Full-Duplex in a Hand-held Device - From Fundamental Physics to Complex Integrated Circuits, Systems and Networks: An Overview of the Columbia FlexICoN project

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FlexICoN

Full-duplex wireless: from Integrated Circuits to Networks

flexicon.ee.columbia.edu

Columbia University in the City of New York

wim.net Wireless & Mobile Networking Lab

Outline

- Introduction
- Integrated Full-Duplex Radios
  - RF Frequency-Domain Equalization
  - RF/mm-Wave TRX with Polarization-Based Antenna SIC
  - Integrated Non-Magnetic Passive Circulator with Baseband SIC
- Cross-Layer Analysis and Design of Full-Duplex Wireless Systems and Networks
- Conclusion

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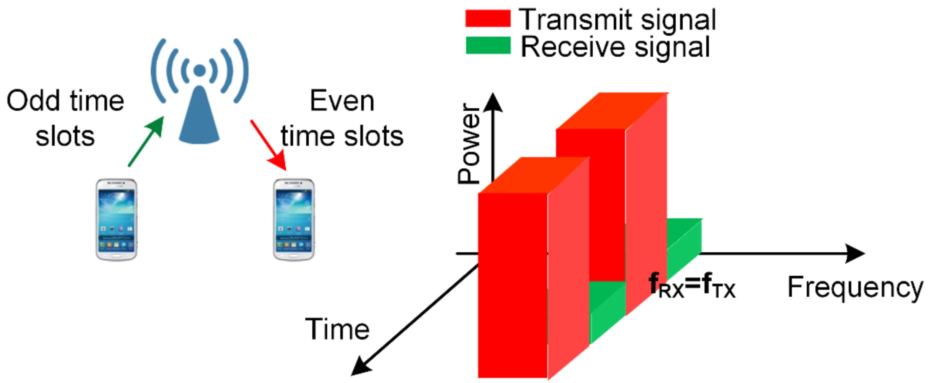
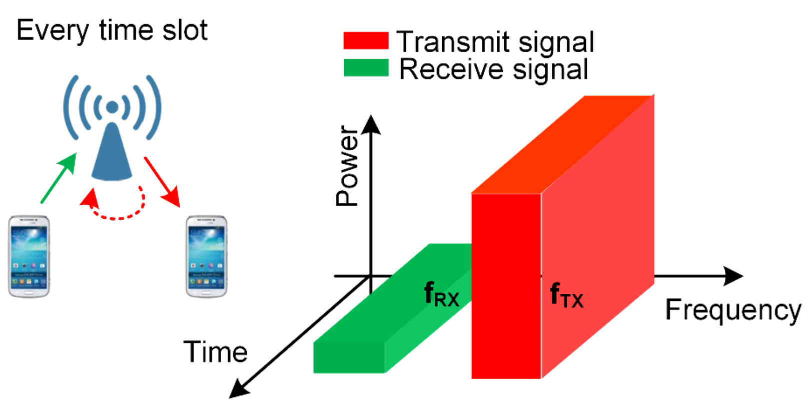
Full-Duplex Wireless

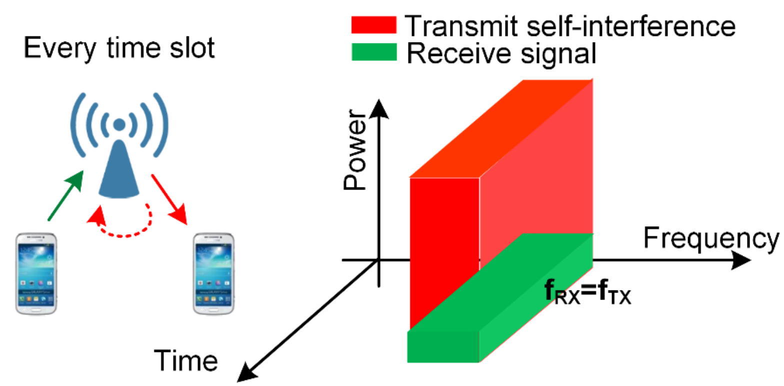
Time-Division Duplexing (TDD)



Frequency-Division Duplexing (FDD)



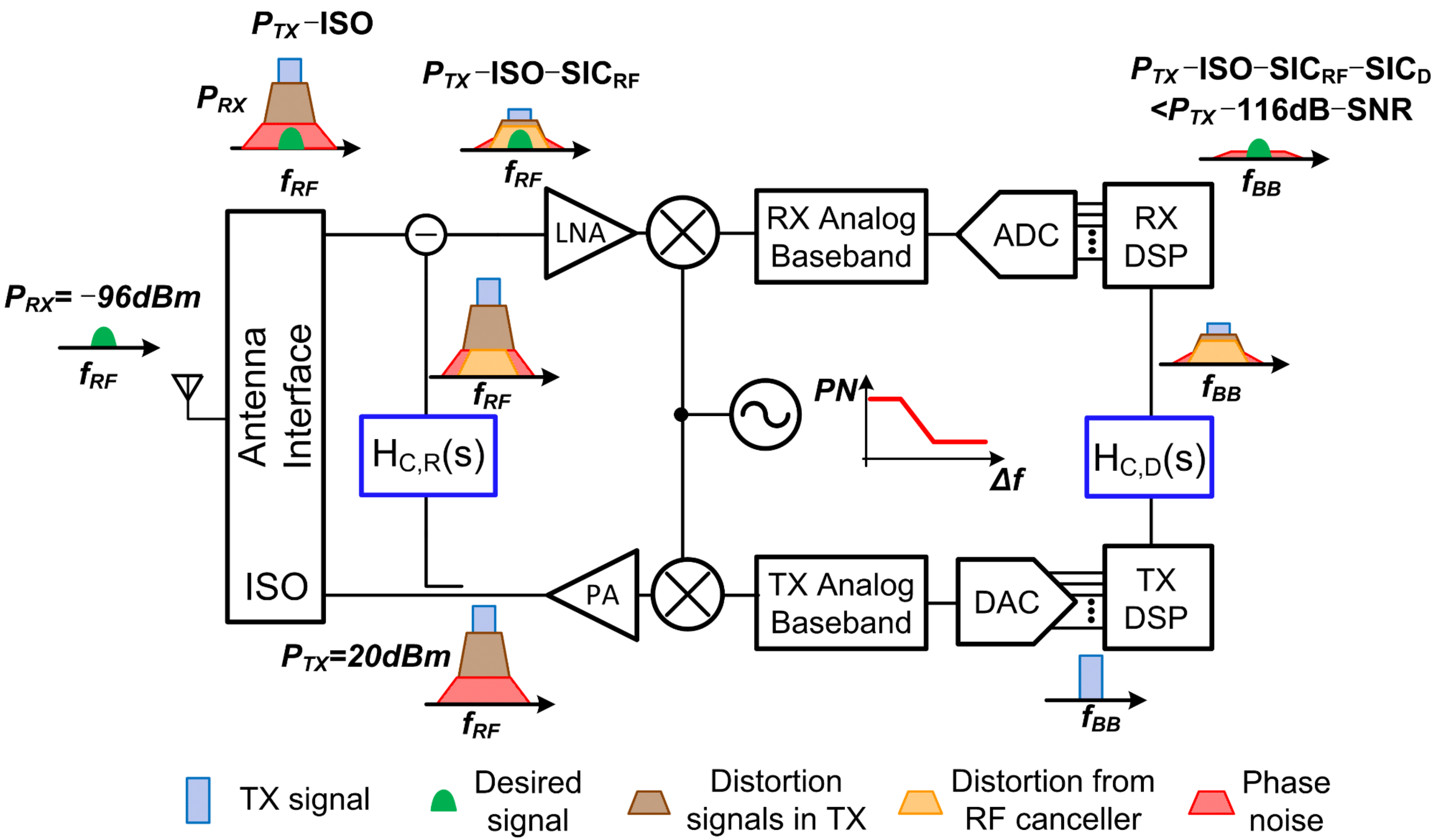
Full-Duplex (FD)



- **Increased throughput**
- **Flexible spectrum use**

▪ Same-channel full-duplex -- simultaneous transmission and reception at the same frequency -- can greatly improve network performance.

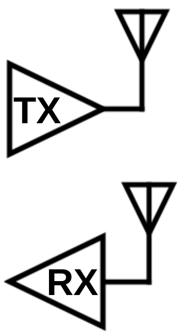
Self-Interference in Full Duplex



Full Duplex requires >120dB of self-interference cancellation, which must be obtained across all domains.

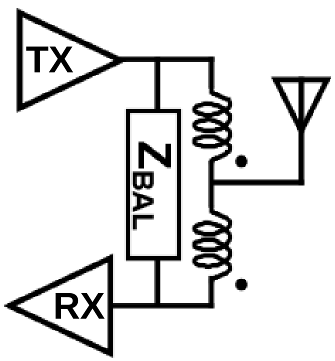
Fighting Fundamental Physics

Antenna Pair



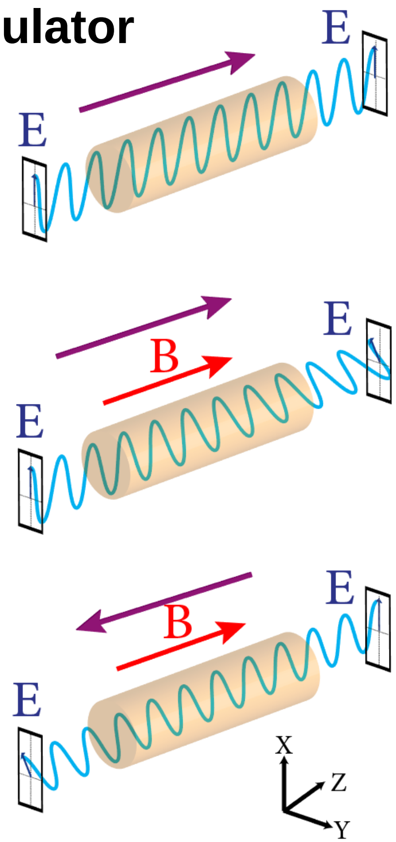
❌ Form factor

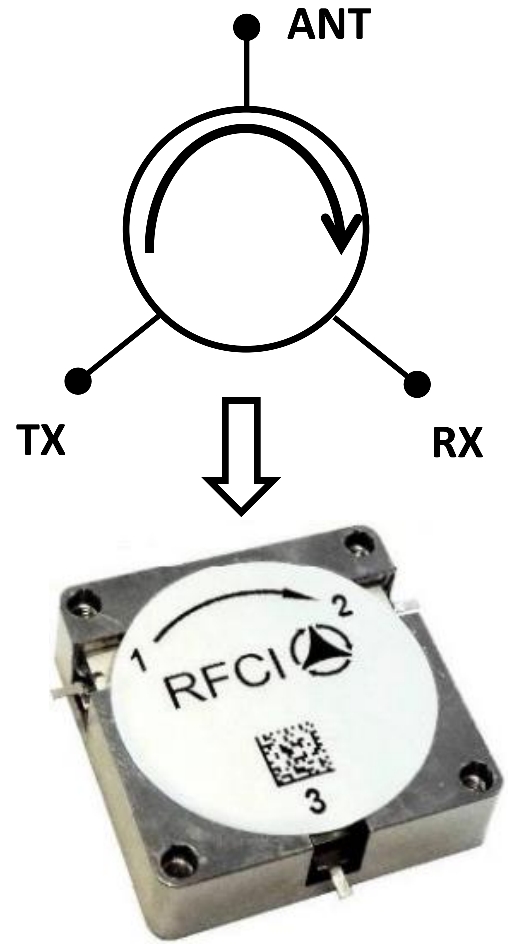
Balanced Duplexer



❌ Insertion loss

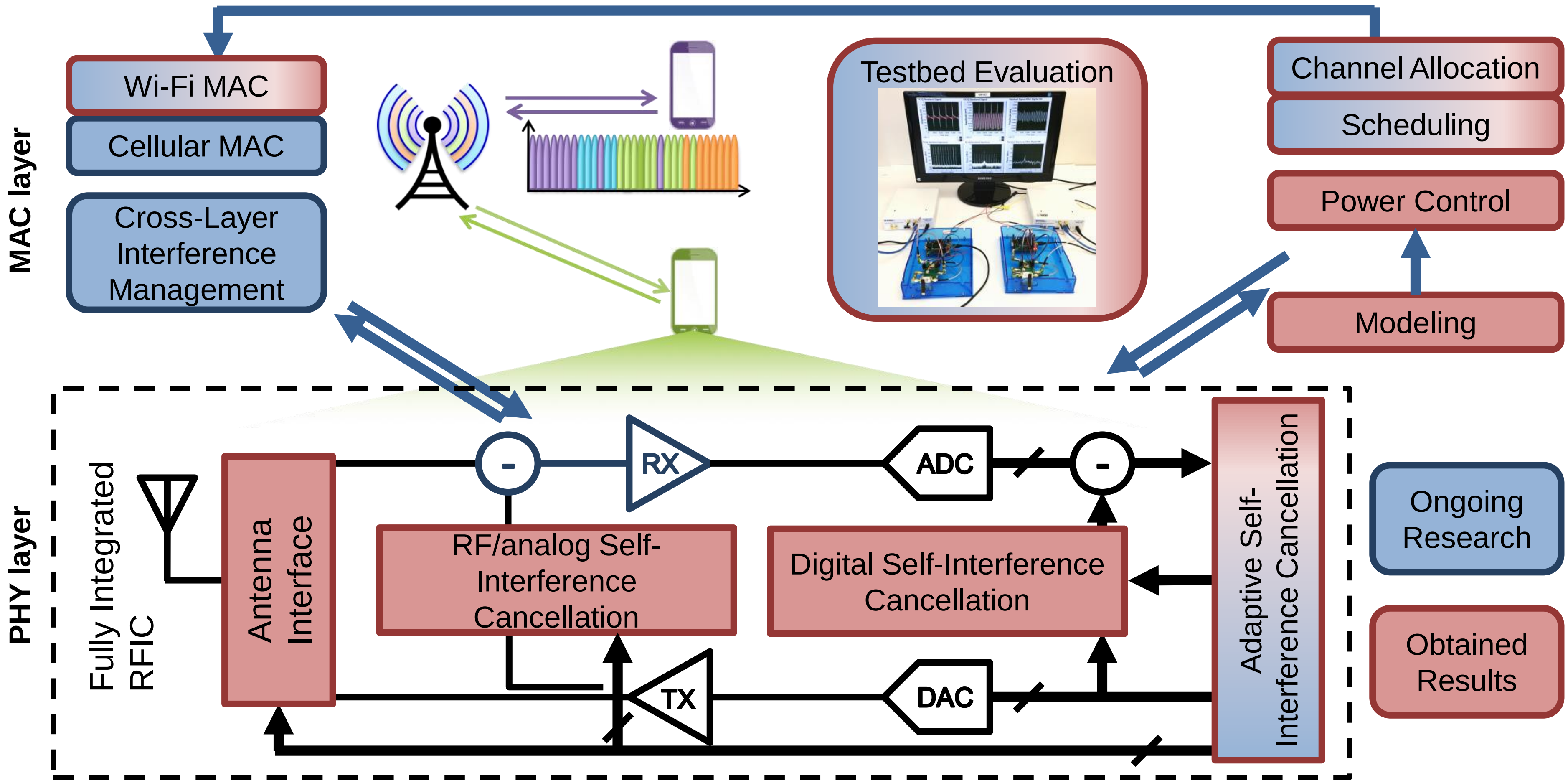
Nonreciprocal Circulator





Breaking Lorentz Reciprocity requires exploiting the magneto-optic Faraday Effect.

Full-Duplex Cross-Layer Research



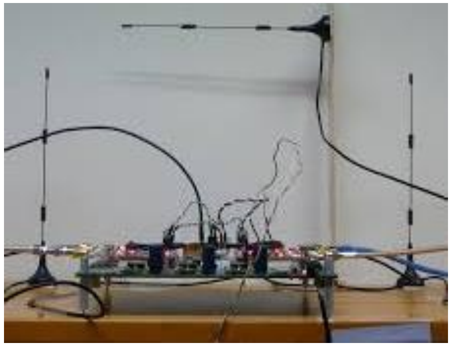
FlexICoN
Full-duplex wireless: from Integrated Circuits to Networks

SPAR ACT RF-FPGA 2015-16 2016-17

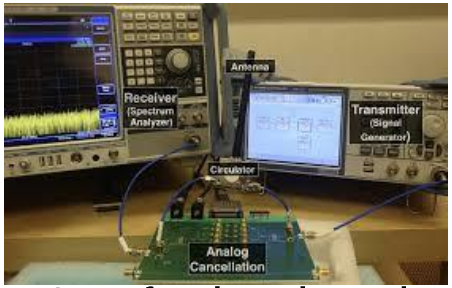
Prof. H. Krishnaswamy
Prof. G. Zussman
Prof. Y. Zhong

State of The Art Full-Duplex Radios

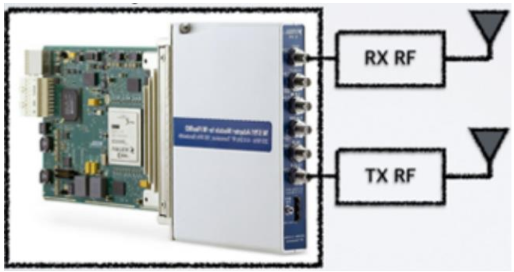
Discrete Full-Duplex Radios



Rice University

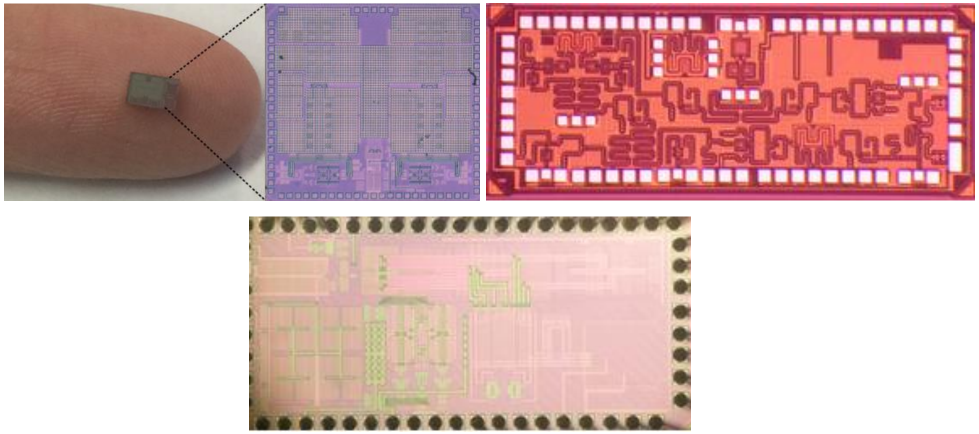


Stanford University



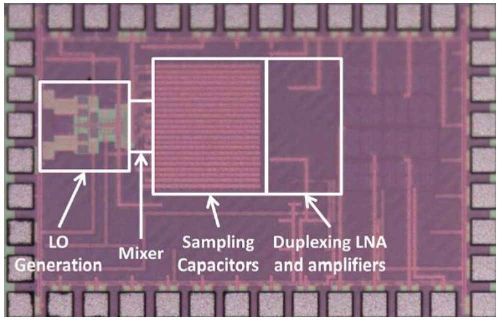
Yonsei University

Integrated Full-Duplex Radios



Columbia University

University of Twente



Cornell University

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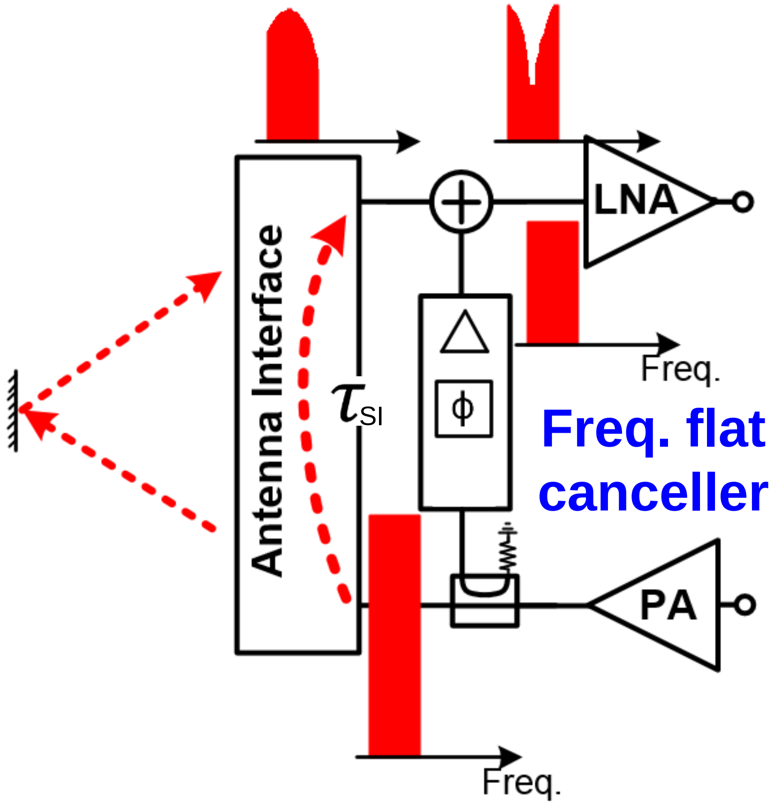
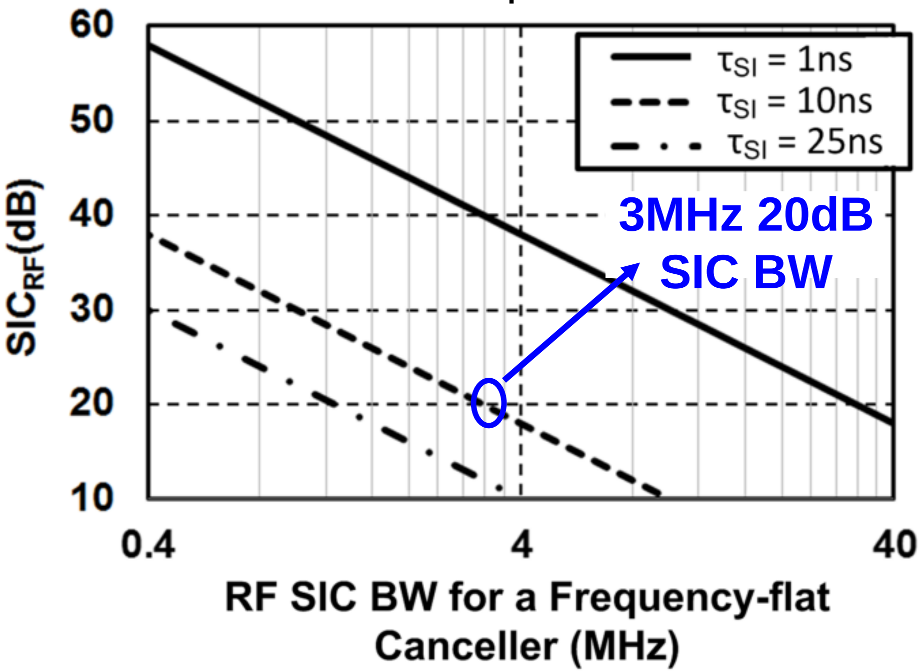
Limited RF Cancellation Bandwidth



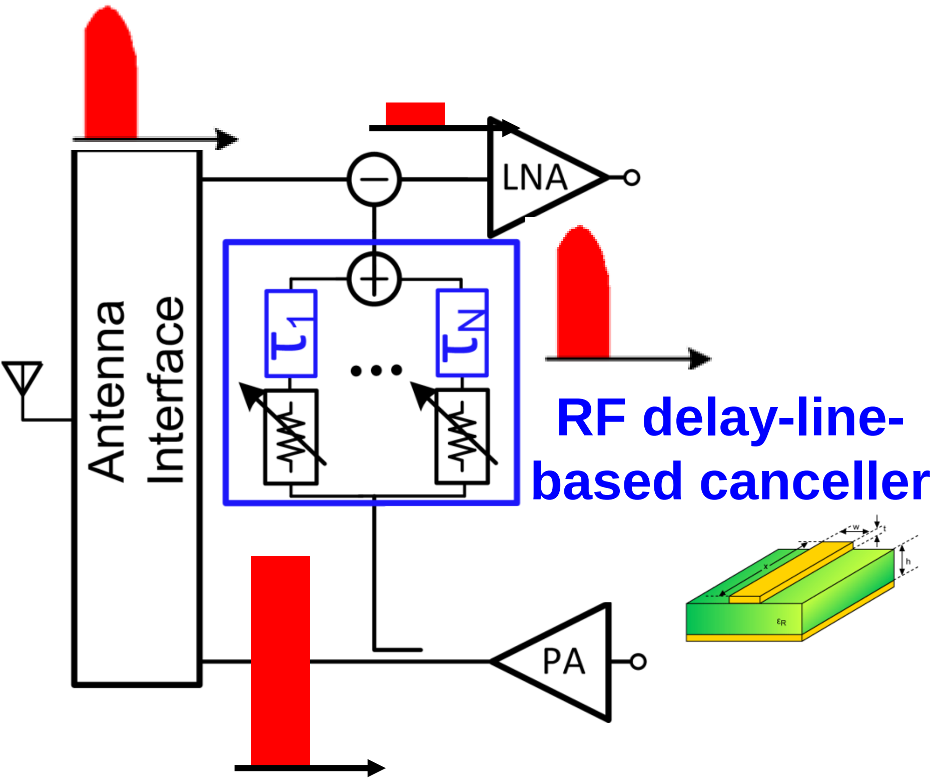
Calculated RF SIC BW for a given RF SIC with a freq. flat canceller

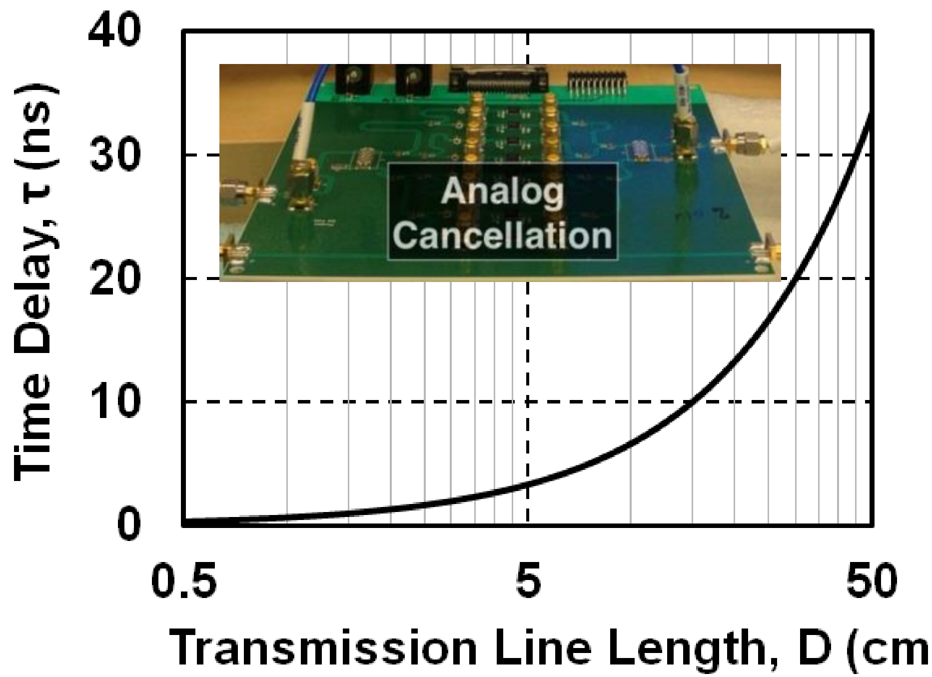


$$\omega_{BW} = \frac{2}{\sqrt{SIC_{RF}\tau_{SI}}}$$

- 10ns delay in the SI channel results in a 20dB SIC BW of 3.2MHz.

Delay-Based Wideband RF Cancellation

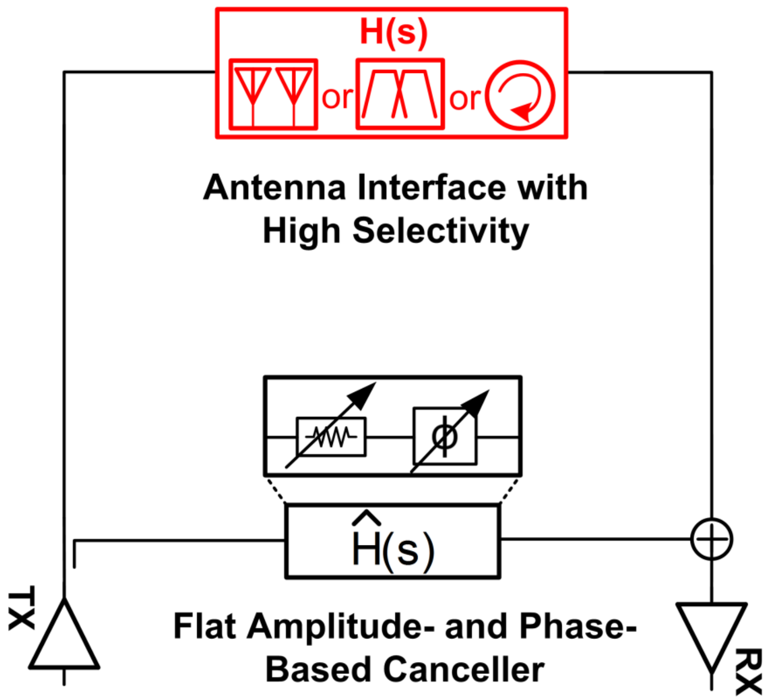


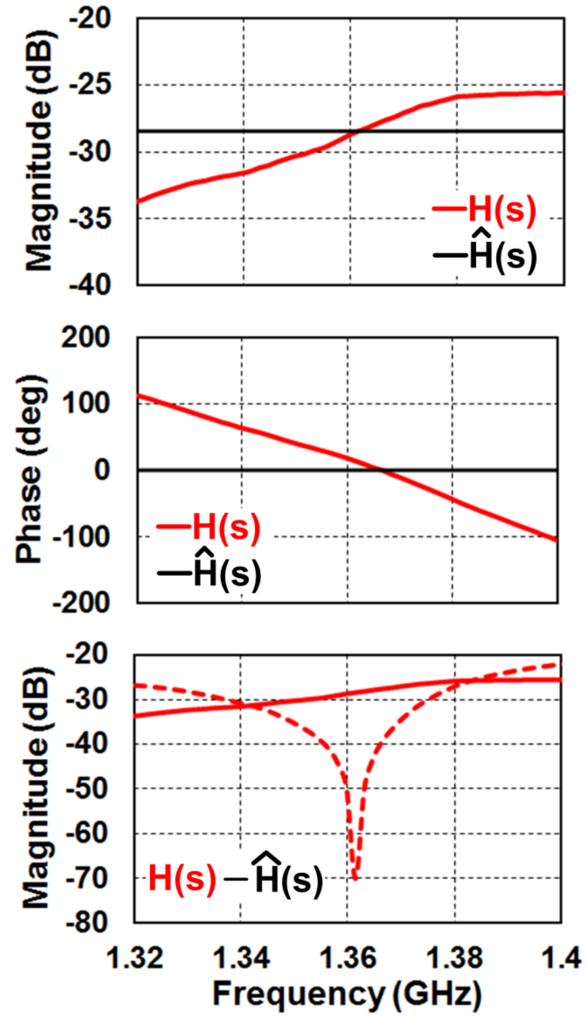


[Stanford University, SIGCOMM 2013]

Conventional wideband RF self-interference cancellation requires silicon-averse bulky and lossy delay lines.

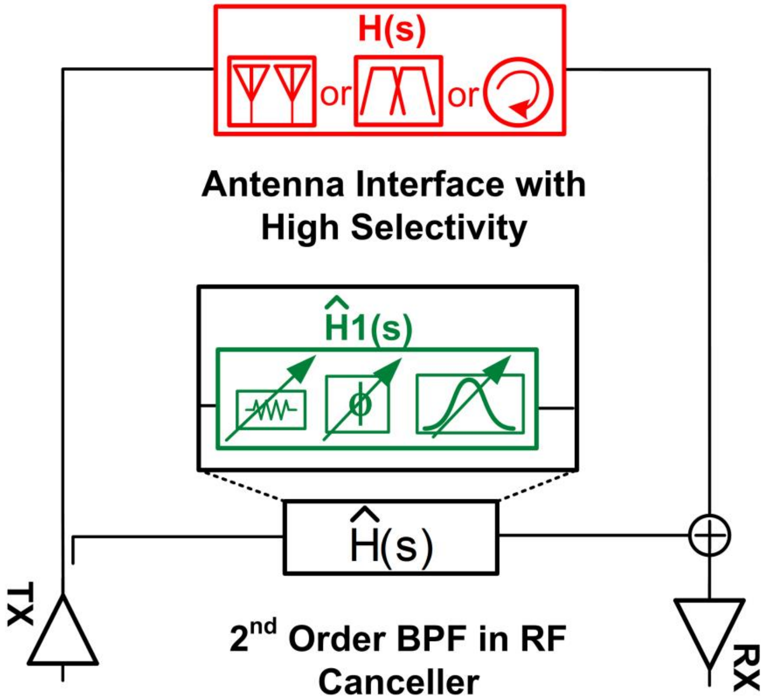
Conventional Integrated RF SI Canceller

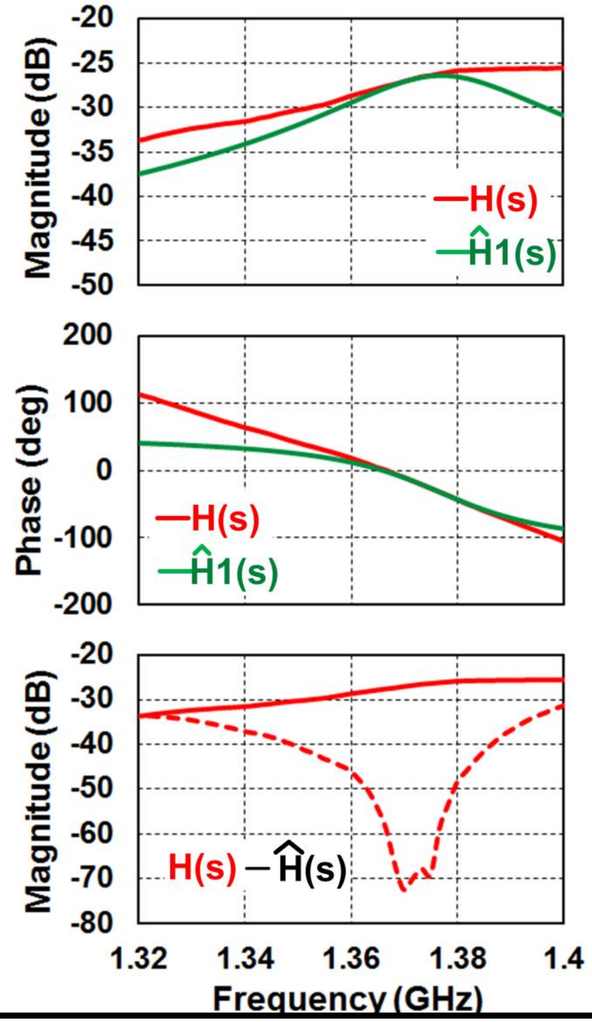




- A frequency-flat RF canceller can emulate a frequency-selective antenna interface *only at one frequency*.

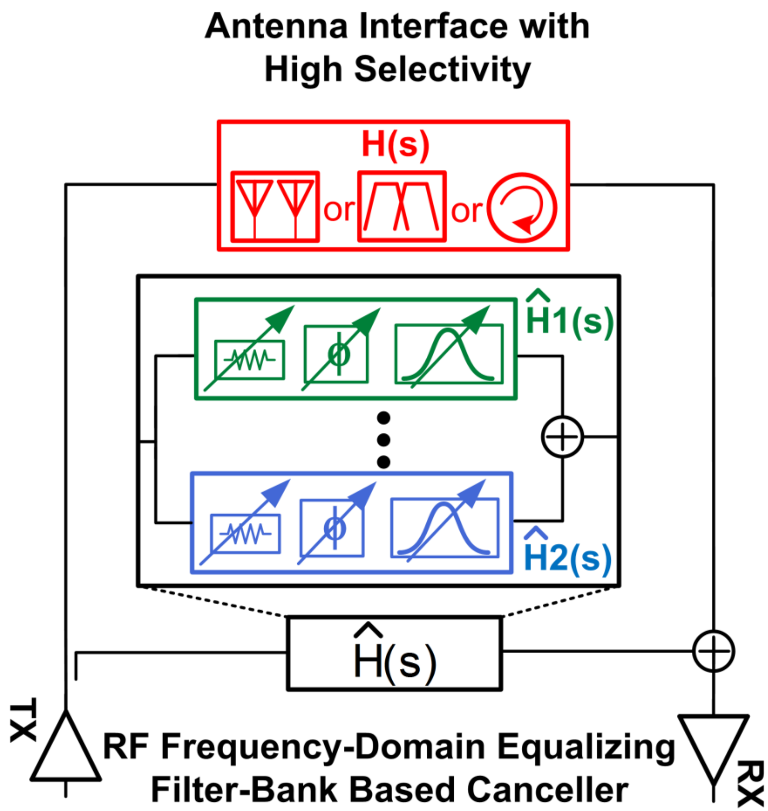
RF Canceller with 2nd Order BPF

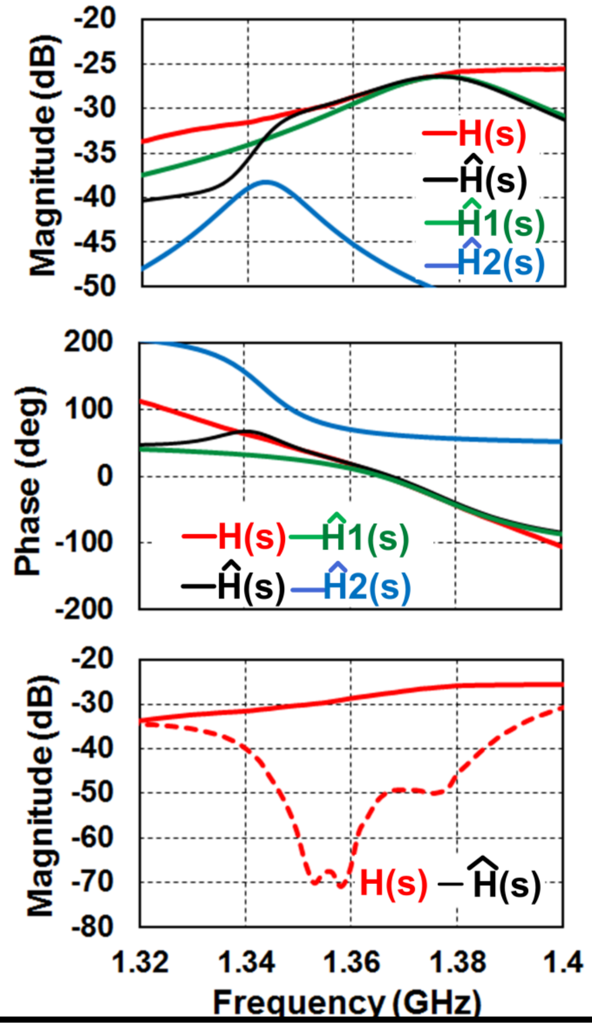




Replication of not only the amplitude/phase, but also the slope of the amplitude/phase(i.e. group delay).

Freq. Domain Equalization (FDE) at RF

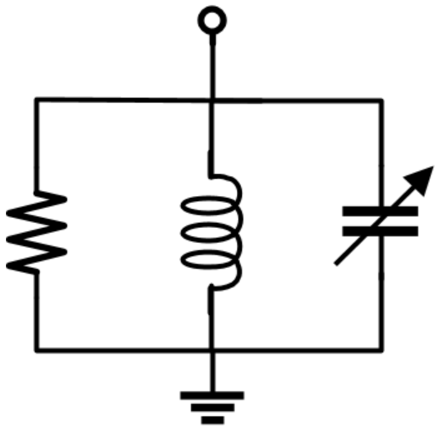




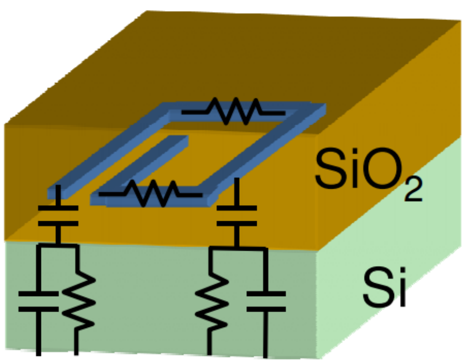
A filter bank enables replication at multiple points in different sub-bands – *Freq. Domain Equalization (FDE)*.

RF SIC Equalizer Bandpass Filter

Linear Time-Invariant Filter

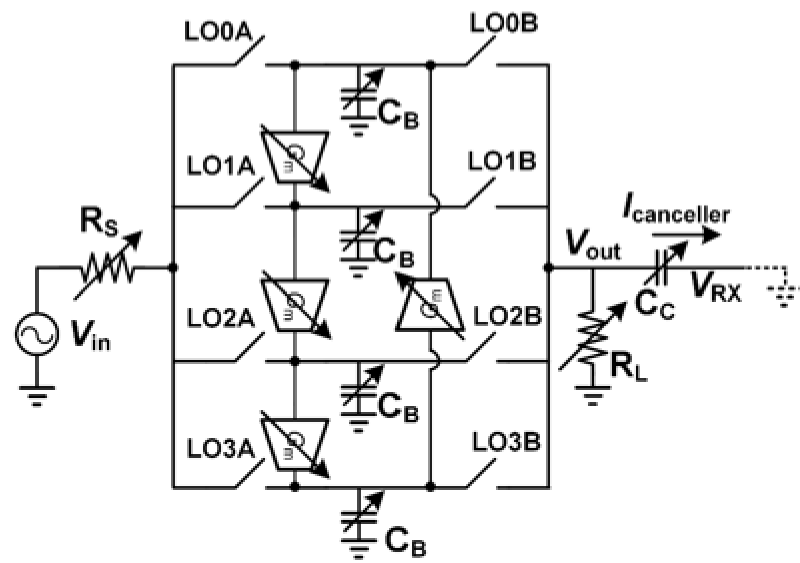


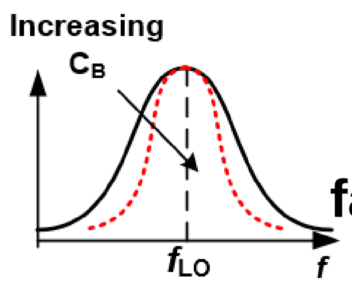
RLC RF bandpass filter



On-chip inductor quality factor at RF is only about 10.

Linear Periodically-Time-Varying Filter (LPTV)

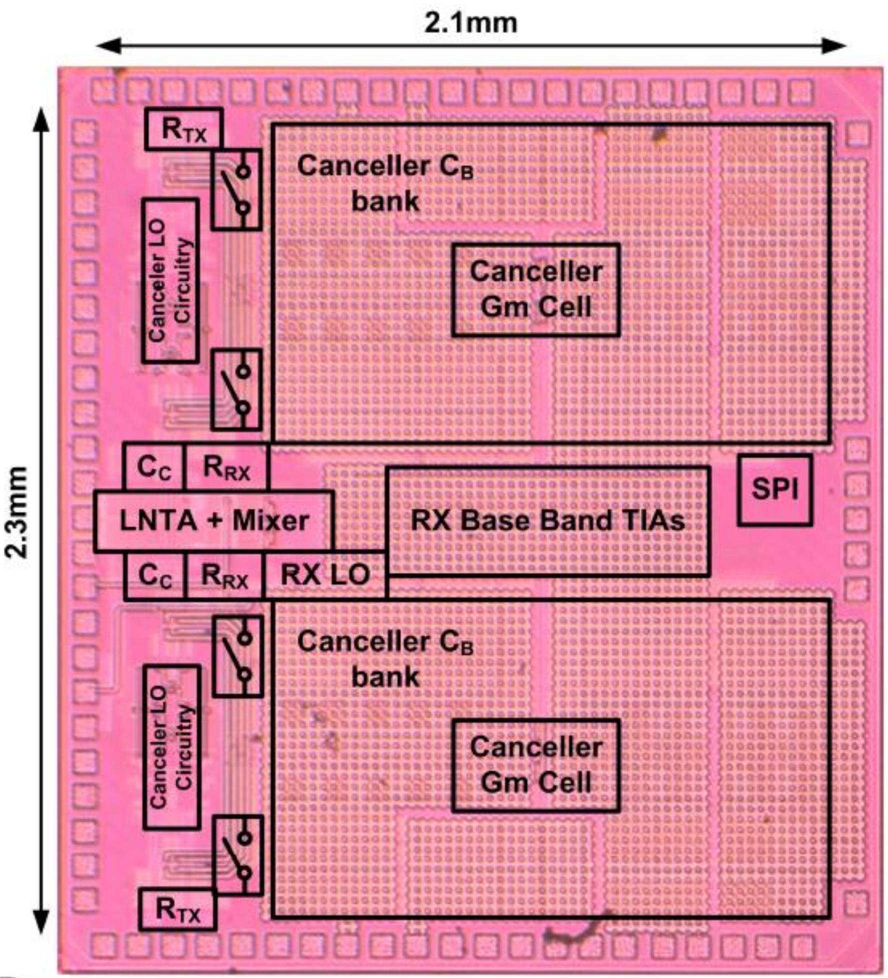


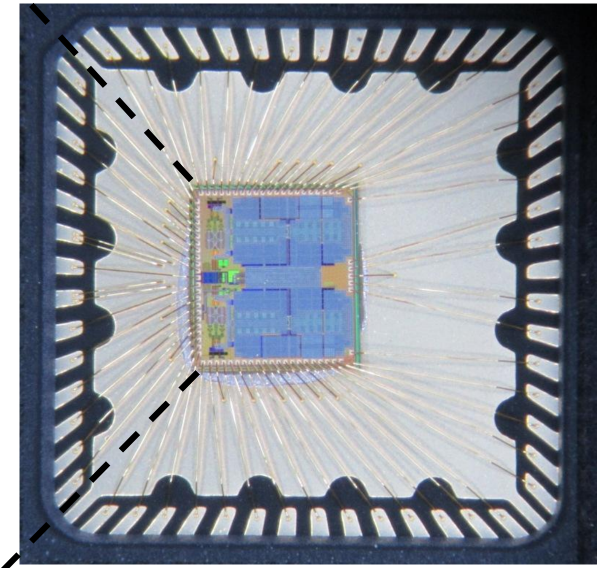


>100 quality factor on silicon

LPTV Switched-Capacitor RF Filter Enables Integrated Reconfigurable High-Q Filters

65nm CMOS Prototype

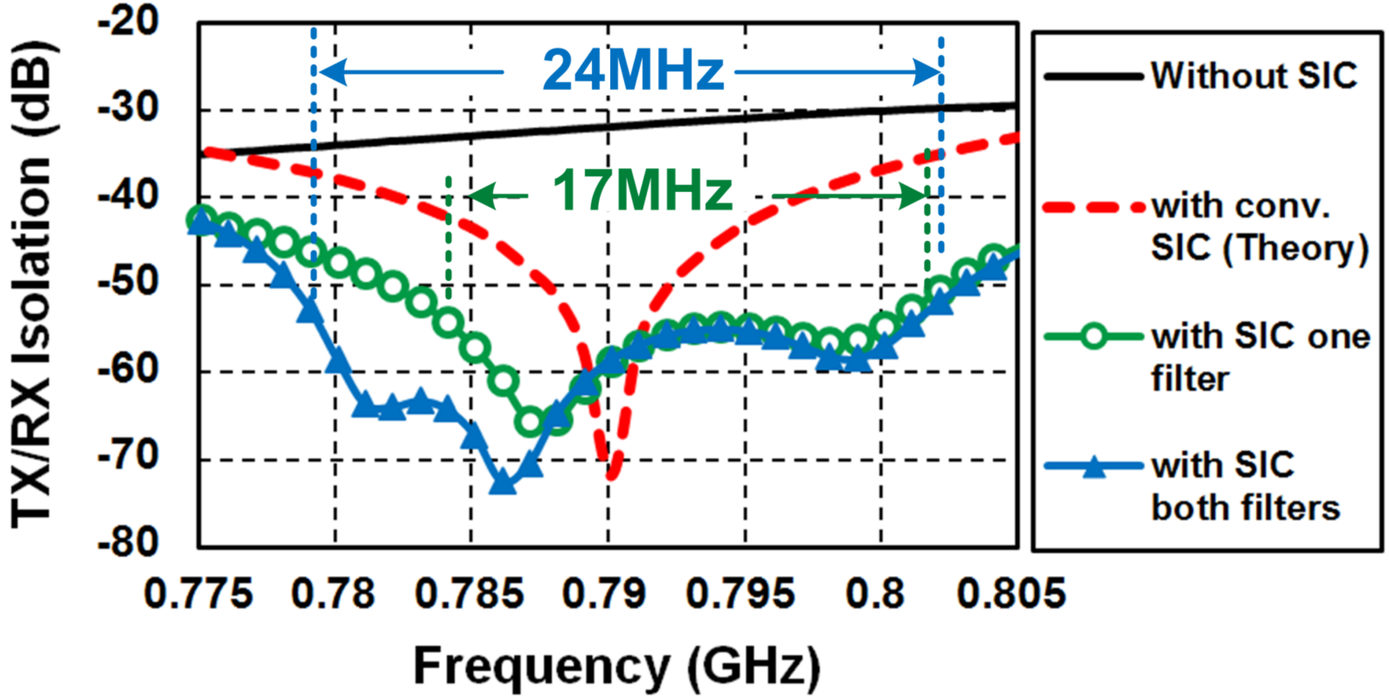




J. Zhou, T-H. Chuang, T. Dinc and H. Krishnaswamy, “Reconfigurable receiver with >20MHz bandwidth self-interference cancellation suitable for FDD, co-existence and full-duplex applications," in 2015 ISSCC, Feb. 2015.

J. Zhou, T-H. Chuang, T. Dinc and H. Krishnaswamy,“Integrated Wideband Cancellation of Transmitter Self-Interference in the RF Domain for FDD and Full-Duplex Wireless,” IEEE JSSC, December 2015 (**invited**).

Measurement Highlights



Proposed canceller has a cancellation BW of 24MHz using two filters (8X improvement!).

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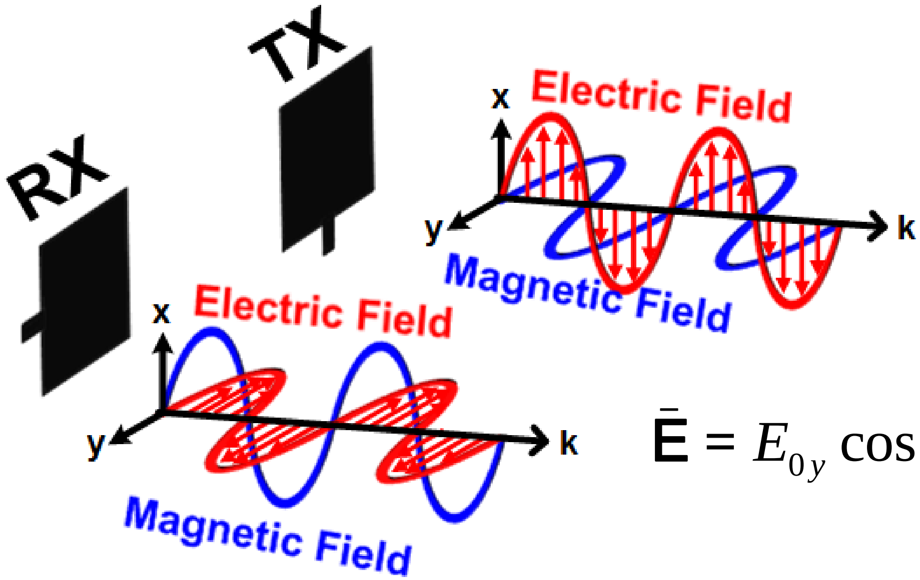
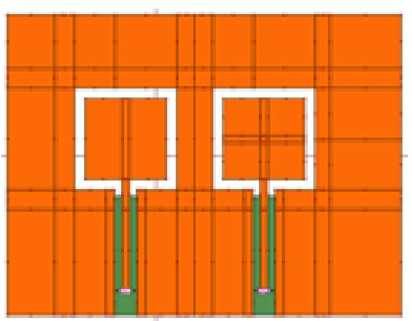
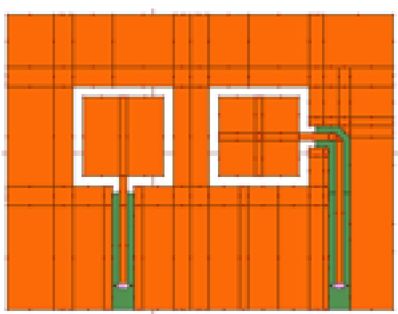
Polarization-Division Duplexing

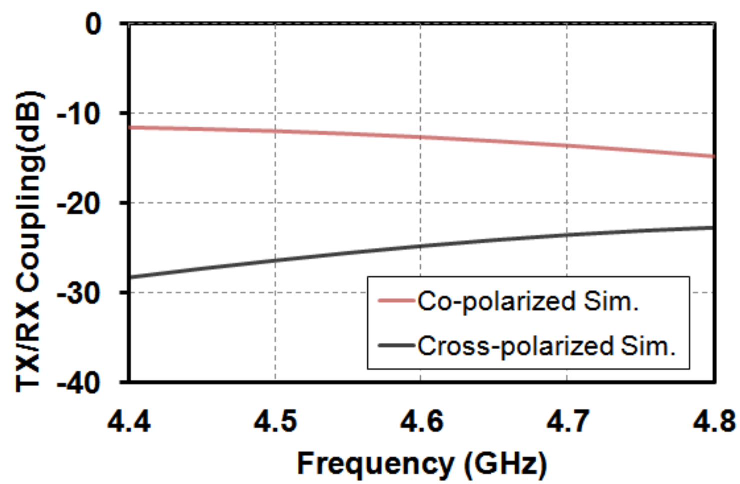


$$\bar{\mathbf{E}} = E_{0x} \cos\left(2\pi f\,(t - \frac{z}{c})\right)\bar{\mathbf{x}}$$

$$\bar{\mathbf{E}} = E_{0y} \cos\left(2\pi f\,(t - \frac{z}{c})\right)\bar{\mathbf{y}}$$

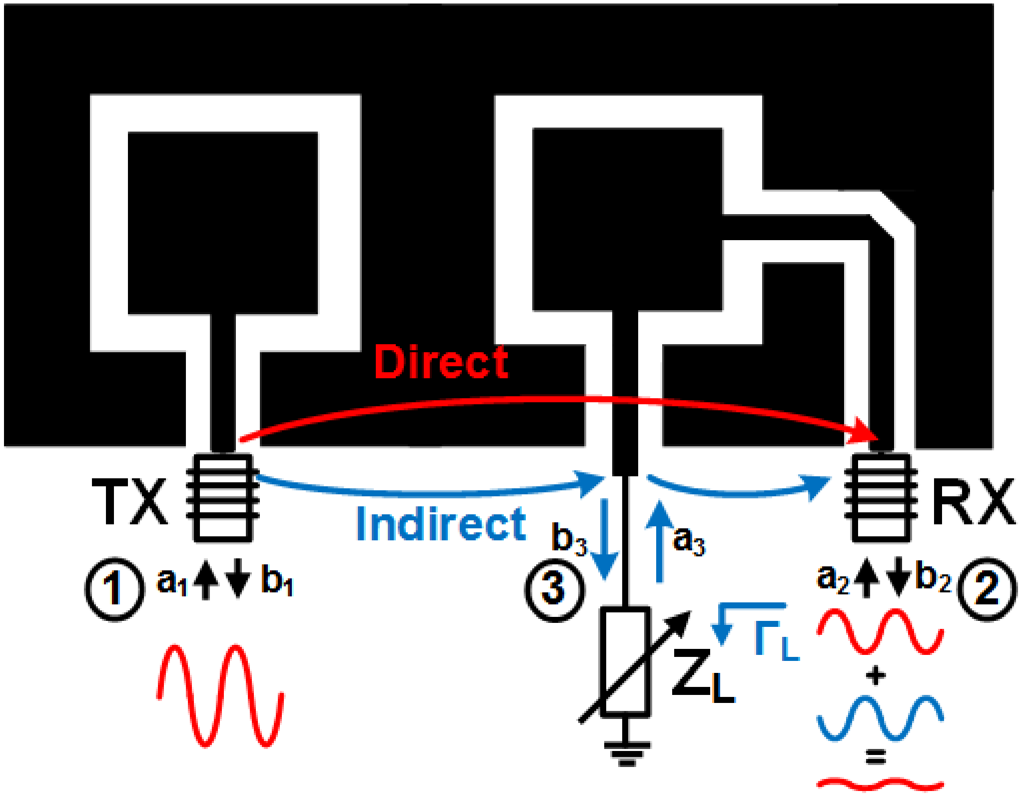






- Using different polarizations for T/R *improves the isolation by 8-16 dB.*

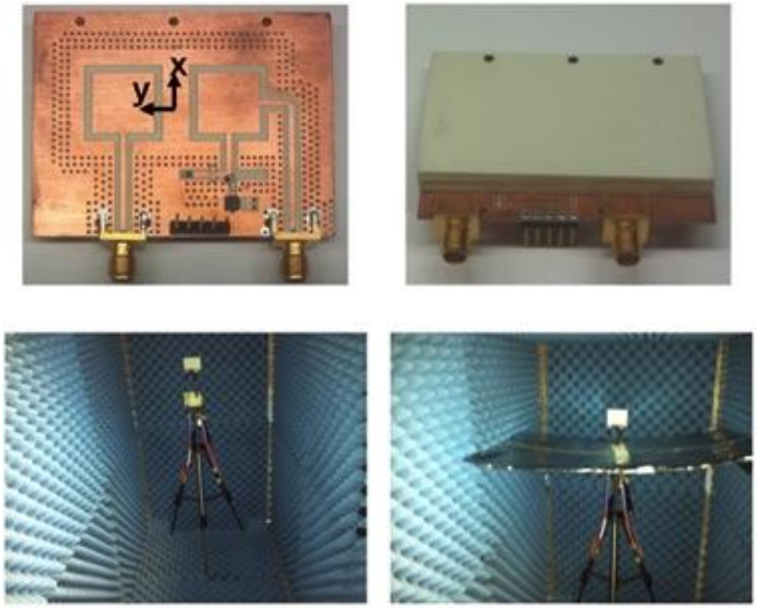
Polarization-Based Antenna SIC

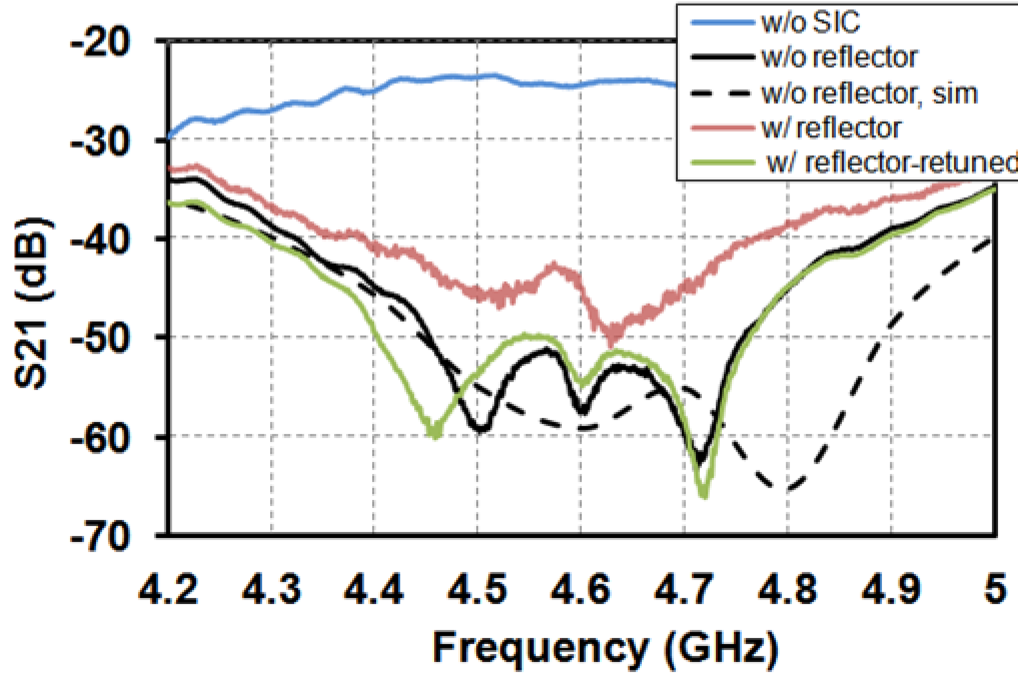


$$b_2 = \left(S_{21} + \frac{S_{23}S_{31}\Gamma_L}{1 - S_{33}\Gamma_L} \right) a_1$$

- An auxiliary port is introduced on the RX antenna that is co-polarized with TX and terminated with a reflective termination to achieve wideband SIC.

5GHz Antenna SIC Results

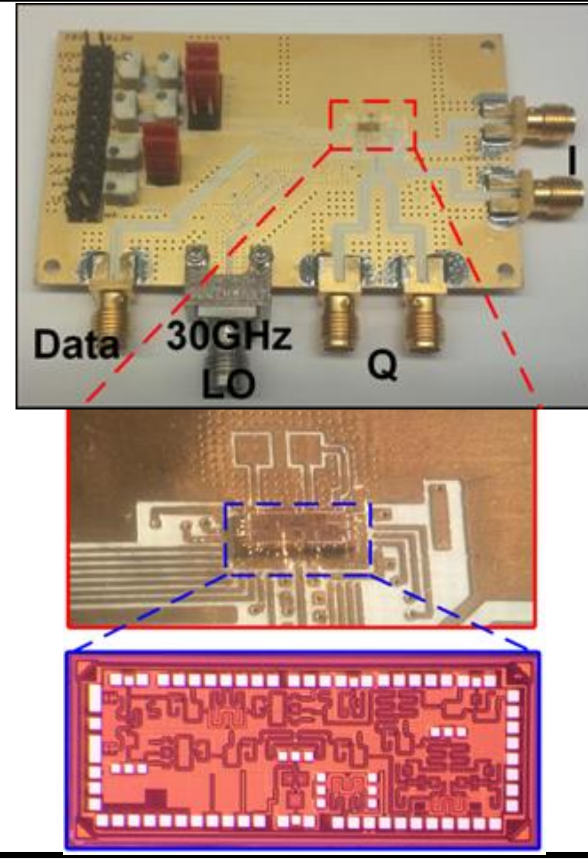




- **50 dB isolation over 300MHz at 4.6 GHz.**
- **Reflective termination can be reconfigured to combat the variable SI scattering from the environment.**

Tolga Dinc and Harish Krishnaswamy, "A T/R Antenna Pair with Polarization-Based Reconfigurable Wideband Self-Interference Cancellation for Simultaneous Transmit and Receive," in the 2015 IEEE International Microwave Symposium, pp. 1-4, May 2015.

60GHz 45nm CMOS Full Duplex TRX

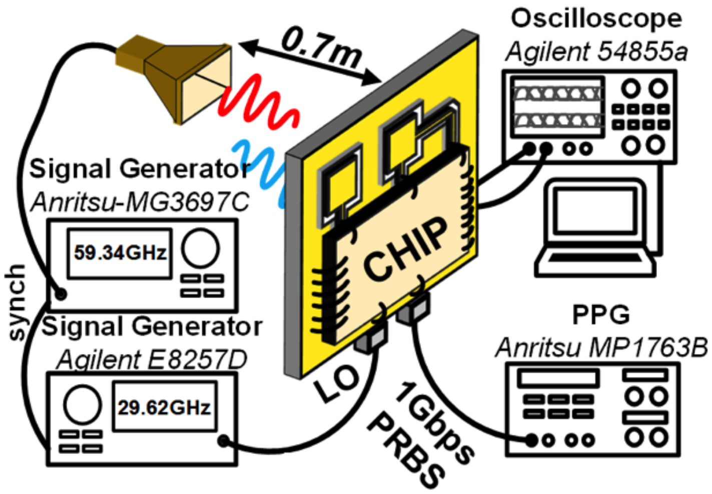


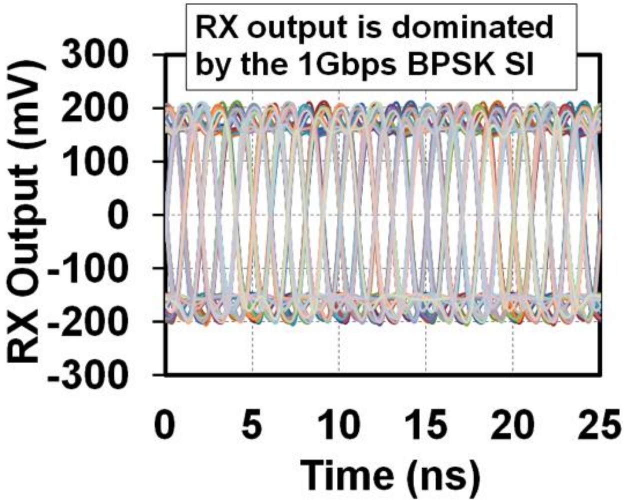
World's first fully-integrated full-duplex TRX front-end.

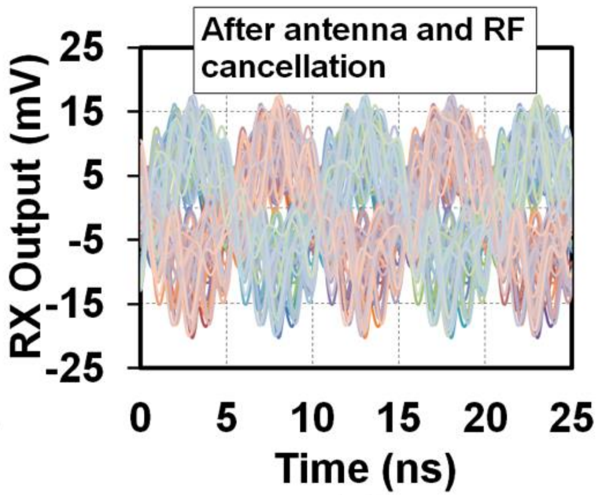
T. Dinc, A. Chakrabarti and H. Krishnaswamy, "A 60 GHz Same-Channel Full-Duplex CMOS Transceiver and Link Based on Reconfigurable Polarization-Based Antenna Cancellation," in the 2015 IEEE RFIC Symposium, May 2015 (**Best Student Paper Award – 1st Place**).

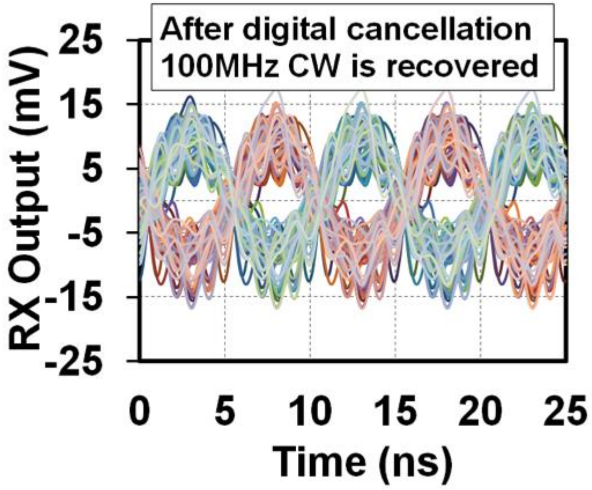
T. Dinc, A. Chakrabarti and H. Krishnaswamy, "A 60GHz CMOS Full-Duplex Transceiver and Link with Polarization-Based Antenna and RF Cancellation," IEEE Journal of Solid-State Circuits, vol. 51, no. 5, pp. 1125-1140, May 2016 (**invited**).

60GHz Full Duplex Wireless Link









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Shared-Antenna Interfaces

Magnetic Materials

[Ref: RF Circulator Isolator, Inc..]

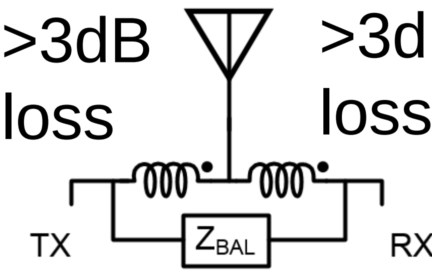
❌ form factor

❌ incompatible with CMOS

Passive Linear Time-Invariant system

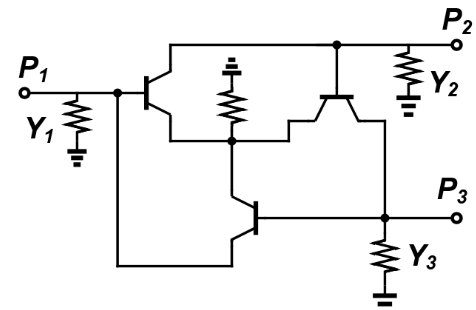
>3dB loss

>3dB loss



[Ref: B. van Liempd, et al., ISSCC 2015.]

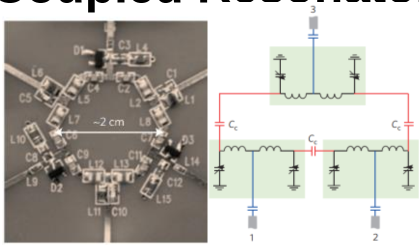
Active Devices



[Ref: S. Tanaka, et al., Proc. of IEEE, 1965.]

❌ poor linearity/noise

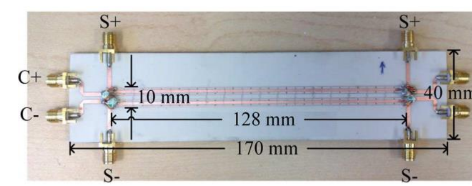
Parametric Modulation of Coupled Resonators



[Ref: N. Estep, et al., Nature Physics 2014.]

❌ >20dB loss or linearity

Distributedly Modulated Capacitors



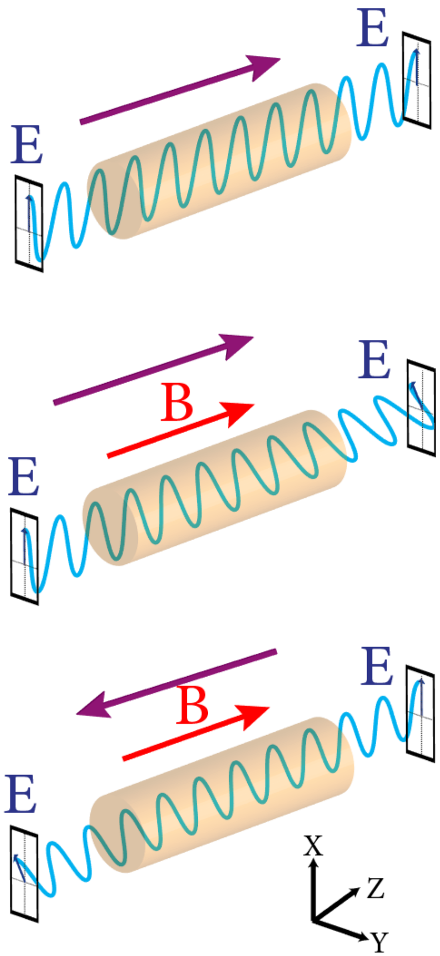
[Ref: S. Qin, et al., IEEE T-MTT 2014.]

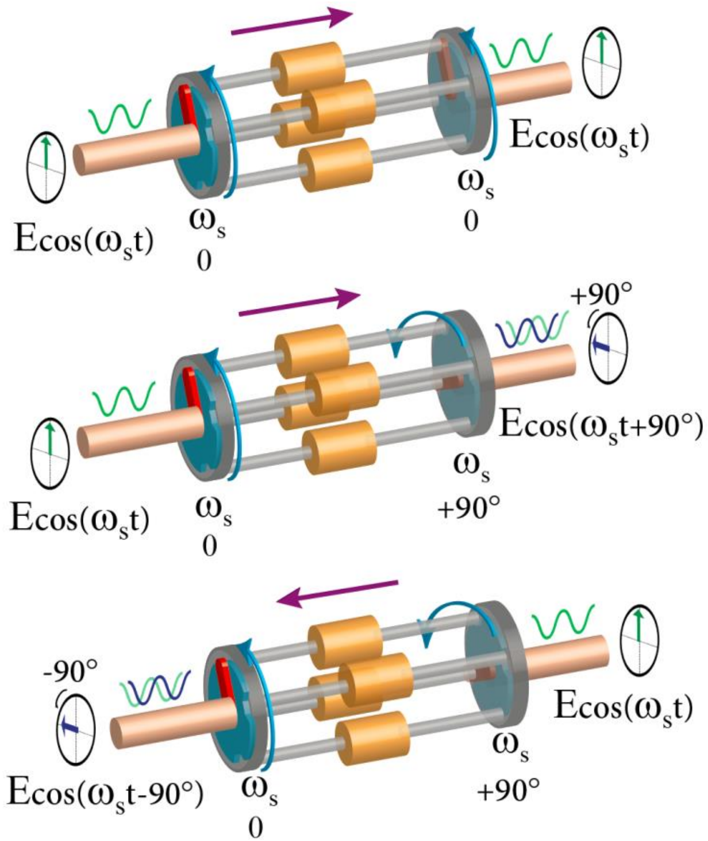
❌ extra duplexer

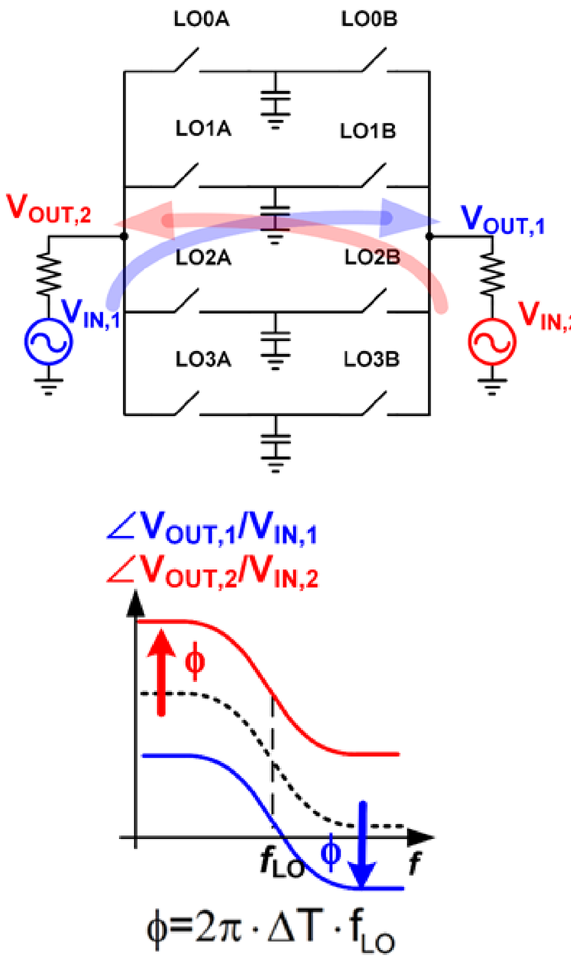
❌ form factor

New techniques for low-loss, compact, passive, highly-linear circulators are desirable.

Staggered Commutation

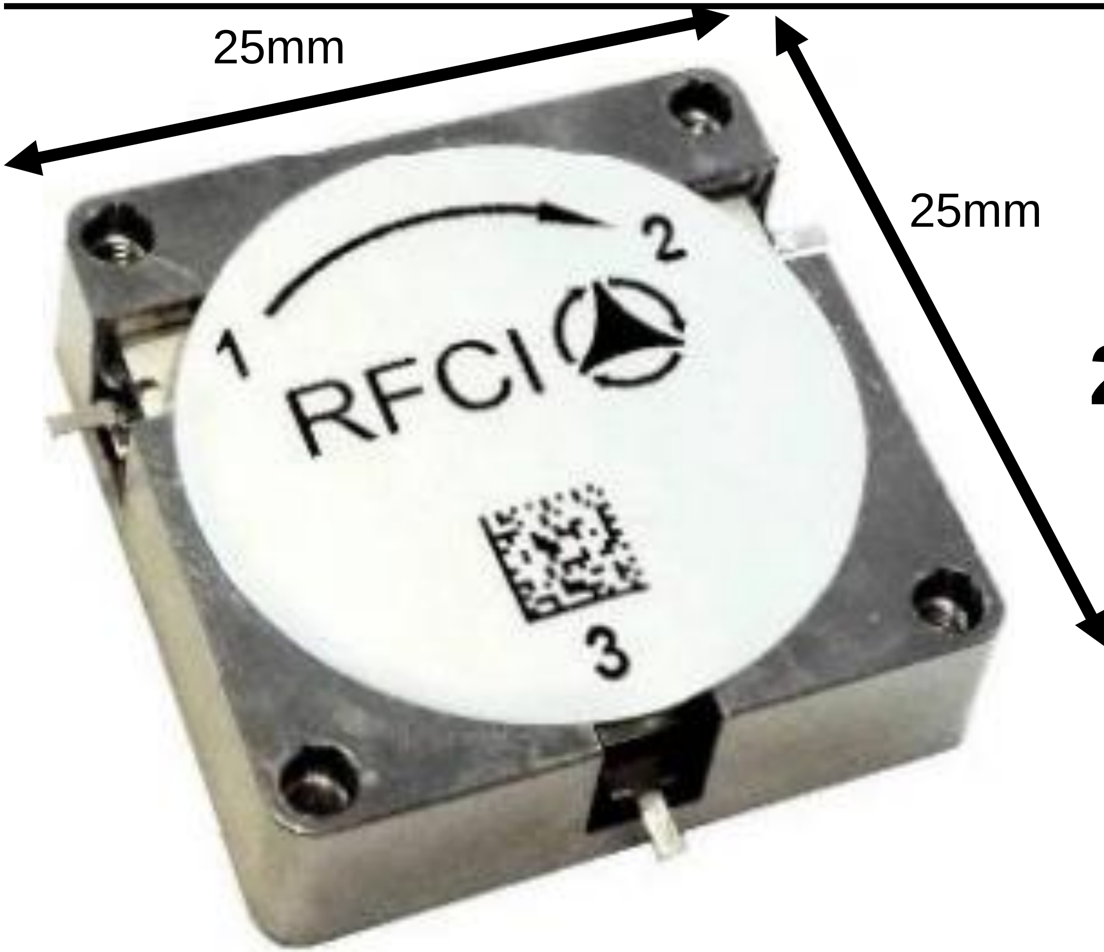




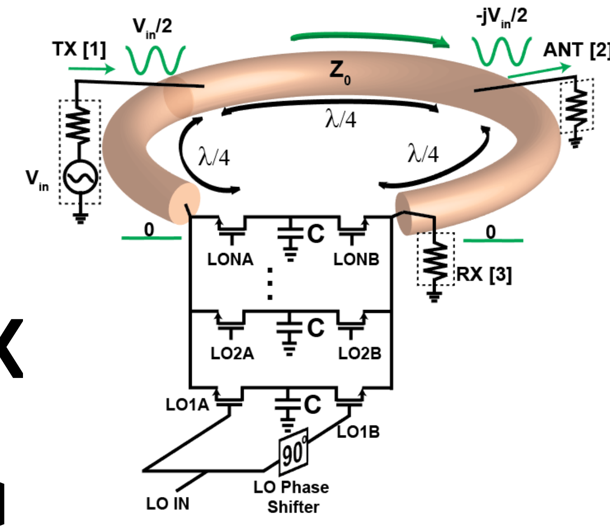


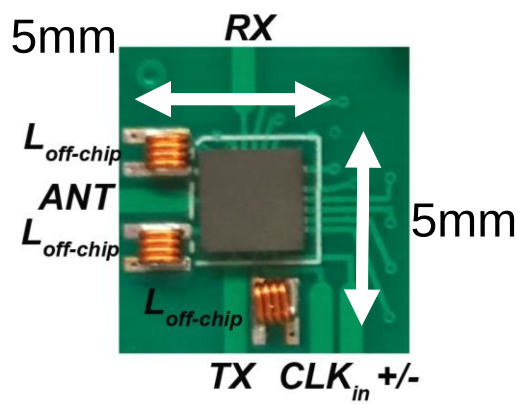
Inspired by Faraday rotation, phase non-reciprocity can be achieved by using staggered commutation.

Non-Magnetic Passive Circulator



25 X >

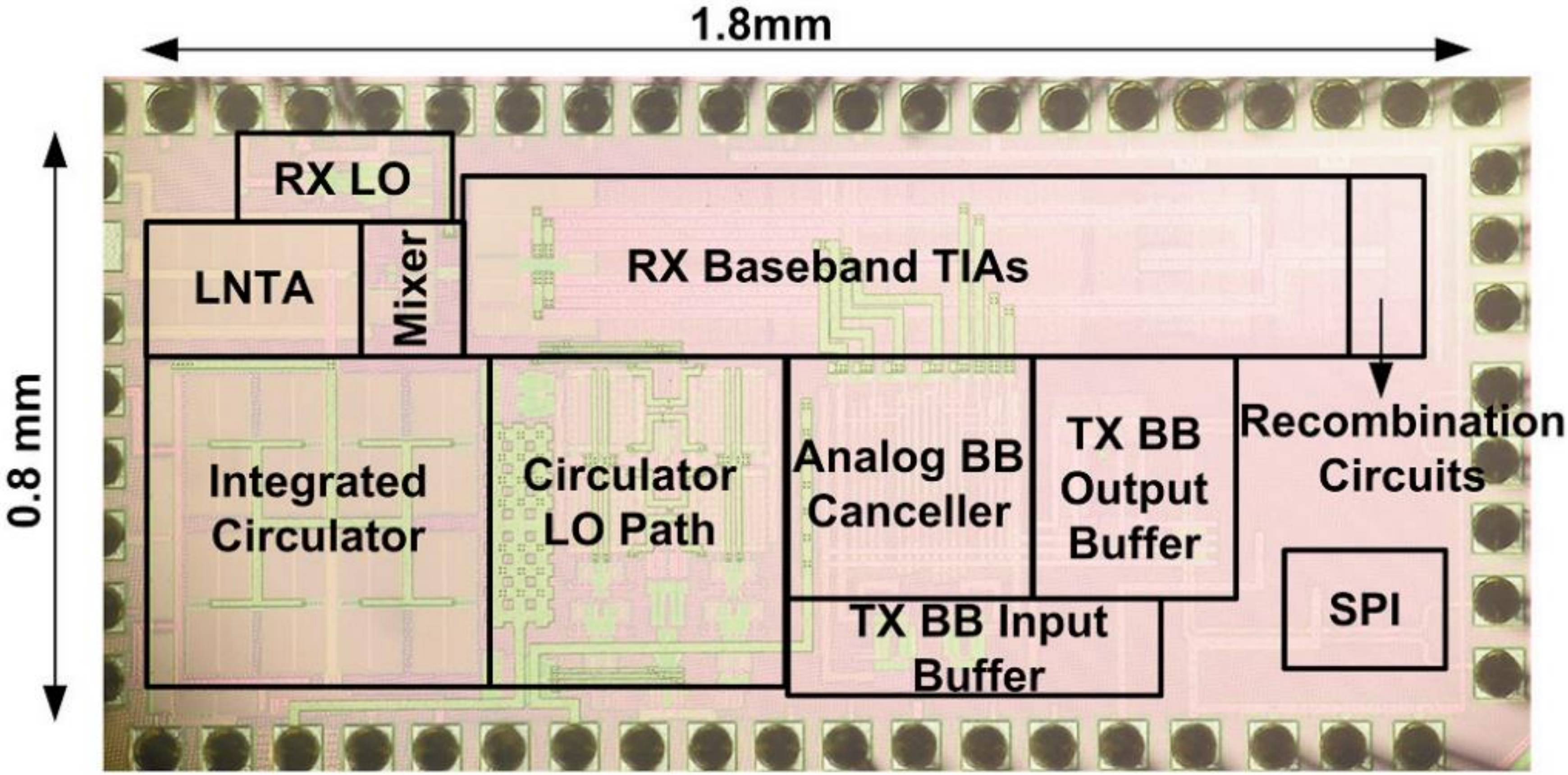




This is the first CMOS non-magnetic passive non-reciprocal circulator IC.

N. Reiskarimian, and H. Krishnaswamy, "Magnetic-free Non-Reciprocity Based on Staggered Commutation," Nature Communications. 7:11217 doi: 10.1038/ncomms11217 (2016).

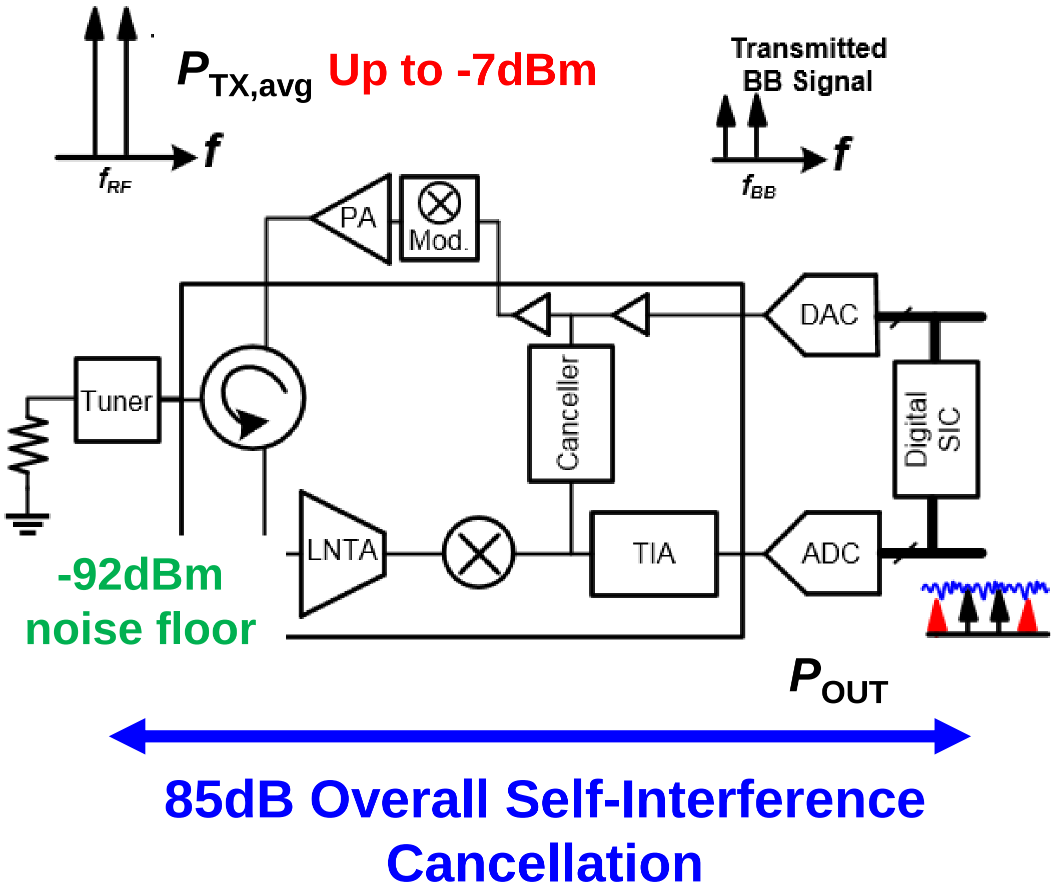
65nm CMOS FD Radio Prototype

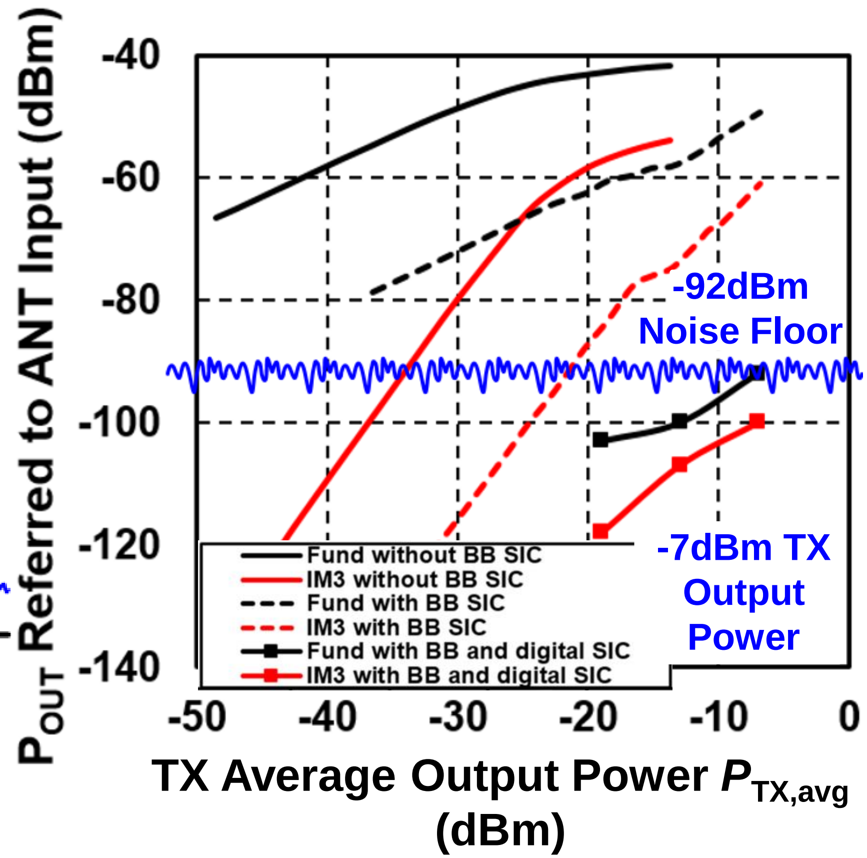


J. Zhou, N. Reiskarimian, and H. Krishnaswamy, " Receiver with Integrated Magnetic-Free N-Path-Filter-Based Non-Reciprocal Circulator and Baseband Self-Interference Cancellation for Full-Duplex Wireless," in 2016 ISSCC, Feb. 2016.

N. Reiskarimian, J. Zhou, and H. Krishnaswamy,"A CMOS Passive LPTV Non-Magnetic Circulator and Its Application in a Full-Duplex Receiver," IEEE JSSC (in revision).

SIC across ANT, Analog and Dig. Domains



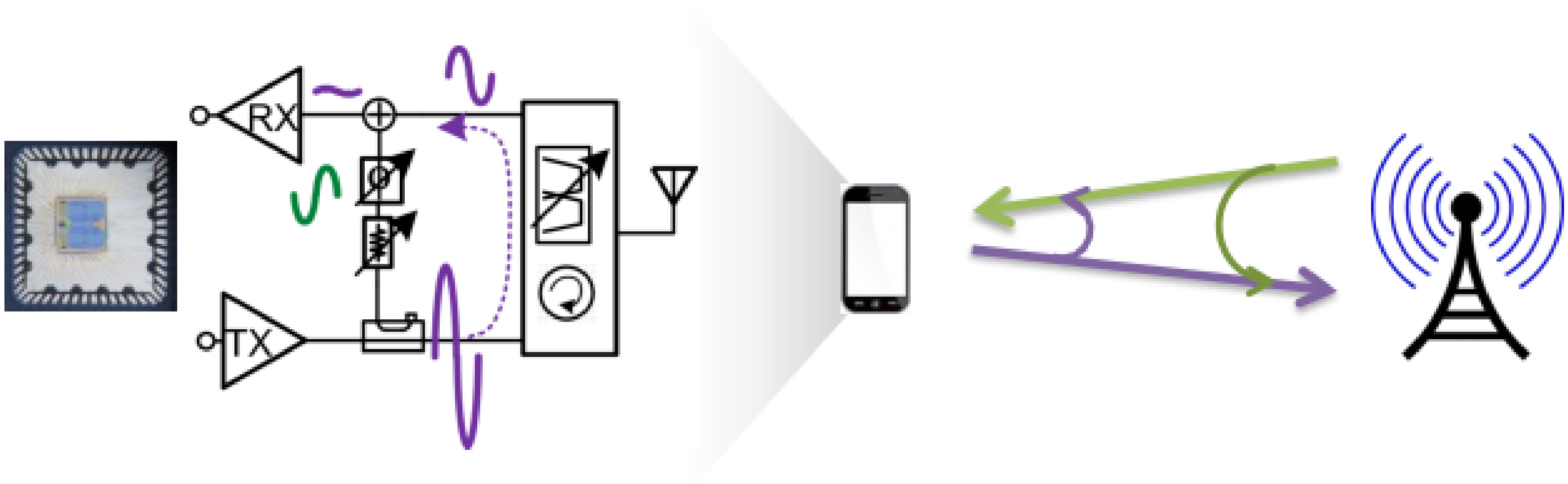


First full-duplex link demonstration with –7dBm TX output power and –92dBm noise floor based on an integrated full-duplex radio.

Outline

- Introduction
- Integrated Full-Duplex Radios
  - SIC RX based on Frequency-Domain Equalization
  - RF/mm-Wave TRX with Polarization-Based Antenna SIC
  - Integrated Non-Magnetic Passive Circulator with Baseband SIC
- Cross-Layer Analysis and Design of Full-Duplex Wireless Systems and Networks
- Conclusion

Power Allocation and Rate Gains in Practical Full-Duplex Systems

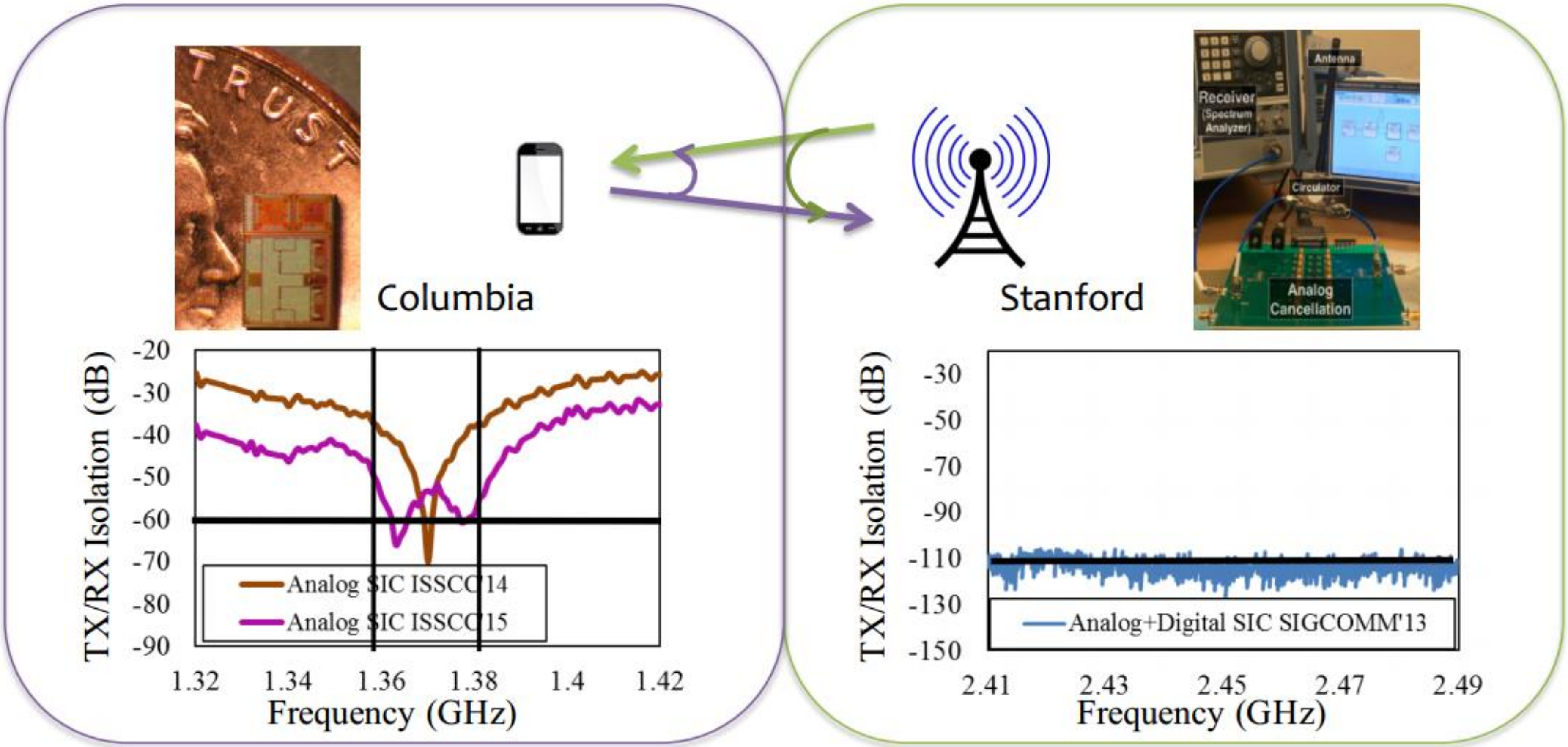


J. Marašević, J. Zhou, H. Krishnaswamy, Y. Zhong and G. Zussman, "Resource Allocation and Rate Gains in Practical Full-Duplex Systems," in Proceedings of the 2015 ACM (Association for Computing Machinery) SIGMETRICS, June 2015

J. Marašević, J. Zhou, H. Krishnaswamy, Y. Zhong, and G. Zussman, “Resource allocation and rate gains in practical full-duplex systems,” IEEE/ACM Transactions on Networking, 2016.

Prior Work: Assumes Perfect SIC

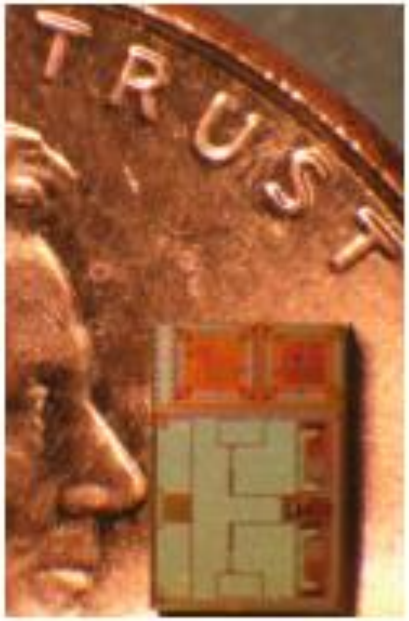
Our Work: Realistic MS Model

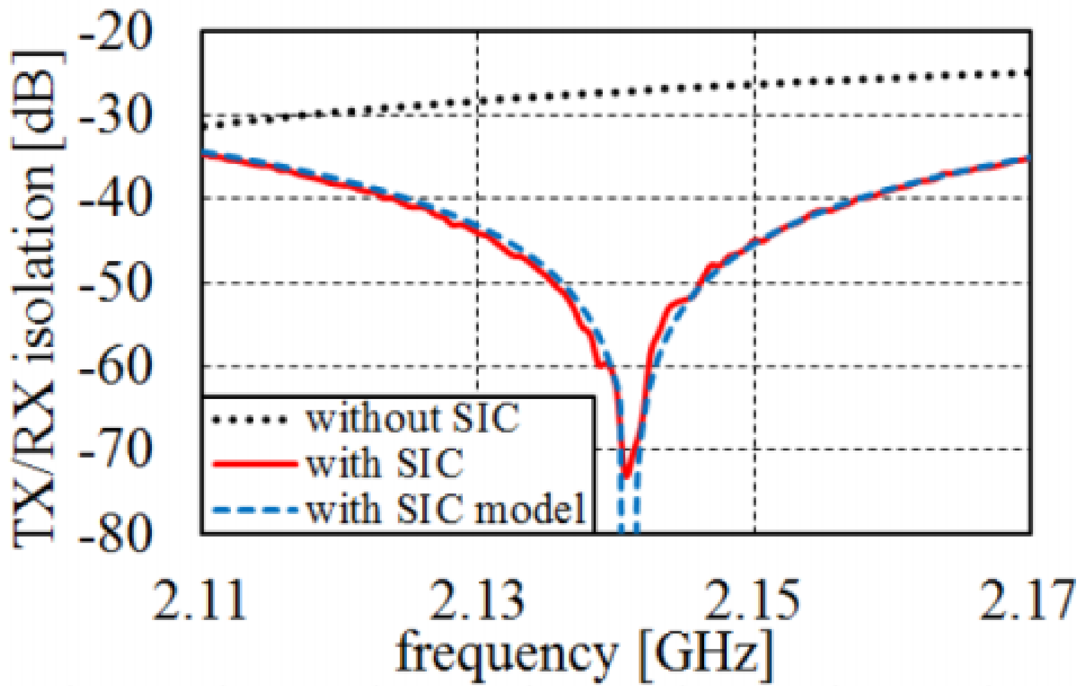


- Prior work considered in the SIGMETRICS paper is based on a mathematical model that assumes the perfect self-interference cancellation.

- The analytical study presented in the rate gain characterization is based on full-duplex networks that captures the practical frequency-dependent SIC at mobile stations (MSs) using integrated full-duplex radios.

Modeling Cancellation at Integrated MSs

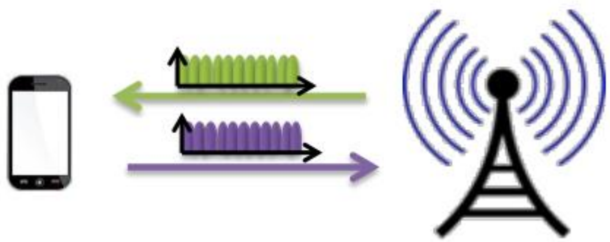




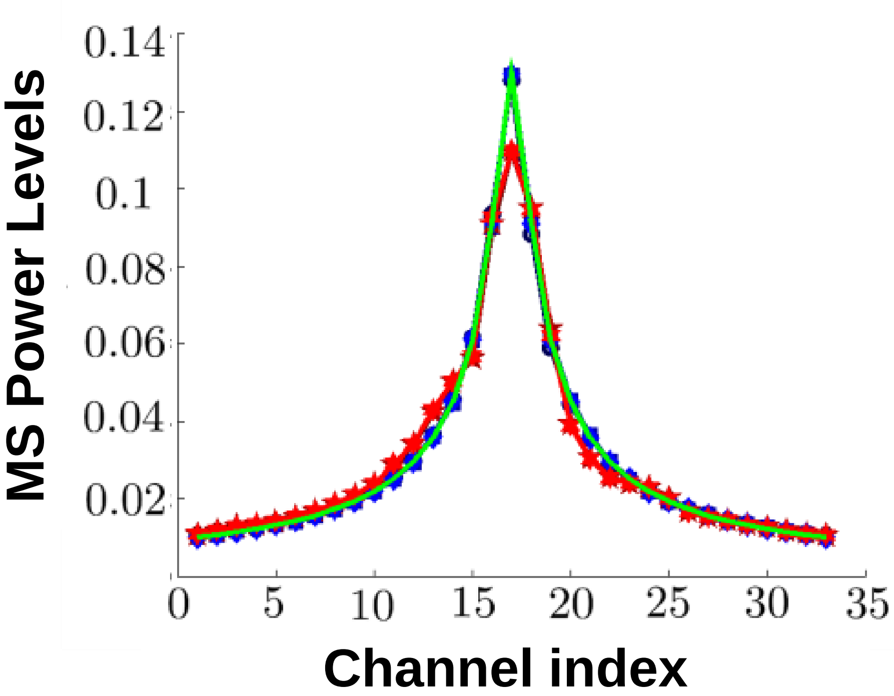
$$
\begin{aligned}
RSI_{m,k} &= 2|H_A|^2 P_{m,k} \left(1 - \cos(2\pi\tau(f_k - f_c))\right) SIC_D^{-1} \\
&= \text{const.} \cdot (f_k - f_c)^2 \cdot P_{m,k}
\end{aligned}
$$

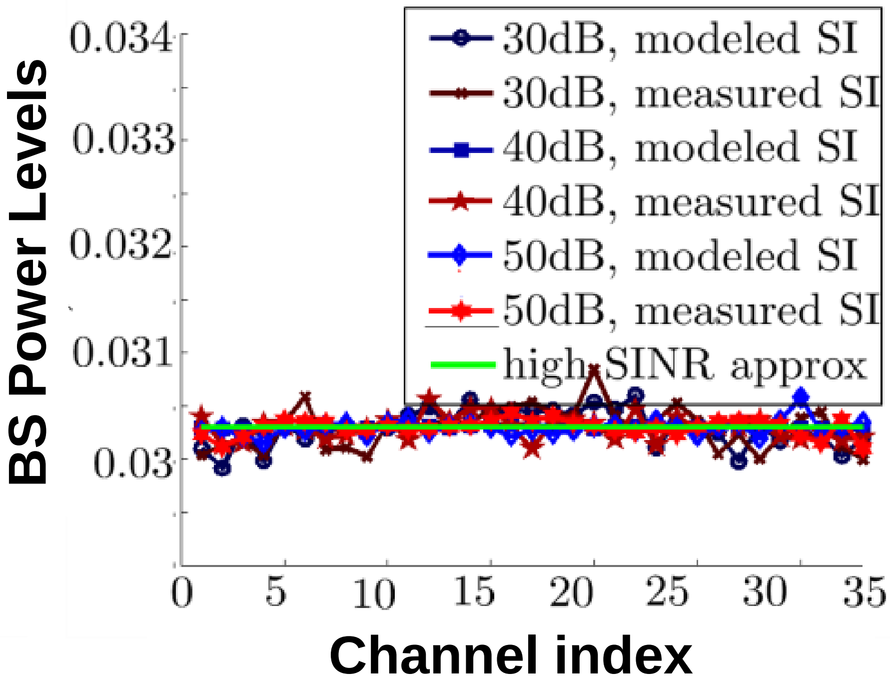
- A mathematical model is developed for the self-interference cancellation achieved by compact integrated radios with frequency-flat cancellers.

Power Allocation Under High SINR

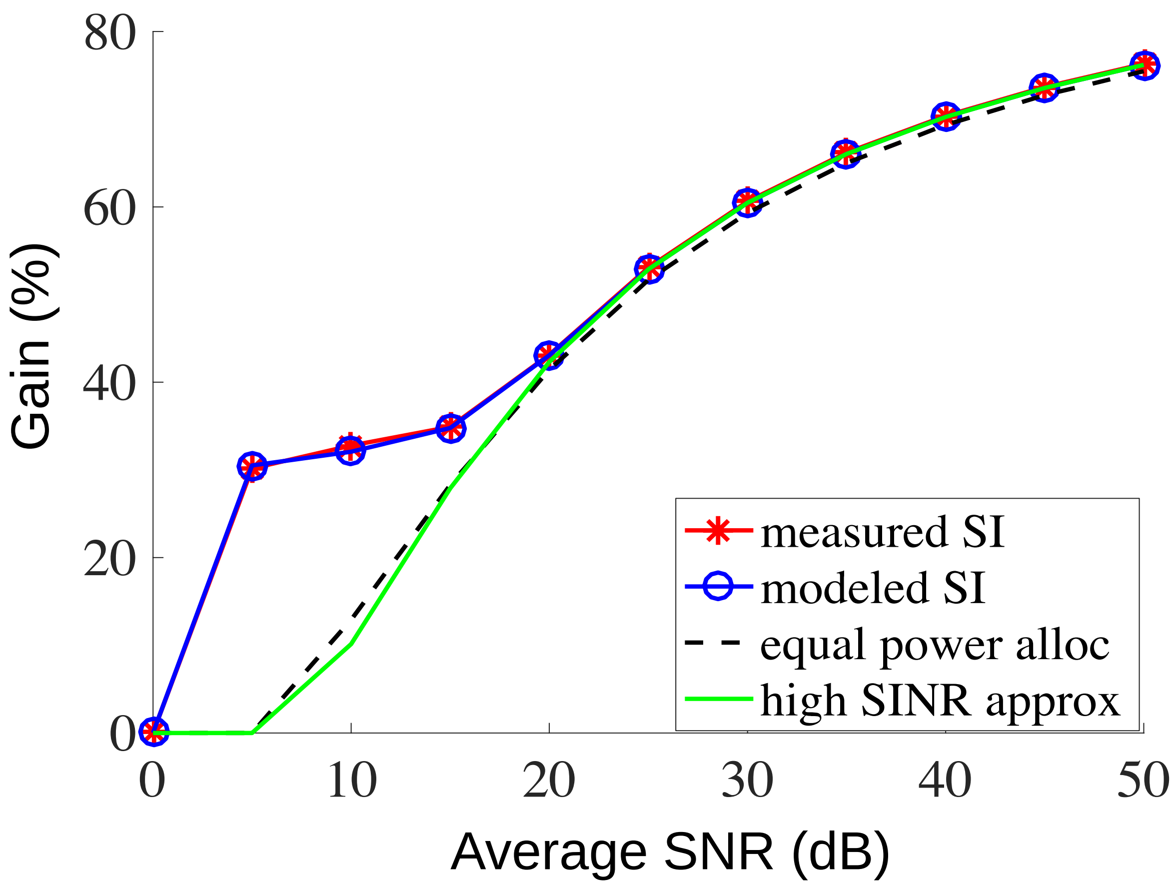


- A bidirectional link between a BS and a MS.
- 33 channels on a 20MHz bandwidth.





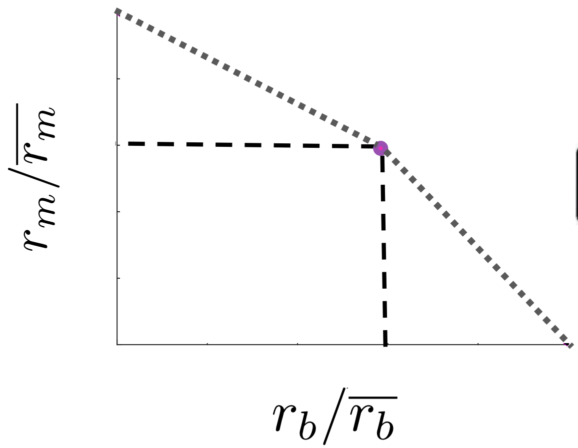
Rate Improvements

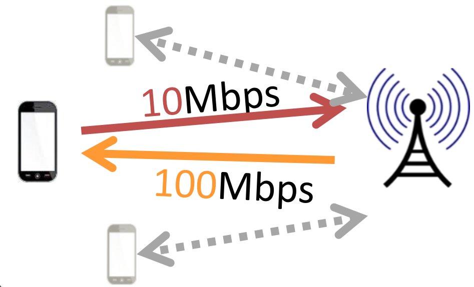


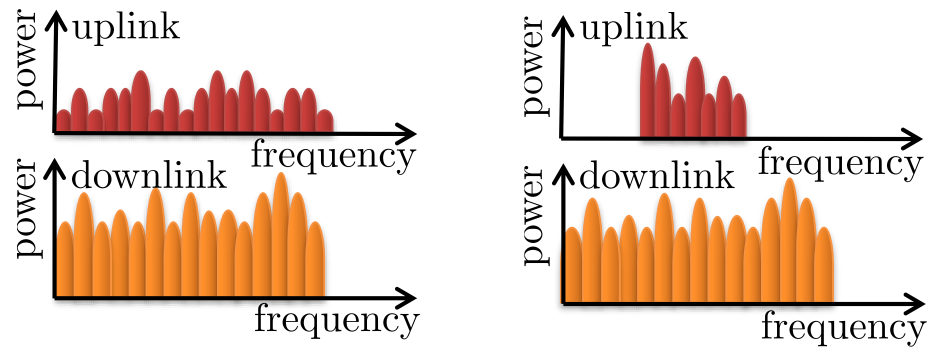
Significant – over 60% throughput gains – are achieved in the high SNR regime.

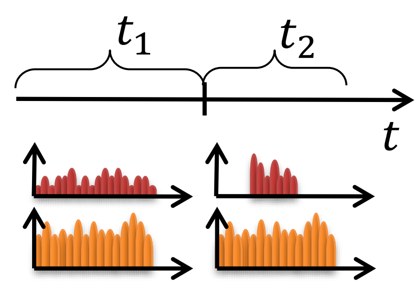
FD and TDFD Capacity Regions

- Maximization of the sum of the rates gives us only one pair of uplink and downlink rates
- But, in many cases we want to prioritize one of the rates
- Using only full-duplex and varying the power allocation will give us one set of achievable rates, which may be non-convex
- Combining FD and TDD "convexifies" the capacity region → time-division FD (TDFD) region
- Having convex capacity region is important for scheduling (and in our case gives higher rates)
- We provide many structural and algorithmic results for constructing FD and TDFD capacity regions, in different single- and multi-channel settings



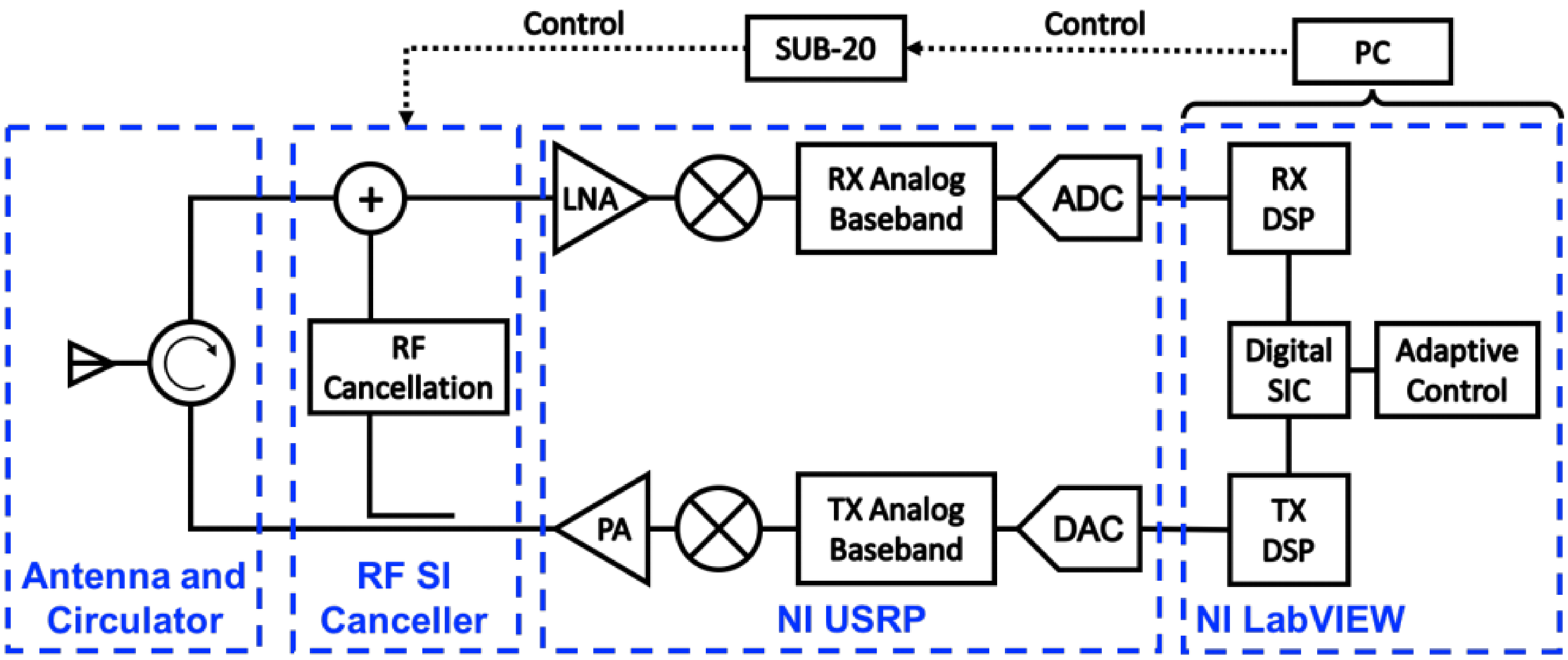






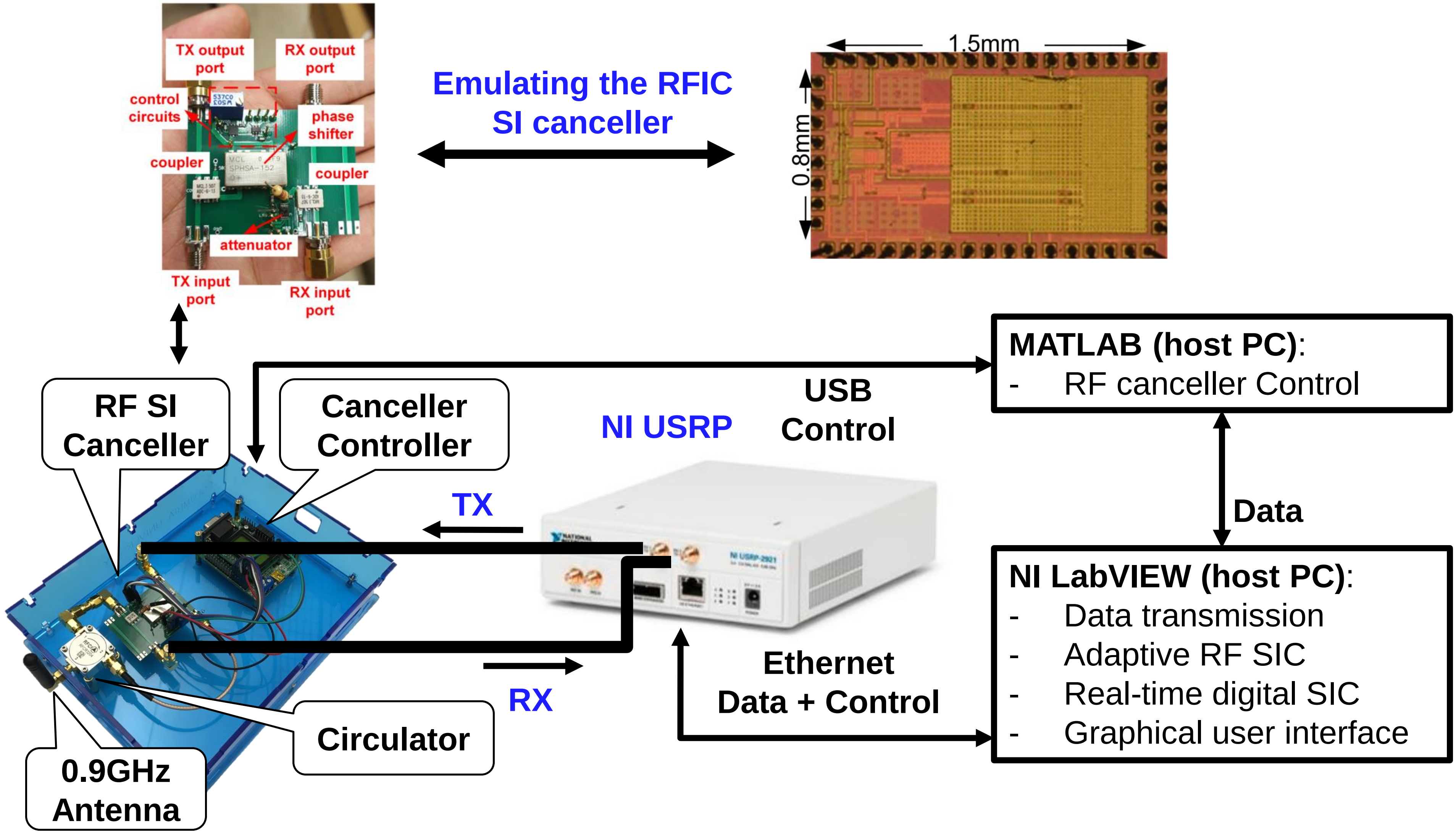
J. Marašević and G. Zussman, "On the Capacity Regions of Single-Channel and Multi-Channel Full-Duplex Links," in Proc. ACM MobiHoc'16, 2016.

Full-Duplex Testbed for Evaluation of MAC Algorithms



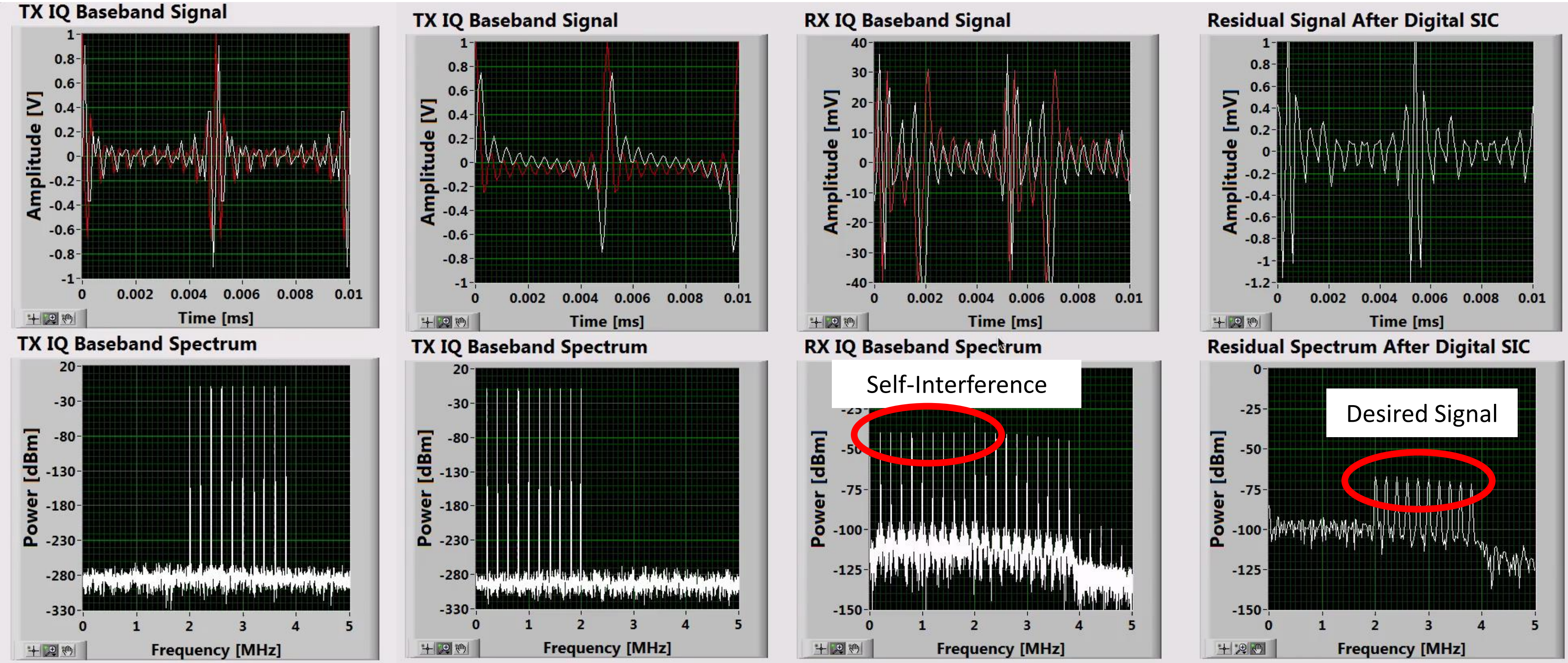
T. Chen, J. Zhou, N. Grimwood, R. Fogel, J. Marašević, H. Krishnaswamy, and G. Zussman, “Demo: Full-duplex Wireless based on a Small-Form-Factor Analog Self-Interference Canceller," in Proc. ACM MobiHoc'16, July 2016.

Software-Defined Full-Duplex Transceiver



- The full-duplex transceiver is equipped with our adaptive RF SIC algorithm and supports real-time digital SIC.

Full-Duplex Demo at ACM MobiHoc 2016



Transmitted signal at Radio 1

Transmitted signal at Radio 2

Received signal after analog SIC at Radio 2

Received signal after digital SIC at Radio 2

~90dB overall self-interference-cancellation across the antenna, RF, and digital domains.

Conclusion

- Integrated full-duplex radios with SIC at the antenna, RF, analog, and digital domains are presented at both RF and mm-wave frequencies.
- The first integrated non-reciprocal magnetic-free passive circulator based staggered commutation is introduced.
- Full-duplex power allocation and rate gains are derived based on the model of our integrated full-duplex radios
- Cross-layered full-duplex testbed with real-time SIC is demonstrated.

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