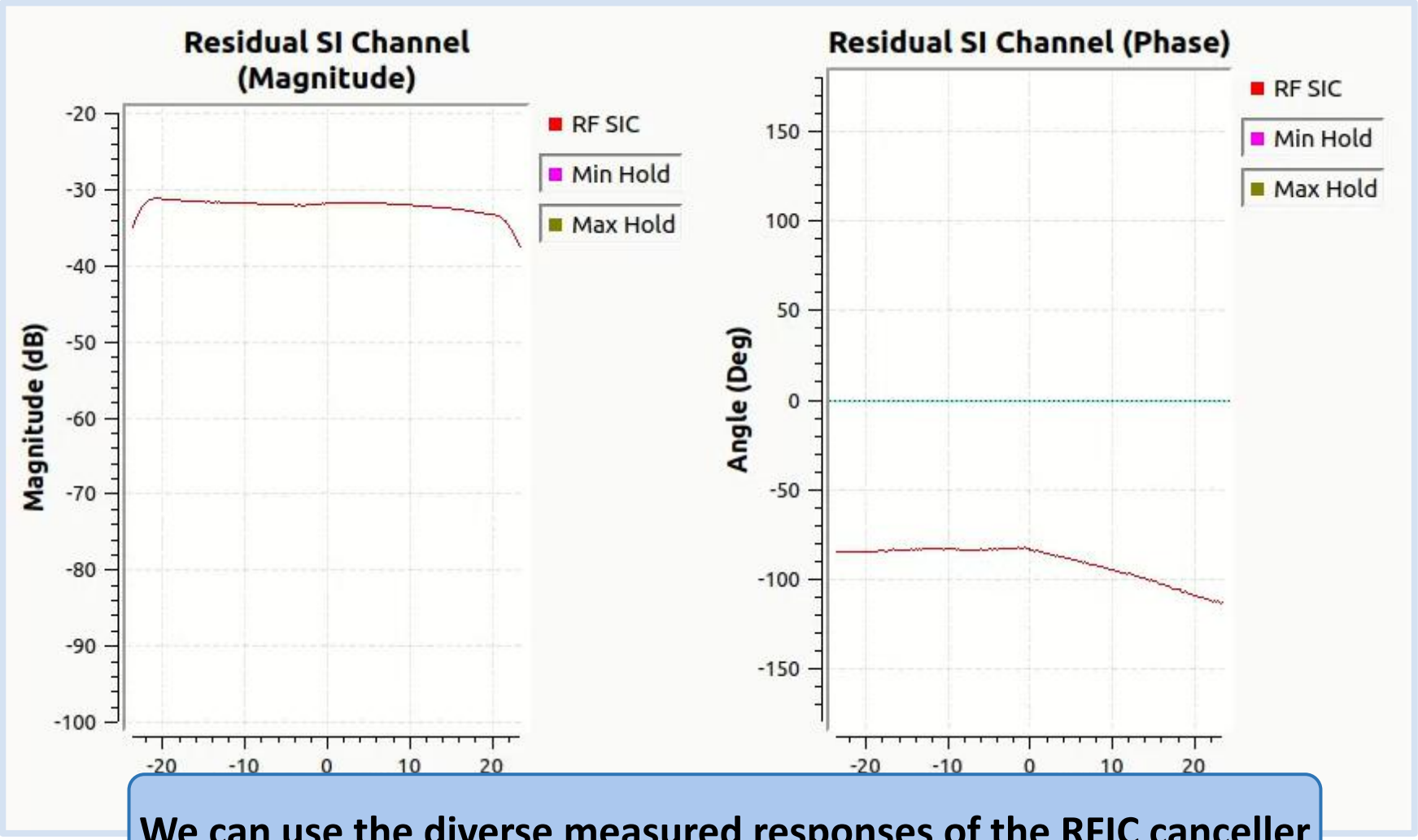

Let $H_{\text{SI}}(f)$ and $H_{\text{RFIC}}(f, \theta)$ represent the frequency responses of the SI channel and the RFIC canceller, configured with $\theta \in \Theta$.

**Goal**: Find the optimal configuration $\theta^\star$ which minimizes the *residue* or, equivalently, maximizes the analog canceller's SIC:

$$\theta^\star := \underset{\theta \in \Theta}{\operatorname{argmin}} \| H_{\text{SI}}(f) - H_{\text{RFIC}}(f, \theta) \|^2$$



# Tap Performance is Non-Ideal… But That's Okay!

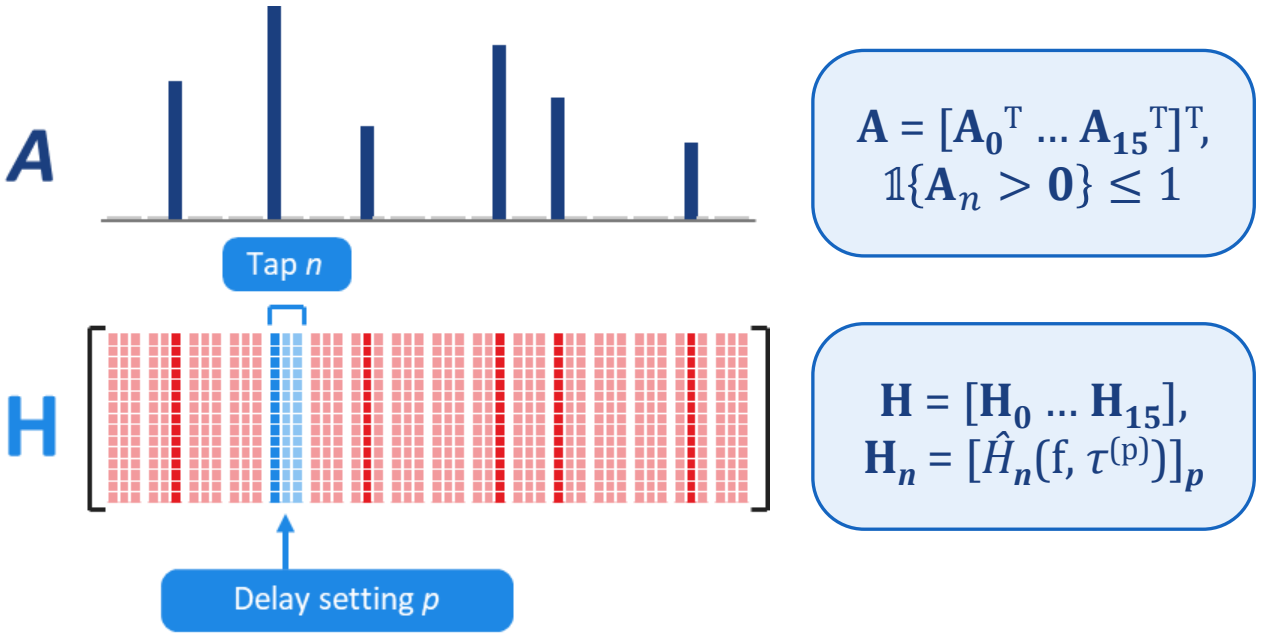



**We can use the diverse measured responses of the RFIC canceller to determine an optimal configuration for any given SI channel!**

# Adaptive RF SIC: Data-Driven Solution

We can model the RFIC response as a sum of linearly-scaled, per-delay *measured responses:*

$$H_{\mathrm{RFIC}}(f,\theta) = \sum_{n=0}^{15} \alpha_n \hat{H}_n(f,\tau_n)$$




$$\mathbf{A} = [\mathbf{A_0}^{\mathrm{T}} \ldots \mathbf{A_{15}}^{\mathrm{T}}]^{\mathrm{T}},$$
$$\mathbb{1}\{\mathbf{A}_n > \mathbf{0}\} \leq 1$$

$$\mathbf{H} = [\mathbf{H_0} \ldots \mathbf{H_{15}}],$$
$$\mathbf{H_n} = [\hat{H}_n(\mathrm{f}, \tau^{(\mathrm{p})})]_p$$

The optimization problem can be expressed as an explicit sparse reconstruction with physics-derived constraints:

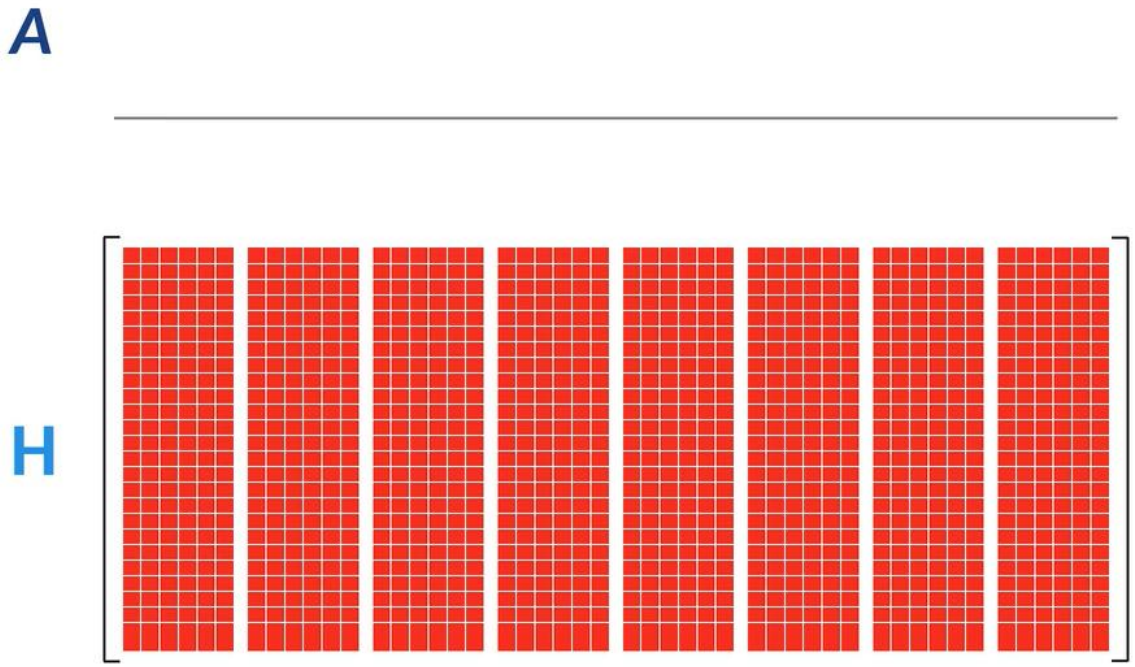
$$\mathbf{A}^\star := \arg\min_{\mathbf{0}\leq\mathbf{A}\leq\mathbf{1}} \|H_{\mathrm{SI}}(f) - \mathbf{HA}\|^2$$
$$\text{s.t.} \quad \|\mathbf{A}\|_1 \leq K$$
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$$\|\mathbf{A_n}\|_0 \leq 1, \ \forall n \in \{0,\ldots,15\}$$

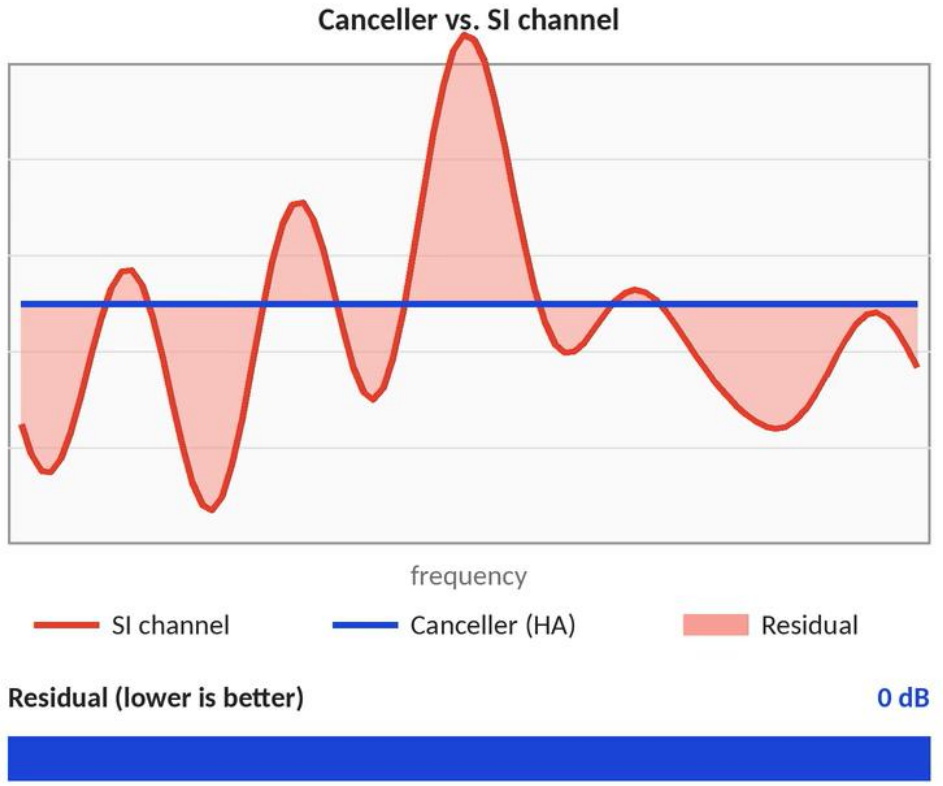
| Keep net gain low to stay in linear region | Enable at most M taps to limit tap cross-talk | Each tap can have at most one delay |
|---|---|---|
| *Net Sum Constraint* | *Global Sparsity Constraint* | *Local Sparsity Constraint* |

# Adaptive RF SIC: Data-Driven Solution

## GLC-OMP: greedy tap-delay selection

Each round: score every candidate, keep the best fit

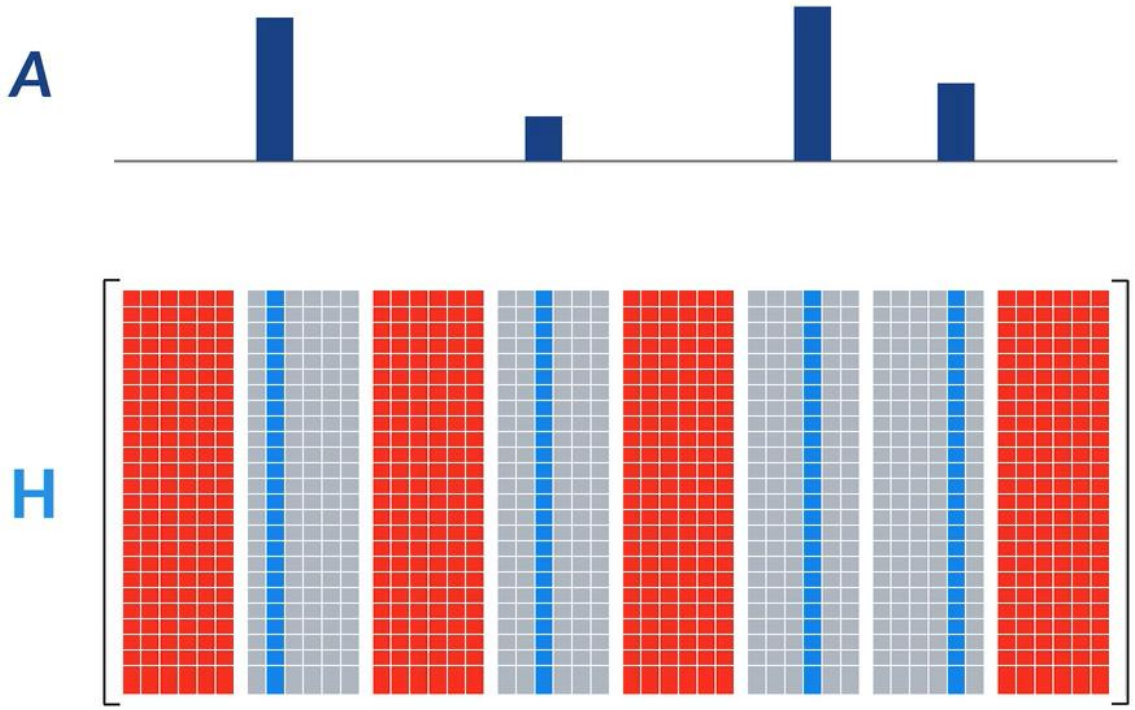


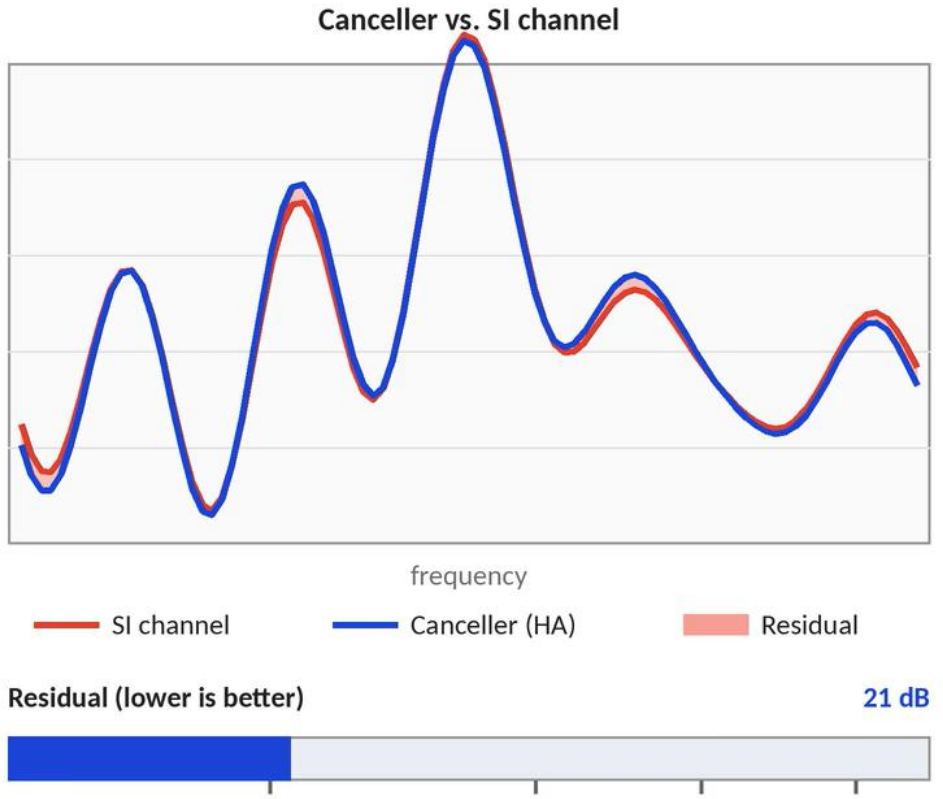



# Adaptive RF SIC: Iterative Adjustment

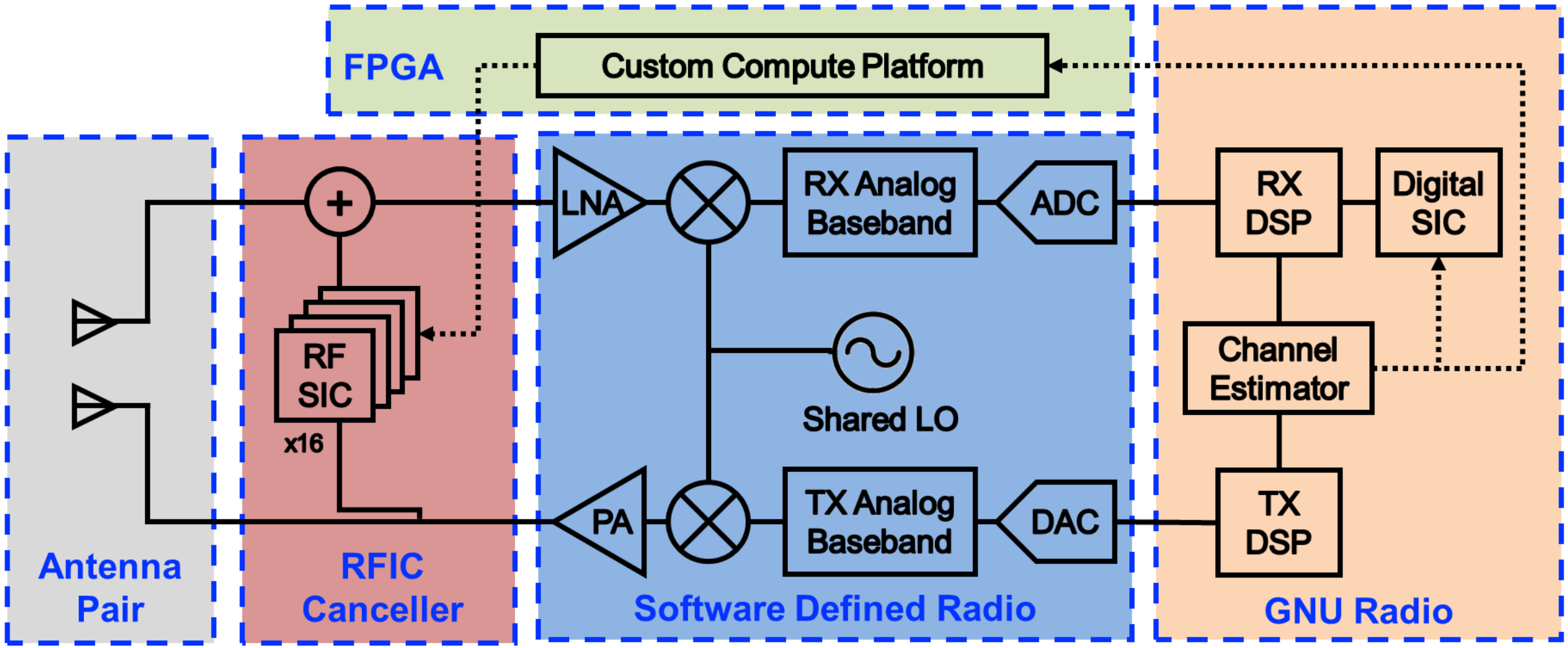
## Quantize and configure the RFIC

Ready to run on the hardware



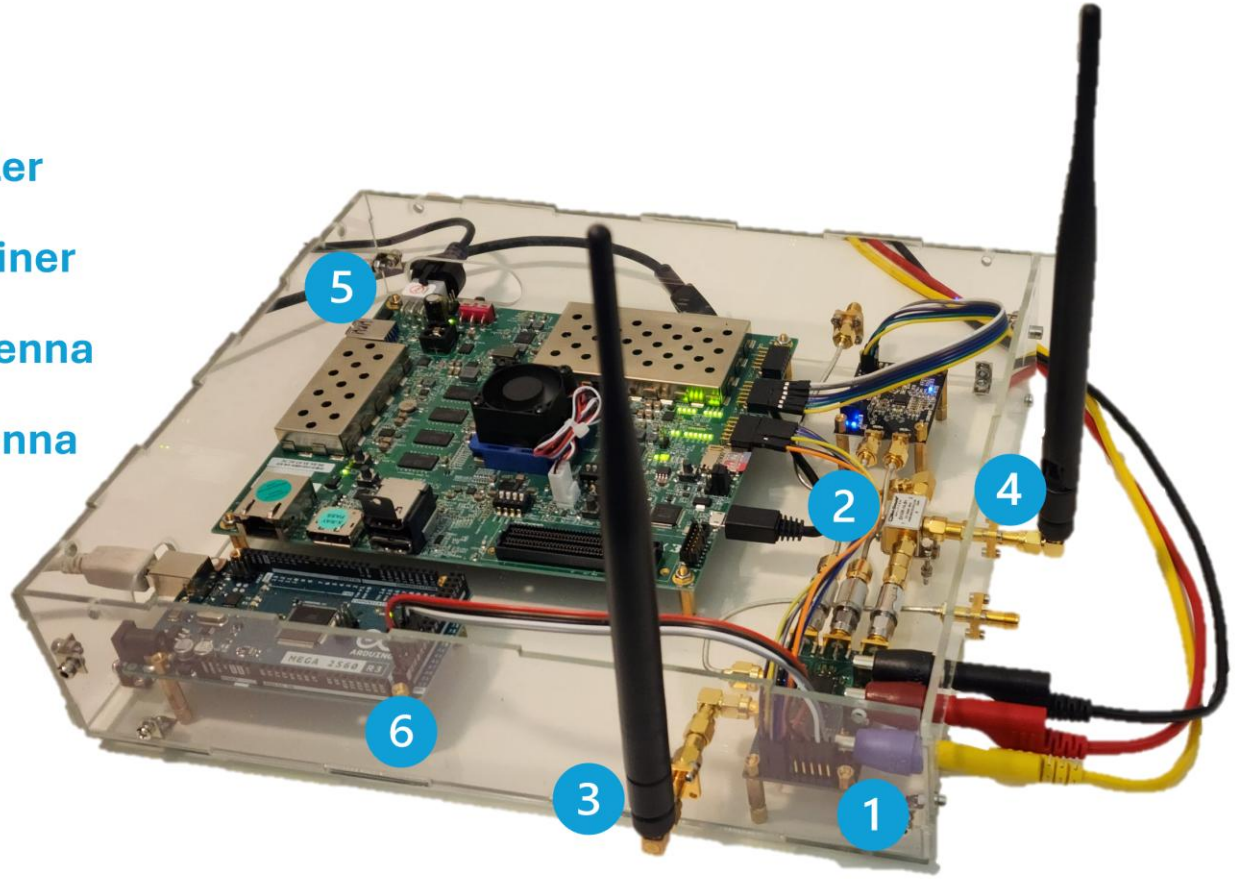



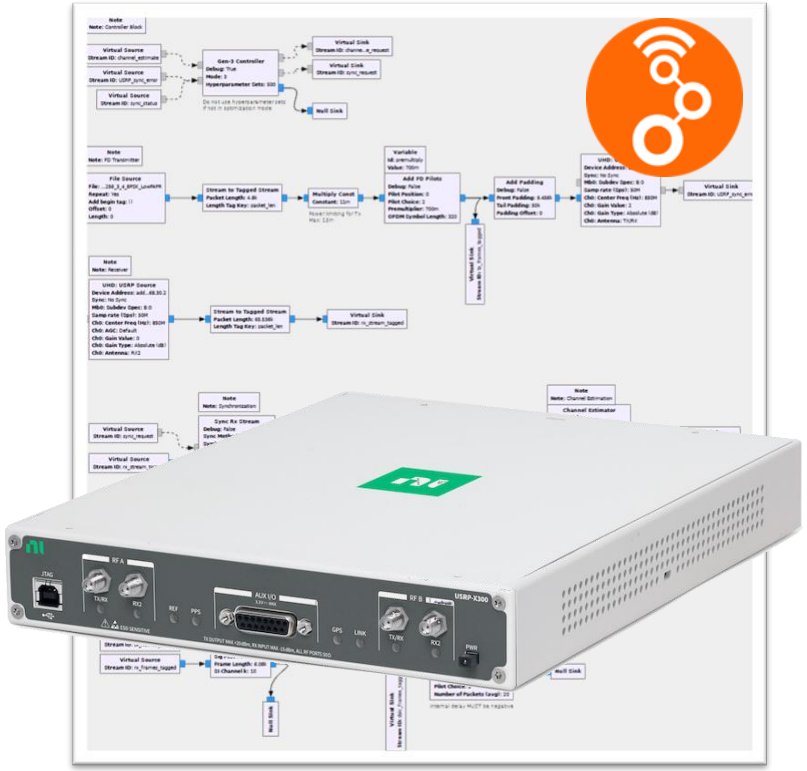
# Implementation: The Wideband Adaptive FD Radio



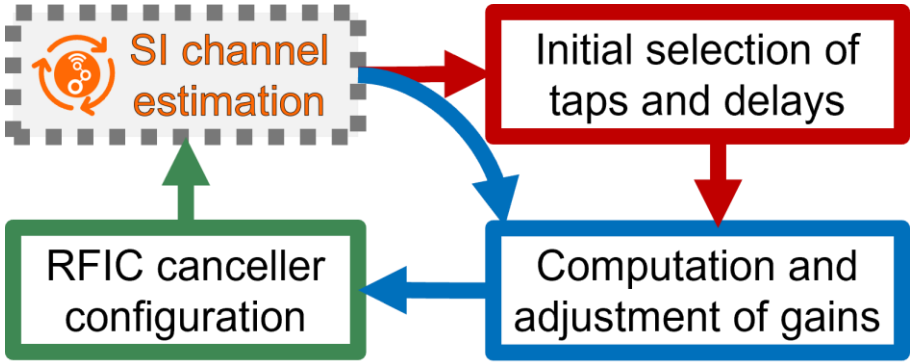
# Implementation: The Wideband Adaptive FD Radio

1. RFIC Canceller
2. Power Combiner
3. Transmit Antenna
4. Receive Antenna
5. FPGA
6. Arduino



# Adaptive SIC: Real-Time on an FPGA

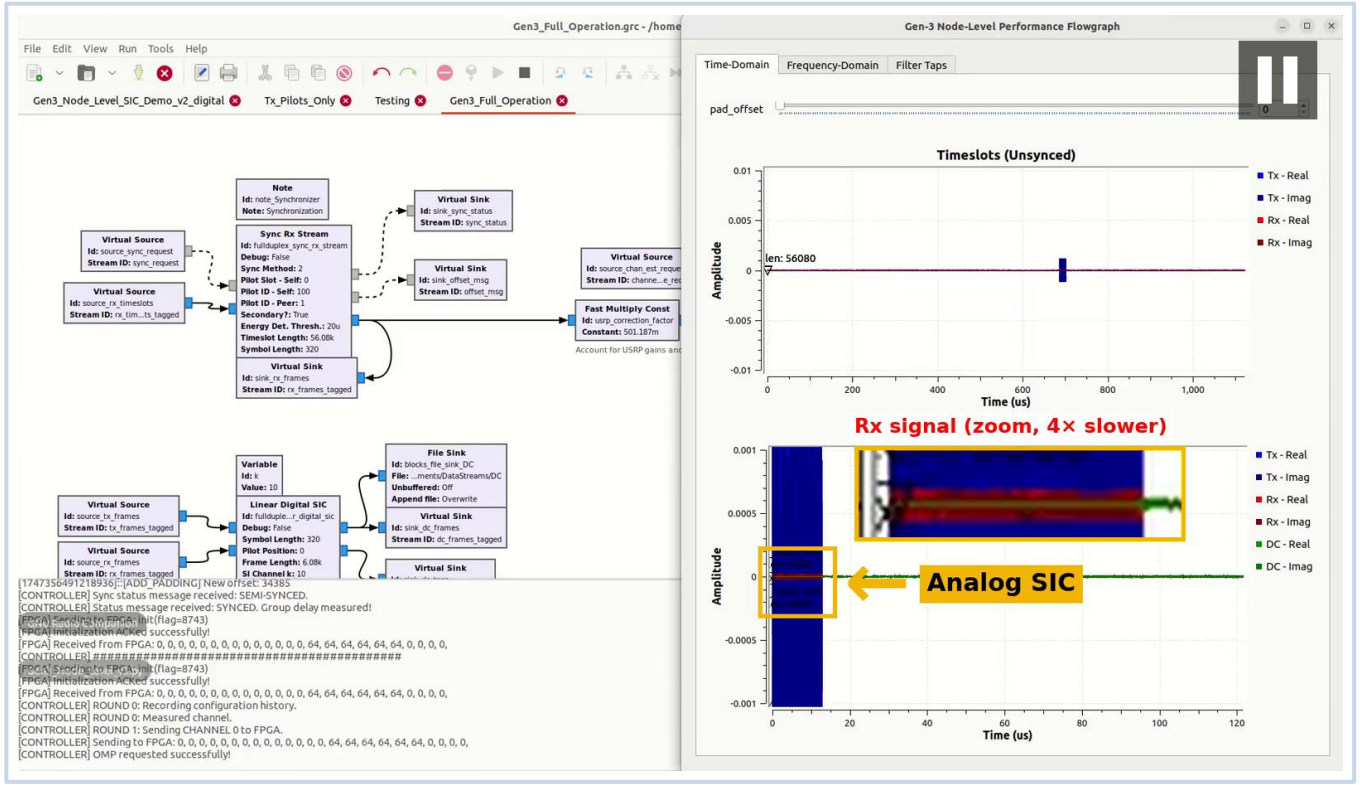



**GLC-OMP: about 94 ms**

Greedily picks the (tap, delay) pairs that best minimize the SI residue

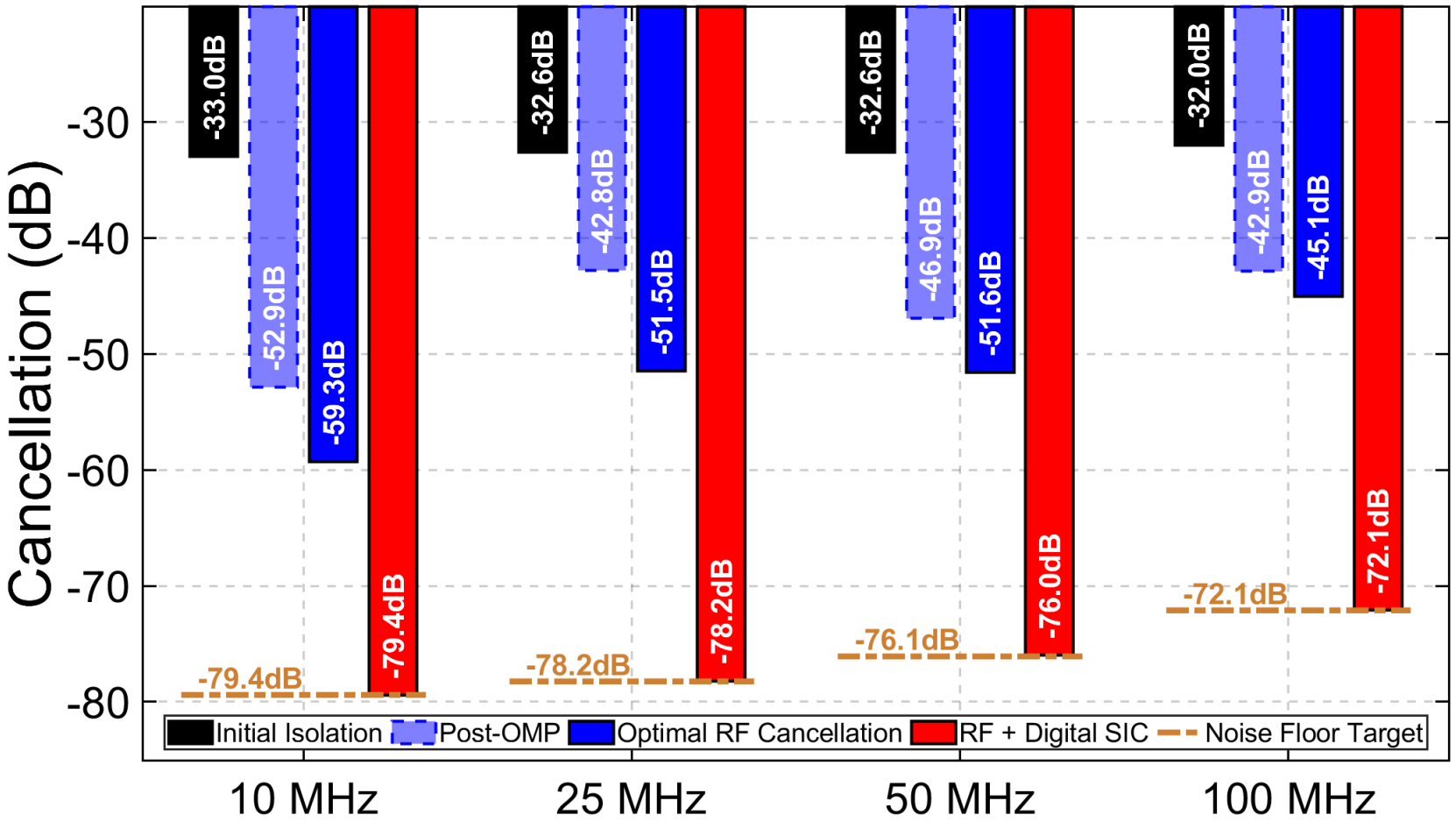
**PGD: about 735 µs**

Adjusts the gains, with taps and delays fixed, in order to track the dynamic SI



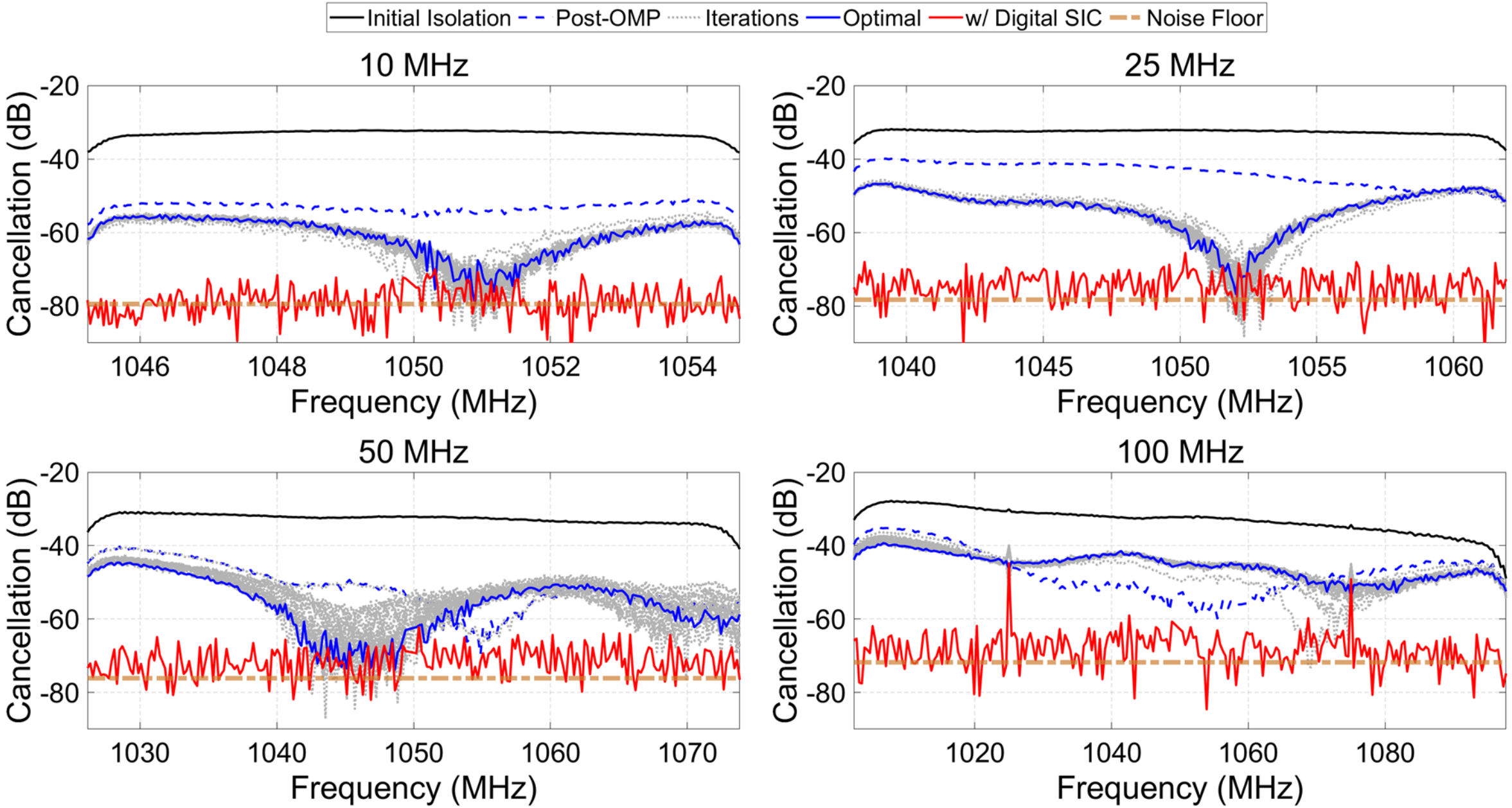

**Converges within about ten PGD iterations after the initial GLC-OMP stage!**

# Node-Level Cancellation

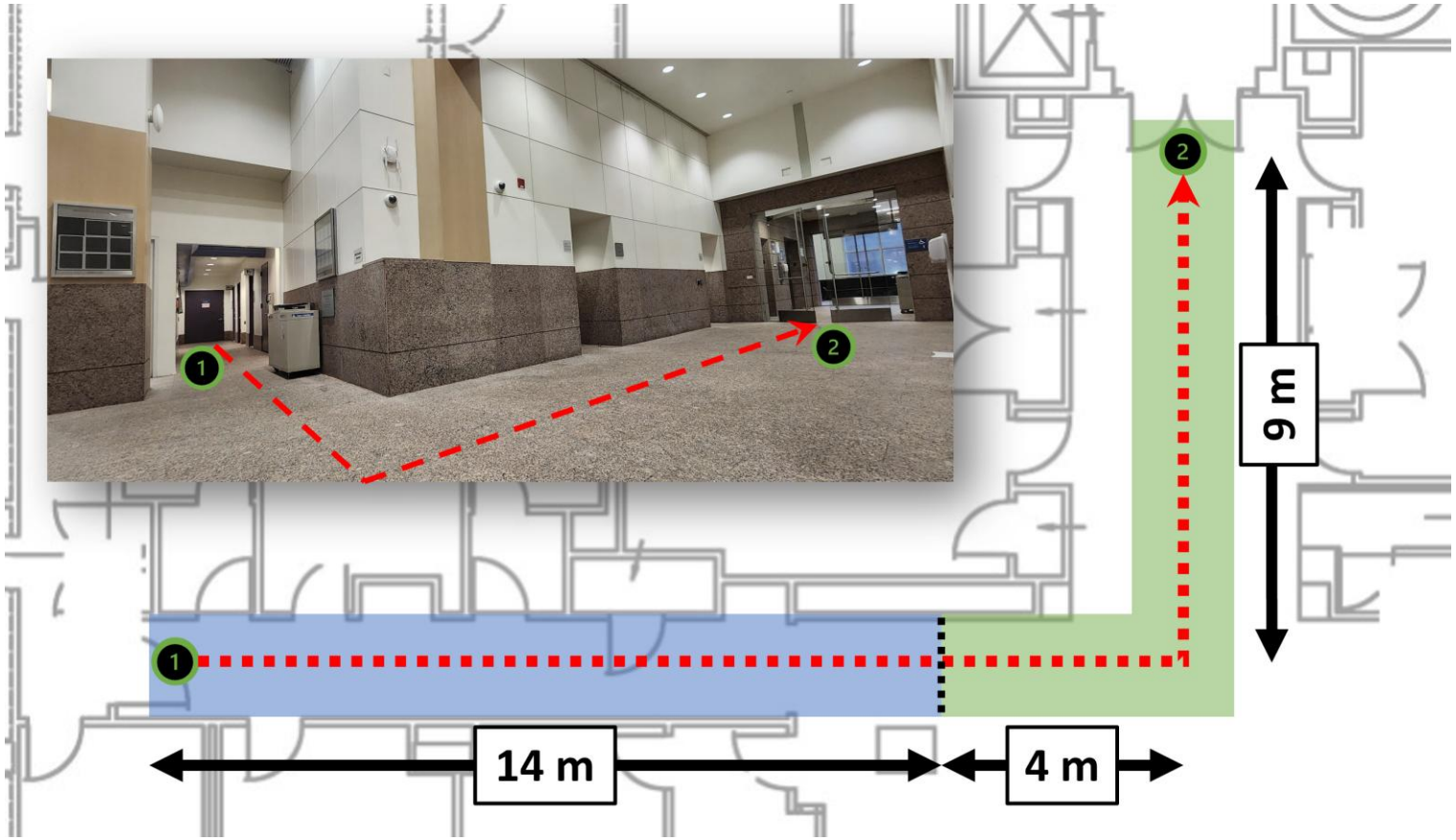



Key findings:

- Noise-floor-level SIC achieved in all bandwidths.
- Digital SIC complements RF SIC in order to reach the noise floor.
- FPGA implementation allows for real-time performance with a reduction in resolution and precision.


Initial Isolation
Post-OMP
Iterations
Optimal
w/ Digital SIC
Noise Floor
10 MHz
25 MHz
50 MHz
100 MHz
Cancellation (dB)
-20
-40
-60
-80
1046
1048
1050
1052
1054
1040
1045
1050
1055
1060
1030
1040
1050
1060
1070
1020
1040
1060
1080
Frequency (MHz)

# Cancellation in Mobile Environments




**Narrow Corridor**
Dense multipath
Abrupt SI channel changes

**Open Atrium**
Fewer reflectors
Stable SI channel, slow drift

## Prior work simulates mobility

- Other works move objects around a static PCB canceller wired to lab test equipment.
- Only a few individual scatterers change, inside an otherwise static multipath environment.

## Mobility is a different problem

- The whole SI channel changes at once, so every component evolves together.
- That is a structurally different and more complex optimization problem.

# Cancellation in Mobile Environments

## Narrow Corridor

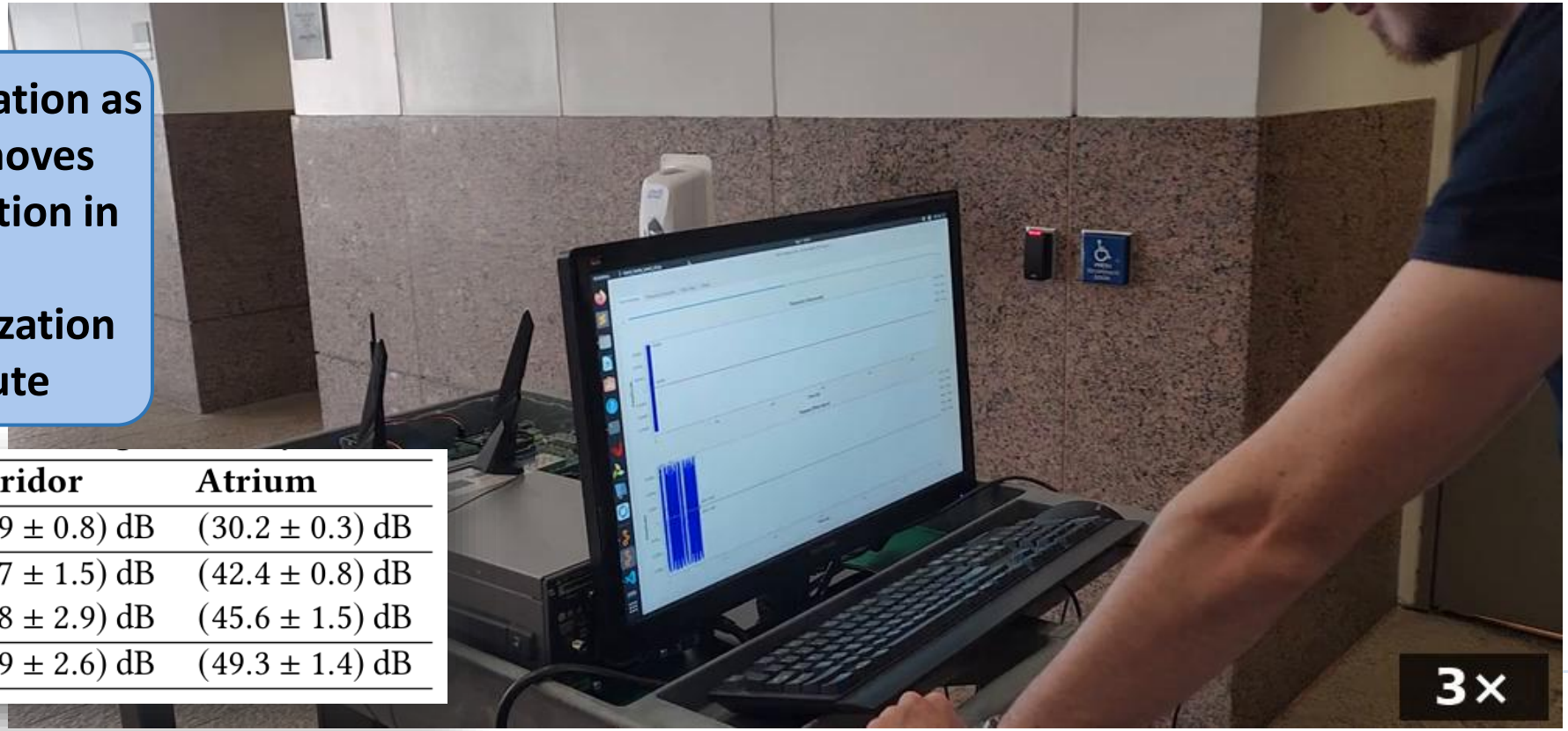
- Many sources of multipath reflections at small distances from the FD node
- High variability in RF cancellation

## Open Atrium

- Relatively free of any major reflectors, with high ceilings and distant walls
- More consistent level of RF cancellation

1. **No analog optimization as the mobile node moves**
2. **One-shot optimization in both directions**
3. **Continuous optimization throughout the route**

| Experiment | Corridor | Atrium |
|---|---|---|
| No Optimization | (29.9 ± 0.8) dB | (30.2 ± 0.3) dB |
| One-Shot (Forward) | (41.7 ± 1.5) dB | (42.4 ± 0.8) dB |
| One-Shot (Reverse) | (43.8 ± 2.9) dB | (45.6 ± 1.5) dB |
| Continuous | (45.9 ± 2.6) dB | (49.3 ± 1.4) dB |



# Cancellation in Mobile Environments

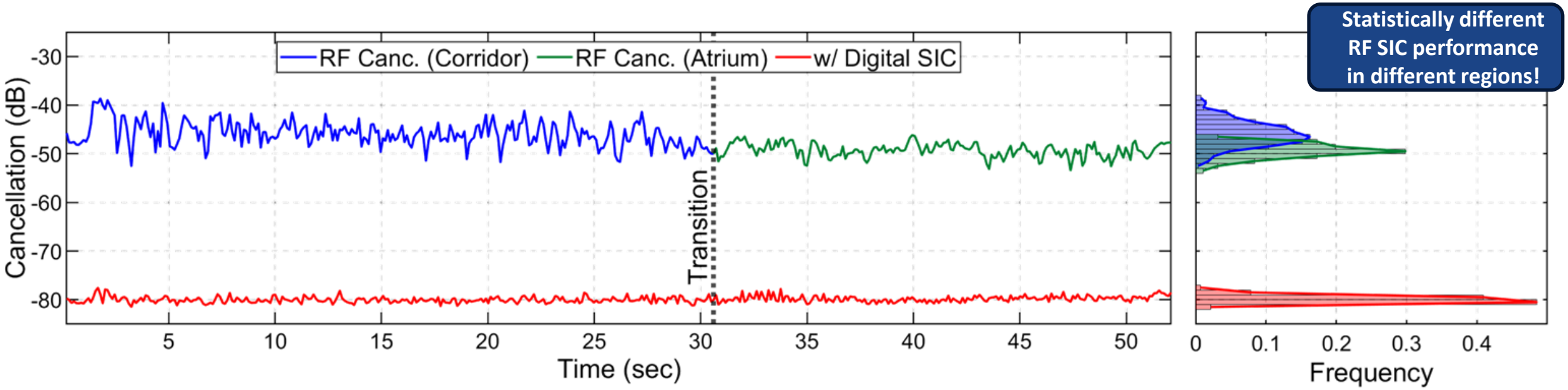
## Narrow Corridor

- Many sources of multipath reflections at small distances from the FD node
- High variability in RF cancellation

## Open Atrium

- Relatively free of any major reflectors, with high ceilings and distant walls
- More consistent level of RF cancellation

**Overall Cancellation Remains Consistent Throughout!**



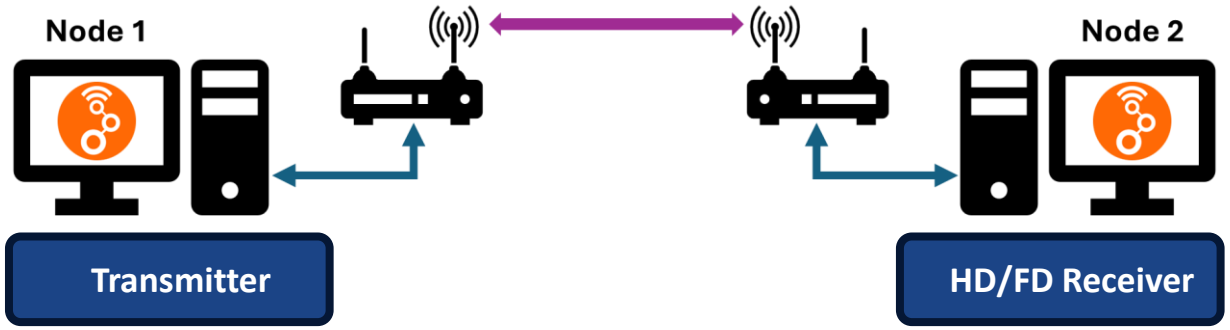
# Link-Level Performance

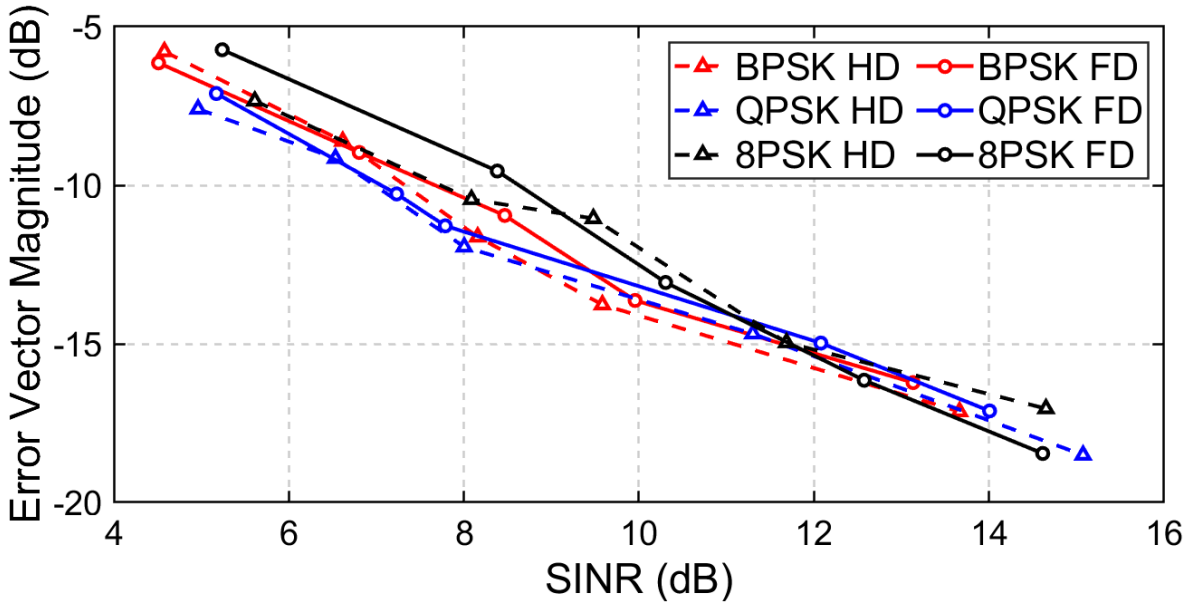
**To double the data rate, FD reception must match HD reception.**

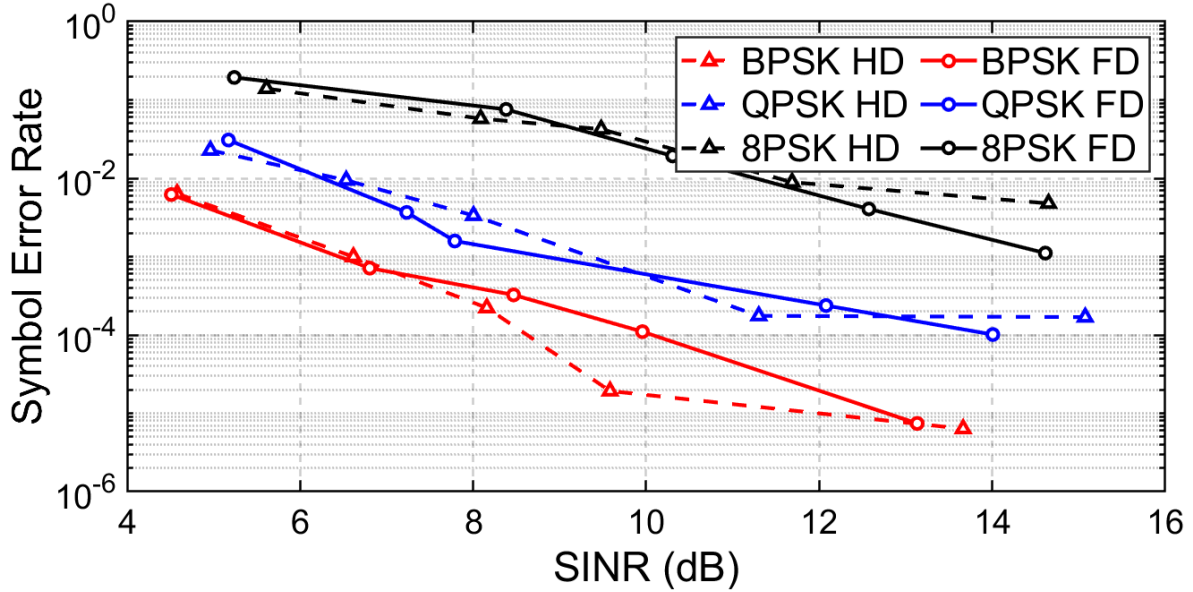
- <0.8 dB EVM degradation
- <0.17 decades SER degradation

## ≈ 1.98× throughput!

**After correcting for the SER gap and RFIC reconfiguration**



# Future Work

- **Advanced link-level experiments**
  - Longer distances and non-line-of-sight scenarios.
  - Test the limits of keeping the post-analog residual inside the SDR's operating range.
- **From one node to networks**
  - Multiple adaptive FD radios in mobile link- and network-level setups.
  - Higher-layer functions: resource scheduling and allocation, and mobility-robust synchronization for direct mobile link evaluation.
- **Open-access testbeds**
  - Integrate the radios into open-access testbeds (CPUs, FPGAs, GPUs), alongside Gen-1/2 nodes.
  - Give the community remote access for hardware-informed FD research in realistic scenarios.

FlexICoN
Full-duplex wireless: from Integrated Circuits to Networks

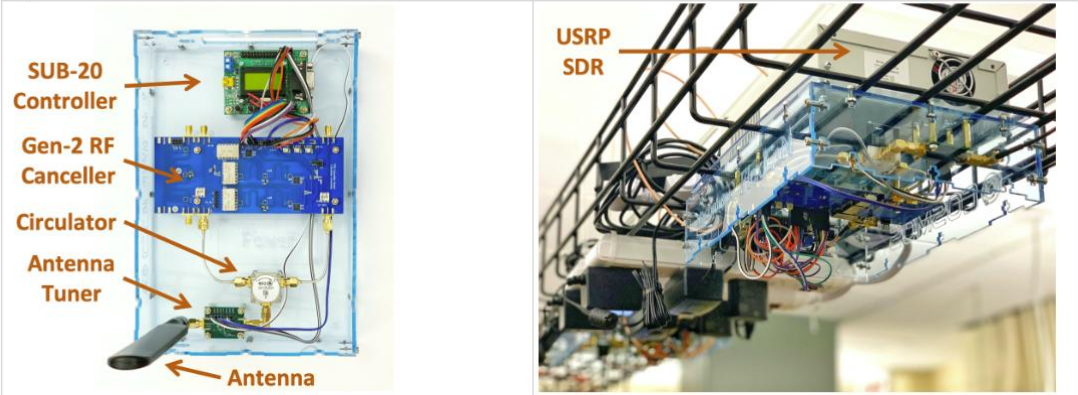
COSMOS

**Full-Duplex Wireless in COSMOS**

Description

In this tutorial, we will use the the integrated Columbia FlexICoN Gen-2 Wideband FD radios equipped with USRP X310 equalization (FDE)-based RF canceller box. The testbed may be accessed via `ssh`, and utilizes the COSMOS servers. The F capabilities of the integrated FD radios.

Figure 1: Gen-2 FDE Canceller Boxes in COSMOS Sandbox 2

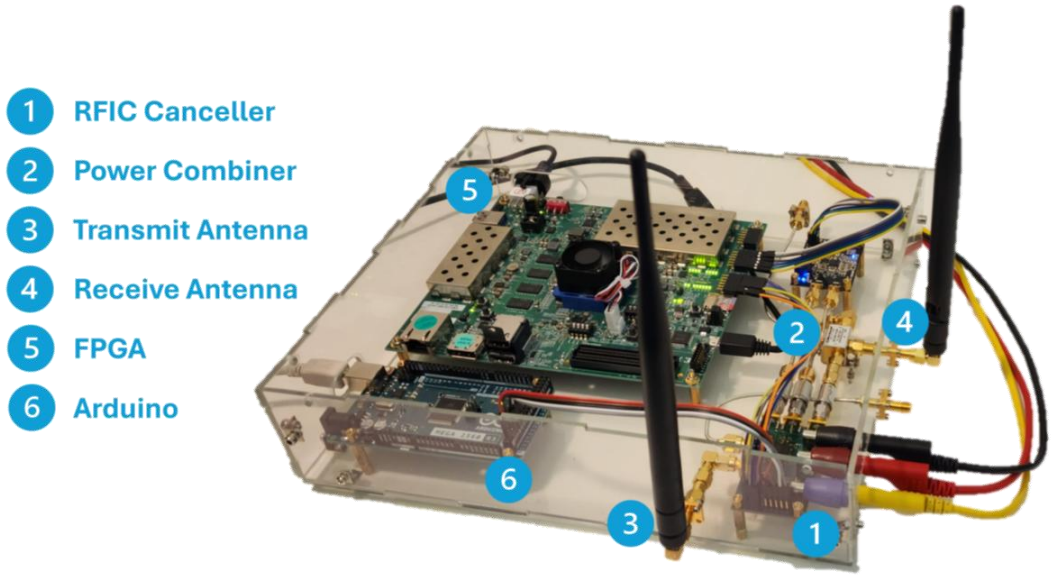



(a) The FlexICoN Gen-2 RF Canceller Box and antenna (b) Rack-mounted, reorganized Gen-2 RF Canceller Box

Publications

# Summary

- **First wideband adaptive FD radio** that achieves and maintains noise-floor-level SIC in both stationary and mobile environments.
- **Two-stage sparsity-based algorithm** configures a 16-tap RFIC canceller:
  - **GLC-OMP** selects the taps, delays and gains under physically-informed net-sum, global and local sparsity constraints.
  - **Iterative adjustment** fine-tunes the gains with projected gradient descent while the selected taps and delays stay fixed.
- **Real-time FPGA-based adaptation** in a practical SDR-based FD radio.
- **Same reception in FD as in HD:** the node receives packets equally well when transmitting in either mode.



# Thank You!


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Supported in part by the NSF, DARPA WARP Program, the DoD NDSEG Fellowship, and the RINGS Program.