

Full-Duplex Wireless: Algorithms and Rate Improvement Bounds for Integrated Circuit Implementations

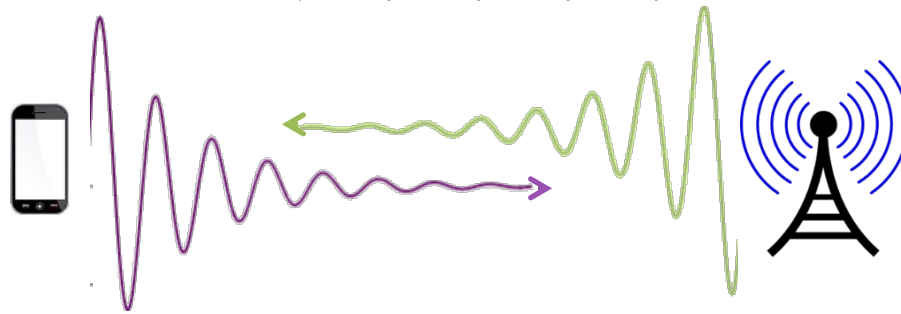
Jelena (Marašević) Diakonikolas, Tingjun Chen, Jin Zhou, Negar Reiskarimian, Harish Krishnaswamy, Gil Zussman

EE department, Columbia University

HotWireless'16, October 2016

Full-Duplex Wireless

- (Same channel) Full-duplex communication = simultaneous transmission and reception on the same frequency channel
- Viability is limited by self-interference



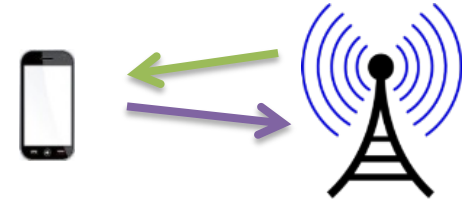
Transmitted signal is billions of times stronger than the received signal!

Legacy wireless systems separate transmission and reception in either:

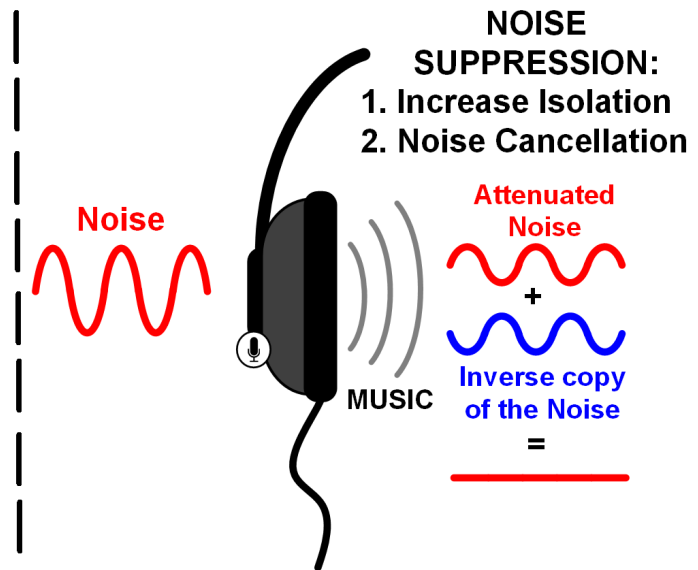
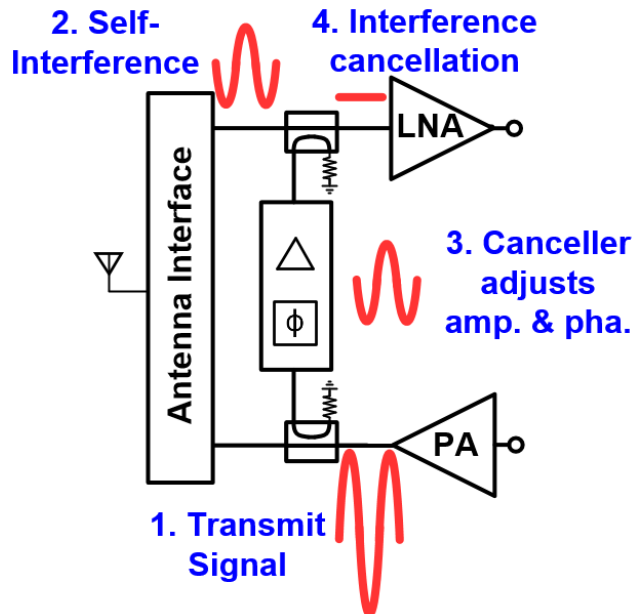
- Time – Time Division Duplex (TDD)
- Frequency – Frequency Division Duplex (FDD)

Full-Duplex Wireless

- Benefits of full-duplex:
 - Increased system throughput
 - More flexible use of the wireless spectrum

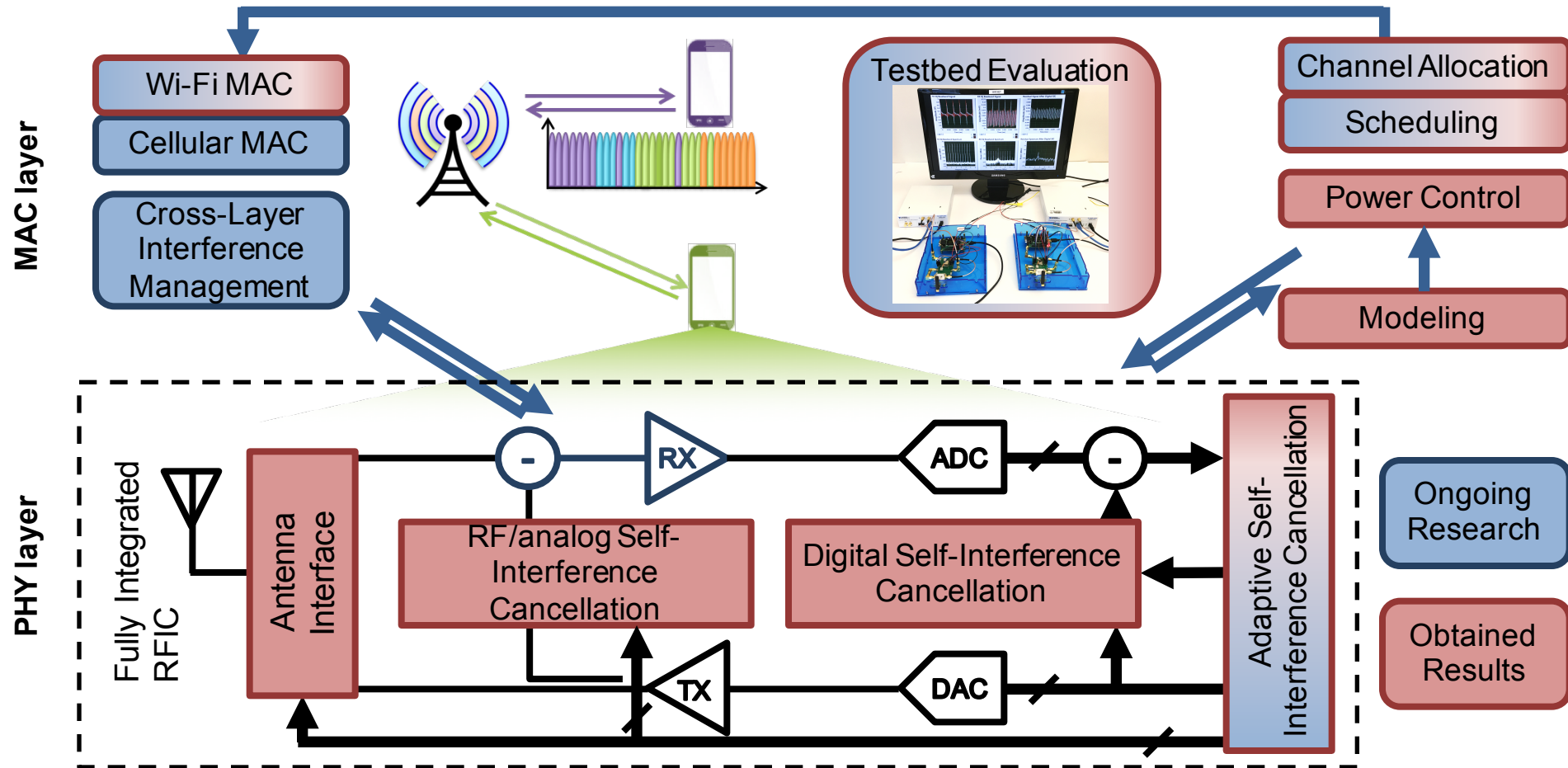


Self-Interference Cancellation (SIC):



FlexiCoN

Full Duplex wireless – from Integrated Circuits to Networks



Related Work

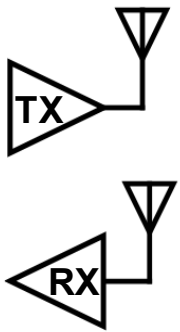
- System design and Wi-Fi heuristics:
[Choi et al. 2010], [Duarte and Sabharwal 2010], [Jain et al. 2011],
[Singh et al. 2011], [Aryafar et al. 2012], [Bharadia et al. 2013],
[Zhou et al. 2013], [Bharadia and Katti 2014], [Duarte et al. 2014]
- Integrated (small form-factor) receiver design
[Zhou et al. 2014], [Zhou et al. 2015], [van den Broek et al. 2015]
- Cellular scheduling heuristics:
[Goyal et al. 2013], [Goyal et al. 2014]
- Throughput gains from full-duplex:
[Sahai et al. 2013], [Xie and Zhang 2014], [Li et al. 2014],
[Nguyen et al. 2014], [Korpi et al. 2015]

Outline

- Antenna Interface: Integrated Circulator
- RF/Analog Cancellation
- Algorithms and Rate Improvement Bounds
 - Sum Rate Maximization
 - Capacity Regions
- Full-Duplex Testbed

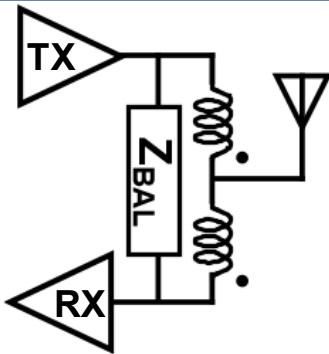
FD Antenna Interfaces

Antenna Pair



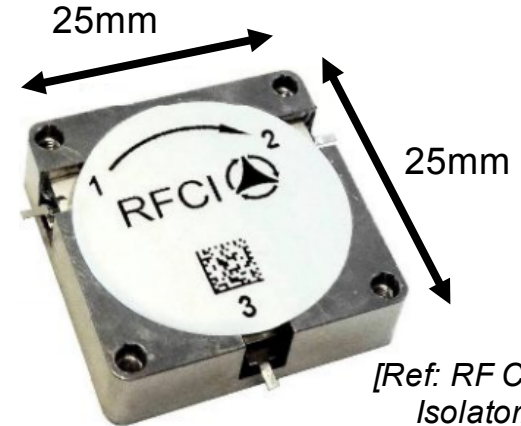
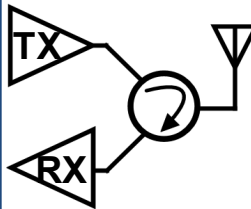
✗ Form factor

Balanced Duplexer



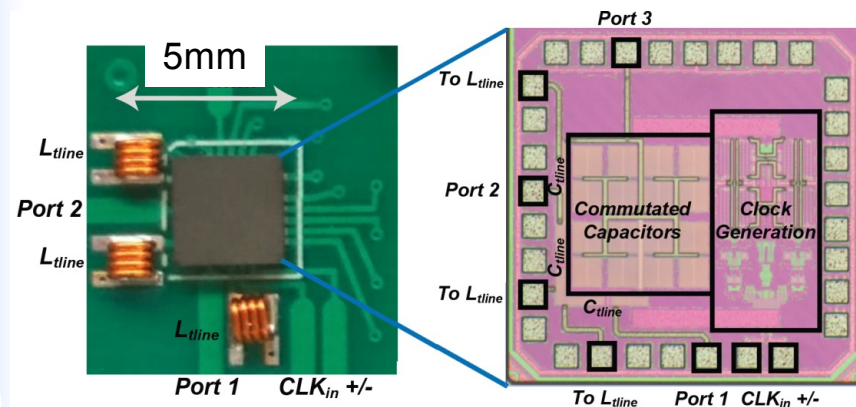
✗ Insertion loss

Circulator



[Ref: RF Circulator Isolator, Inc.]

Ferrite-based circulator



First passive non-magnetic CMOS circulator

Concept and Measured Results

$3\lambda/4$ Transmission line

-270° Phase shift

Reciprocal
Phase Shift

$3\lambda/4$

LONA

LONB

LO2A

LO2B

LO1A

LO1B

LO Phase
Shifter

Non-reciprocal
Phase Shift

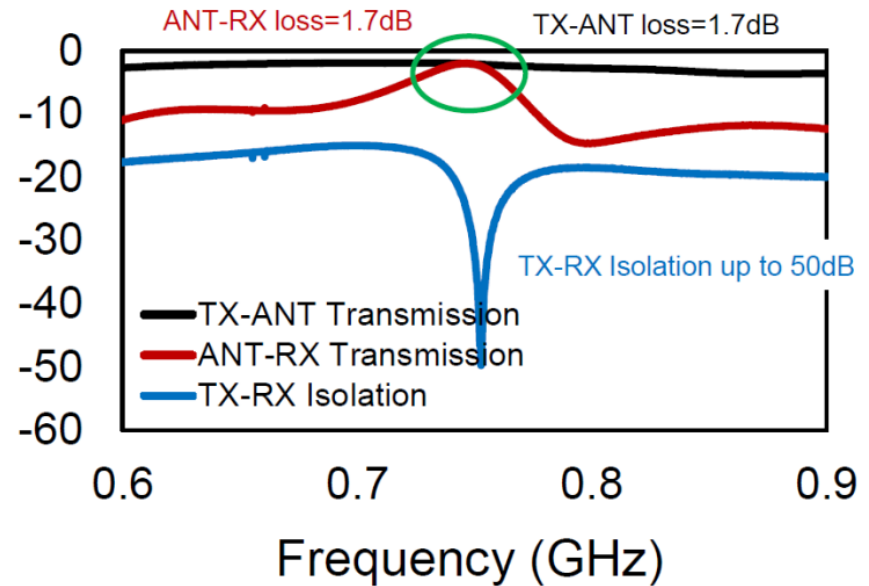
Constructive
Interference

Destructive
Interference

$-270^\circ - 90^\circ = -360^\circ$

$-270^\circ + 90^\circ = -180^\circ$

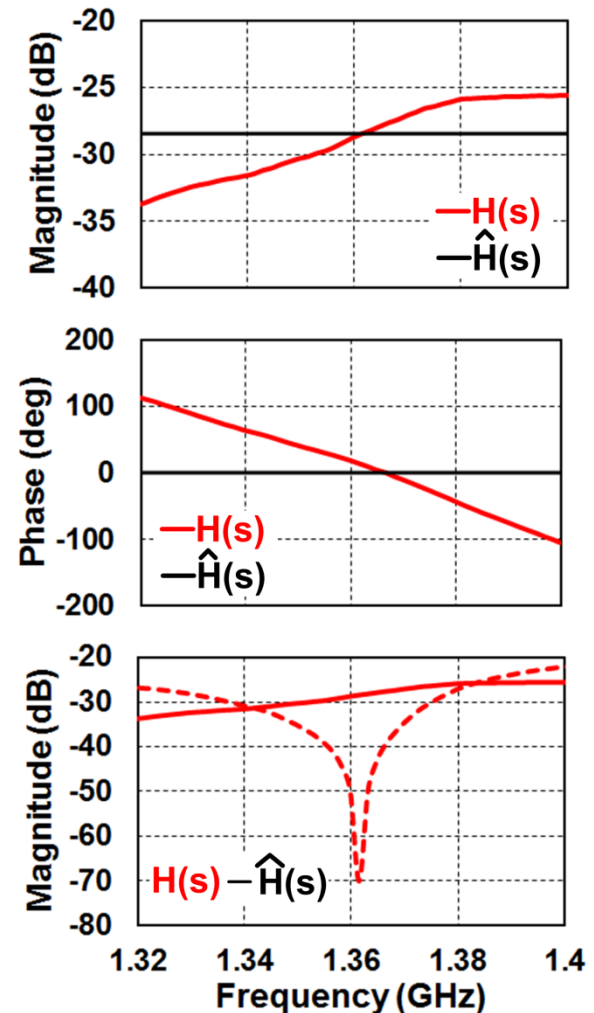
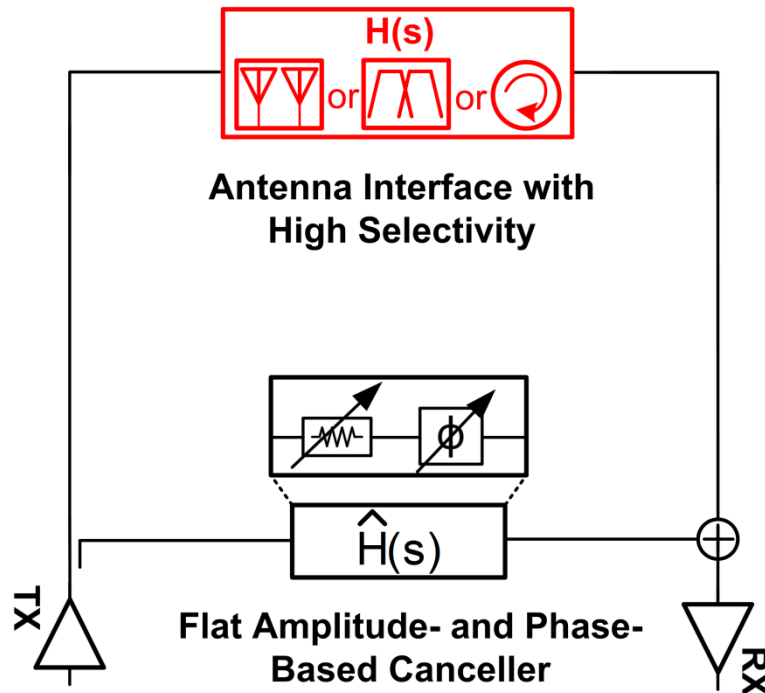
S Parameter (dB)



Outline

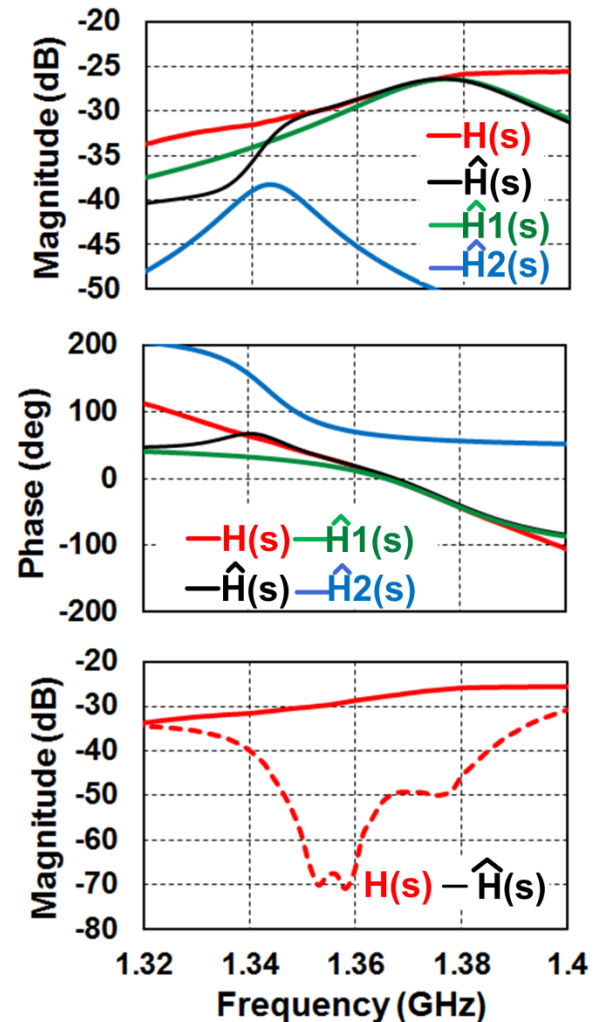
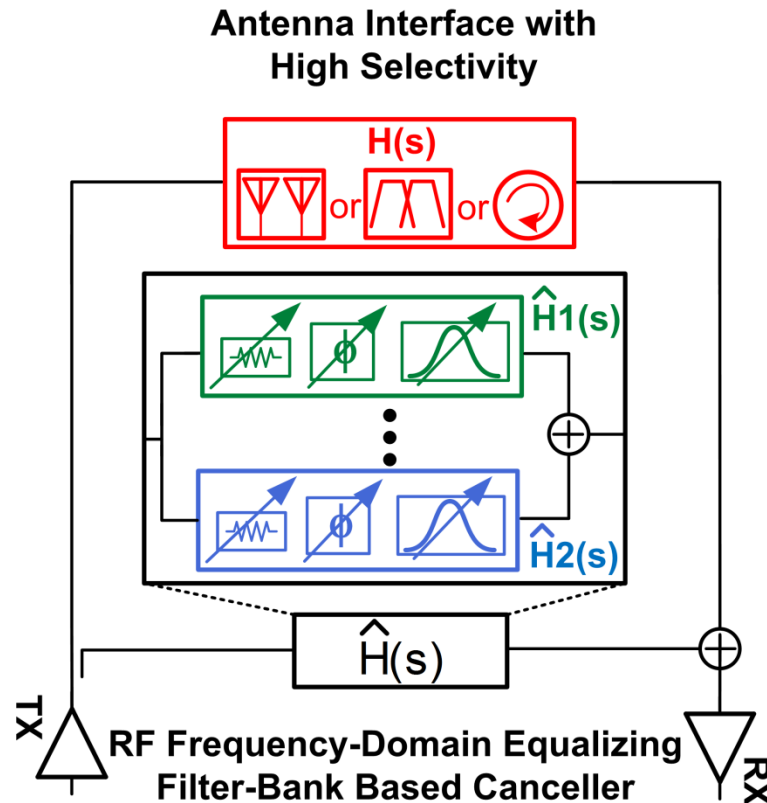
- Antenna Interface: Integrated Circulator
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Conventional Integrated RF SI Canceller



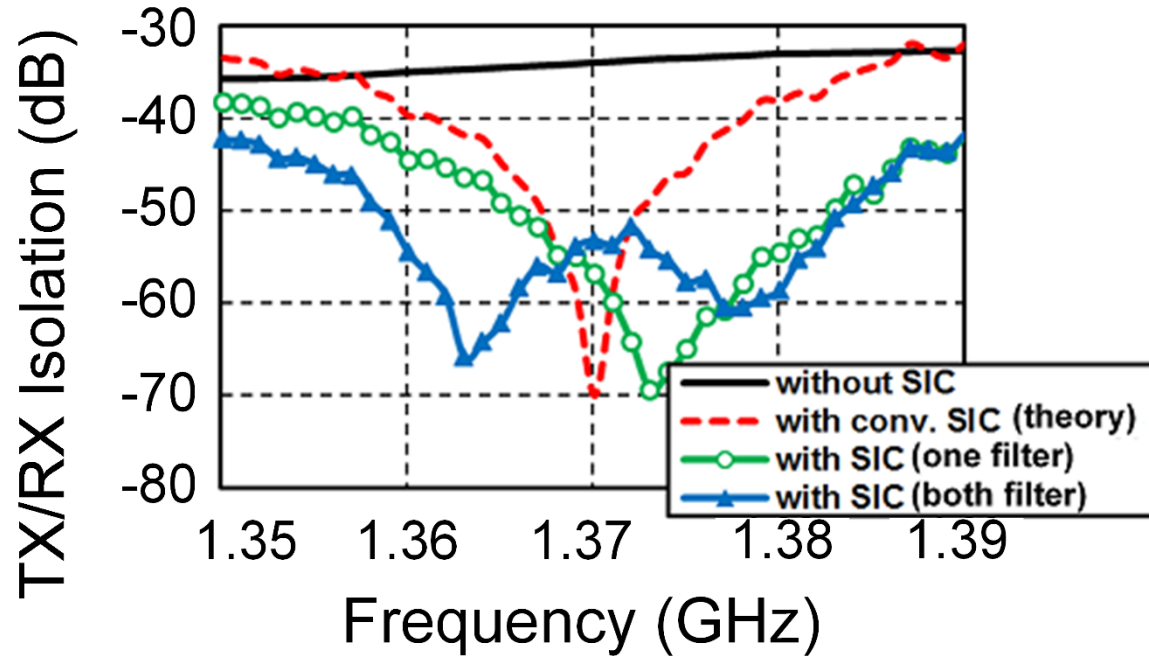
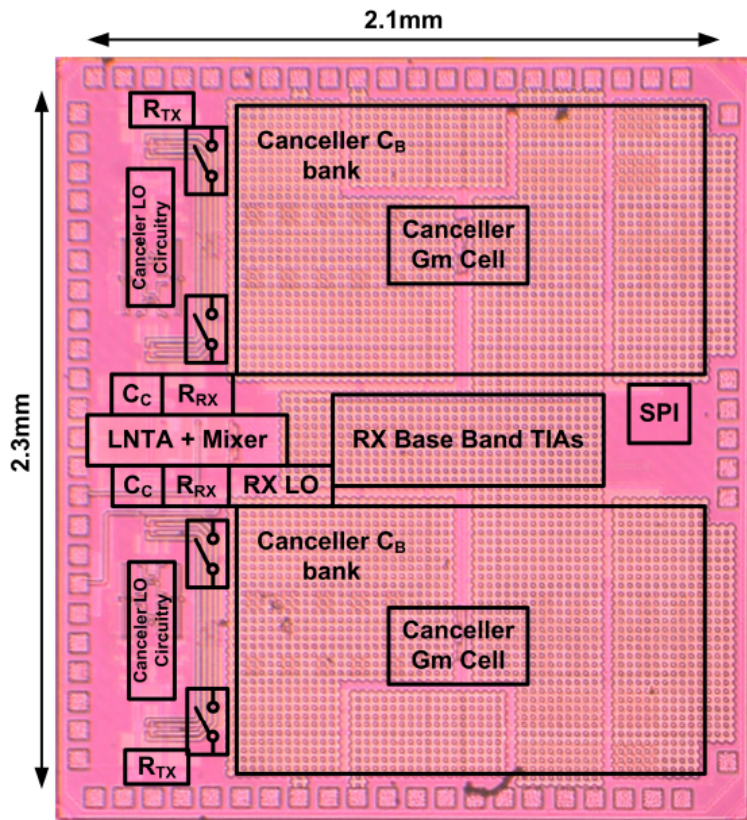
- An integrated frequency-flat canceller can emulate an antenna interface only at one frequency, resulting in narrow cancellation bandwidths.

Frequency Domain Equalization at RF



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

65nm CMOS Implementation and Results

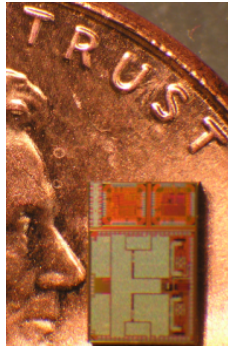


Proposed integrated canceller has a ~10X wider cancellation bandwidths compared to a conventional one.

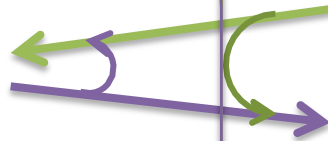
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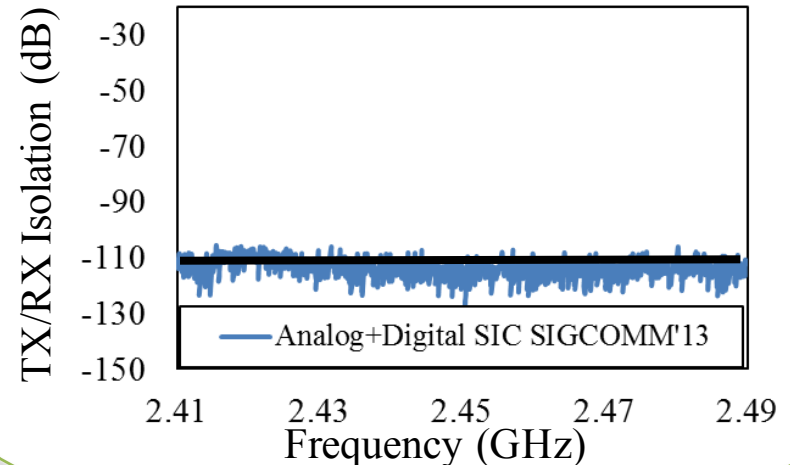
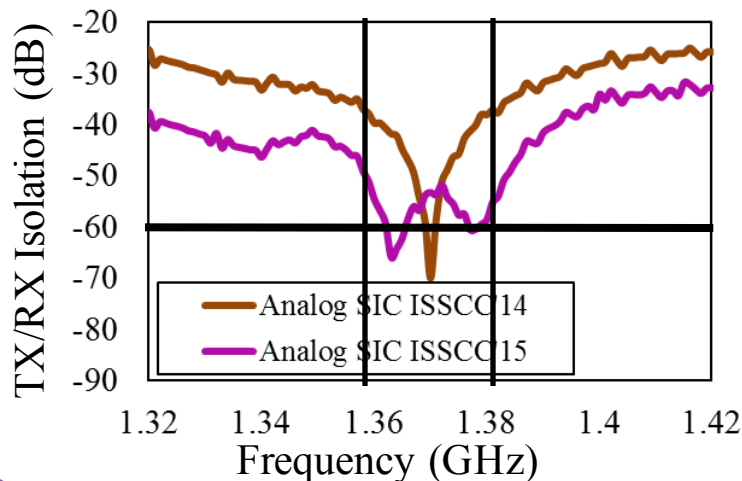
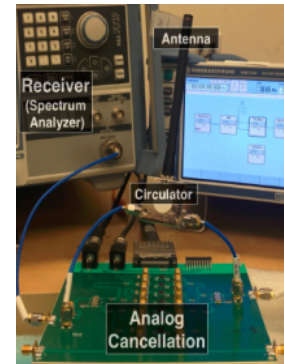
Imperfect Self-Interference Cancellation



Columbia



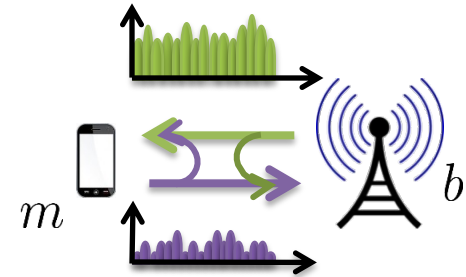
Stanford



- Jin Zhou, Peter R. Kinget and Harish Krishnaswamy, “A Blocker-Resilient Wideband Receiver with Low-Noise Active Two-Point Cancellation of >0 dBm TX Leakage and TX Noise in RX Band for FDD/Co-Existence,” in 2014 *IEEE International Solid-State Circuits Conference Digest of Technical Papers*, pp. 352 – 353, Feb. 2014.
- Jin Zhou, Tsung-Hao Chuang, Tolga Dinc and Harish Krishnaswamy, “Reconfigurable receiver with $>>20$ MHz bandwidth self-interference cancellation suitable for FDD, co-existence and full-duplex applications,” In Proc. *IEEE ISSCC’15*, 2015.
- D. Bharadia, E. McMillin, and S. Katti. “Full duplex radios.” In Proc. *ACM SIGCOMM’13*, 2013.

Model

- k : channel index; K : # of channels
- Self-interference on channel k : constant fraction of the transmission power on channel k ($h_{bb,k}, h_{mm,k}$)
- Variables: transmission power levels $P_{m,k}$ and $P_{b,k}$
- Constraints: $\sum_{k=1}^K P_{b,k} \leq \overline{P}_b \quad \sum_{k=1}^K P_{m,k} \leq \overline{P}_m$
- Remaining notation:
 - Noise: $N_{m,k}, N_{b,k}$
 - Wireless channel gain: $h_{mb,k}, h_{bm,k}$



Shannon capacity formula: $r = \log \left(1 + \frac{\text{received signal}}{\text{noise} + \text{interference}} \right)$

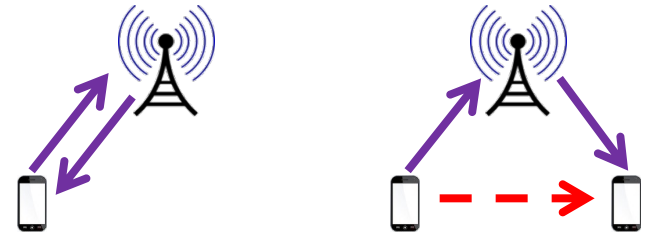
$$r_m = \underbrace{\sum_{k=1}^K \log \left(1 + \frac{P_{m,k} h_{mb,k}}{N_{b,k} + P_{b,k} h_{bb,k}} \right)}_{\text{UL Rate}}$$

$$r_b = \underbrace{\sum_{k=1}^K \log \left(1 + \frac{P_{b,k} h_{bm,k}}{N_{m,k} + P_{m,k} h_{mm,k}} \right)}_{\text{DL Rate}}$$

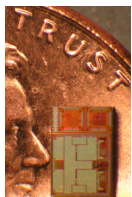
Sum Rate Maximization: Power Control and Throughput Gains

Results for Single Channel:

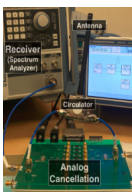
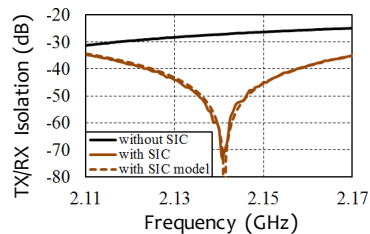
- Always optimal to Tx at maximum power level;
- Characterization of achievable throughput gain;
- Condition for bi-concavity of the sum UL/DL rate in power levels **independent of the circuit model**



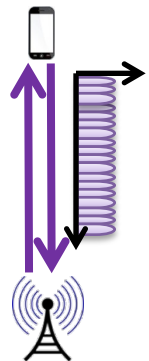
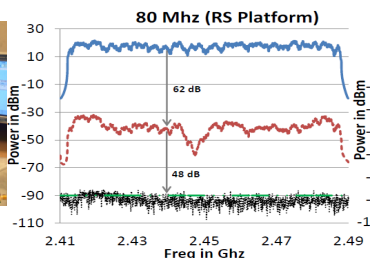
Results for OFDM Channels:



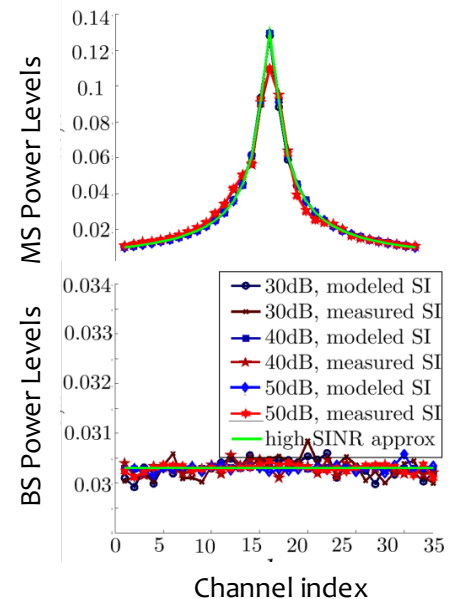
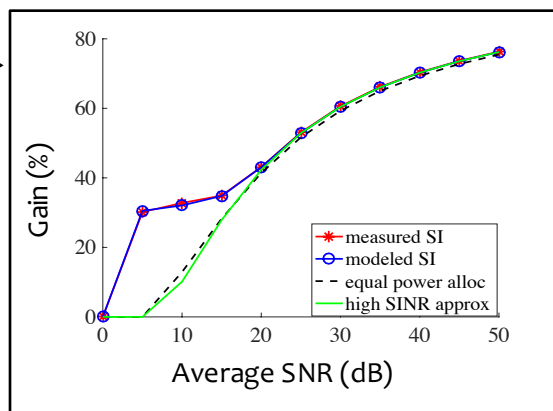
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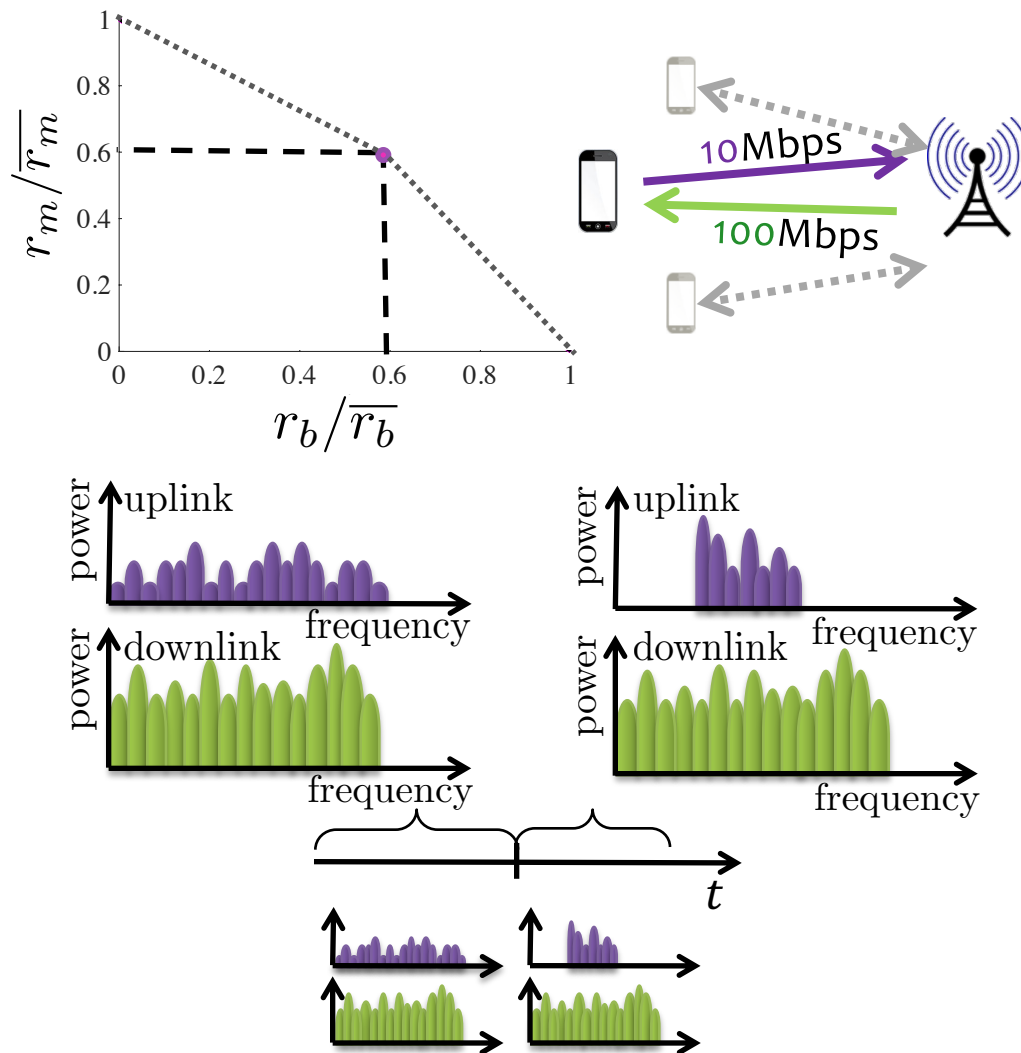


Achievable throughput gain



FD and TDFD Capacity Region

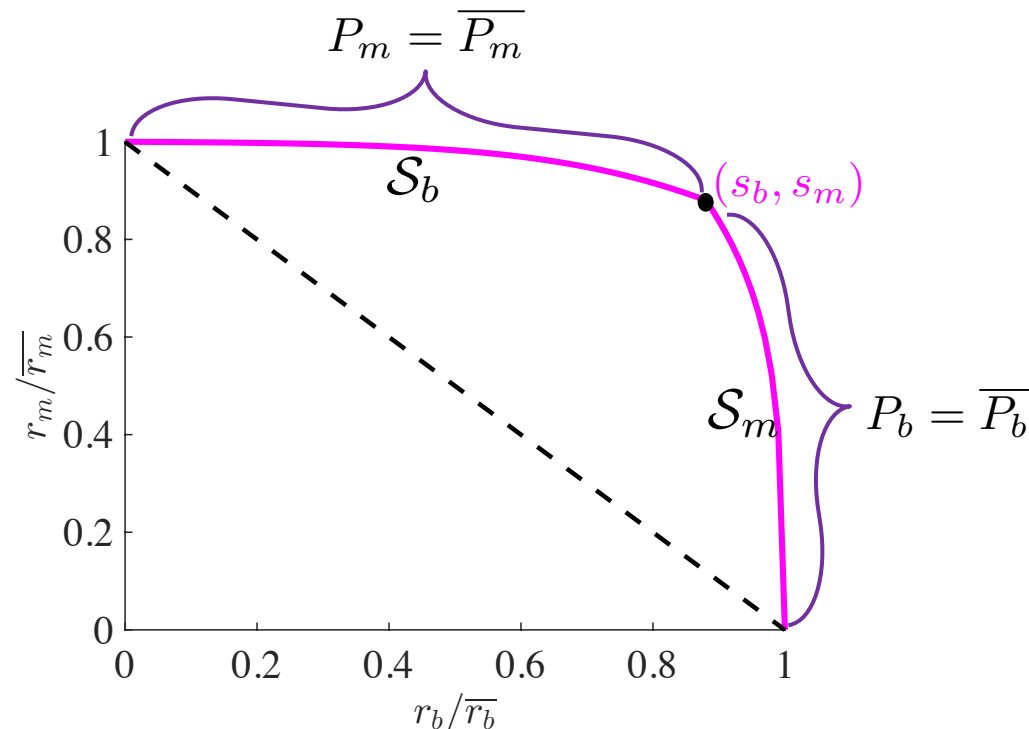
- Maximization of the sum of the rates gives us only one pair of uplink and downlink rates
- But, in many cases we want to prioritize one of the rates
- Using only full-duplex and varying the power allocation will give us one set of achievable rates, which may be non-convex
- Combining FD and TDD “convexifies” the capacity region → time division FD (TDFD)
- Having convex capacity region is important for scheduling (and in our case gives higher rates)



Single Channel: Structural Results

- FD Capacity Region:

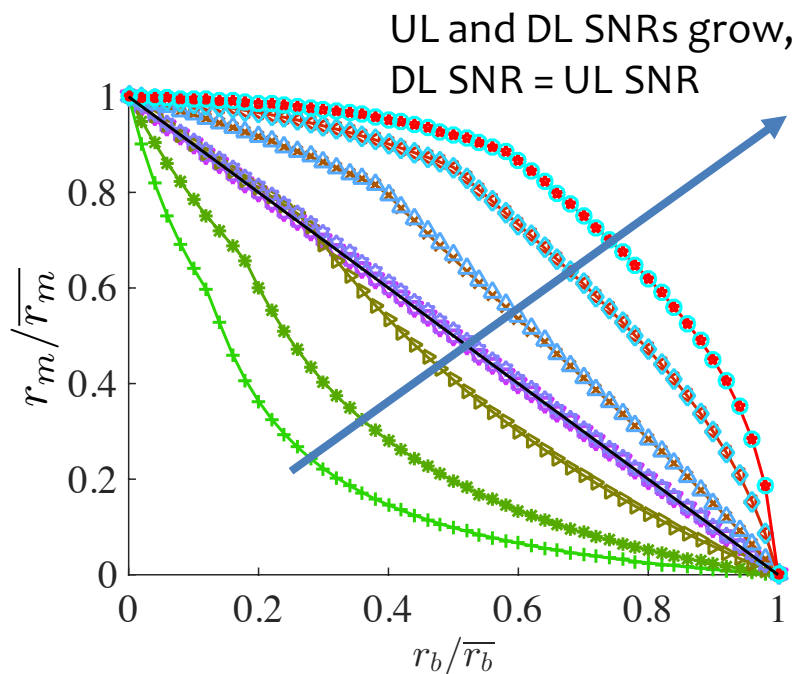
Proposition. At the boundary of the capacity region either the uplink or downlink power must be equal to its maximum value.



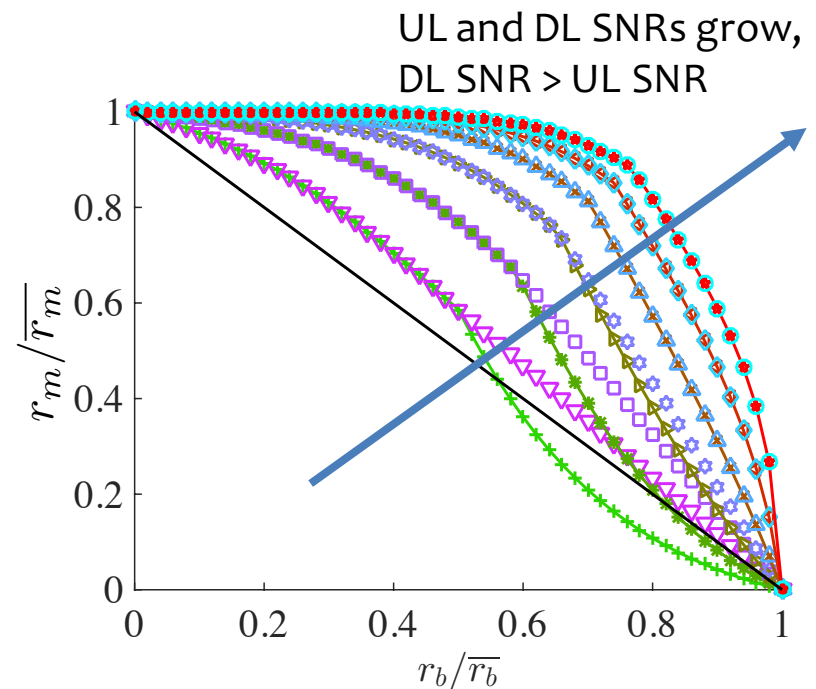
Single Channel: FD and TDFD Capacity Regions

Proposition. Any point on the TDFD capacity region can be determined either in a closed form, or through a simple bisection.

Symmetric UL/DL SNR



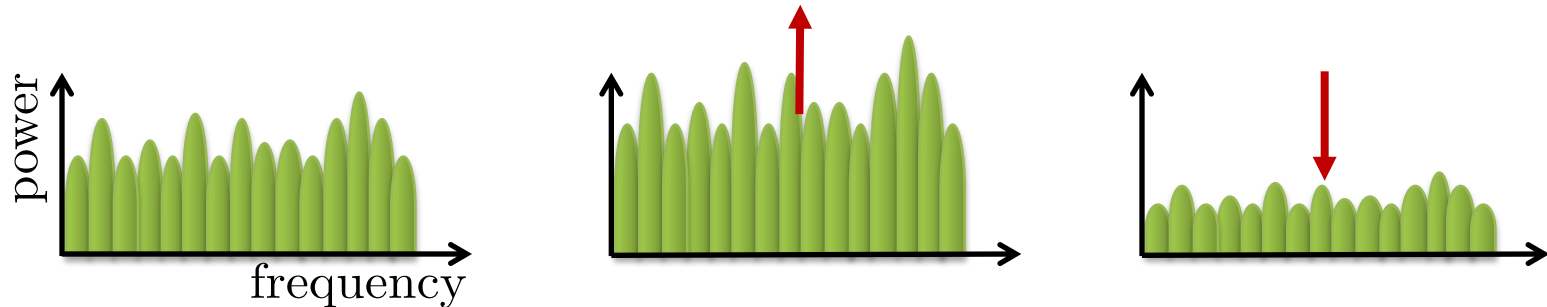
Asymmetric UL/DL SNR



$$\overline{\gamma_{bb}} = 1, \overline{\gamma_{mm}} = 10$$

Fixed Power Allocation

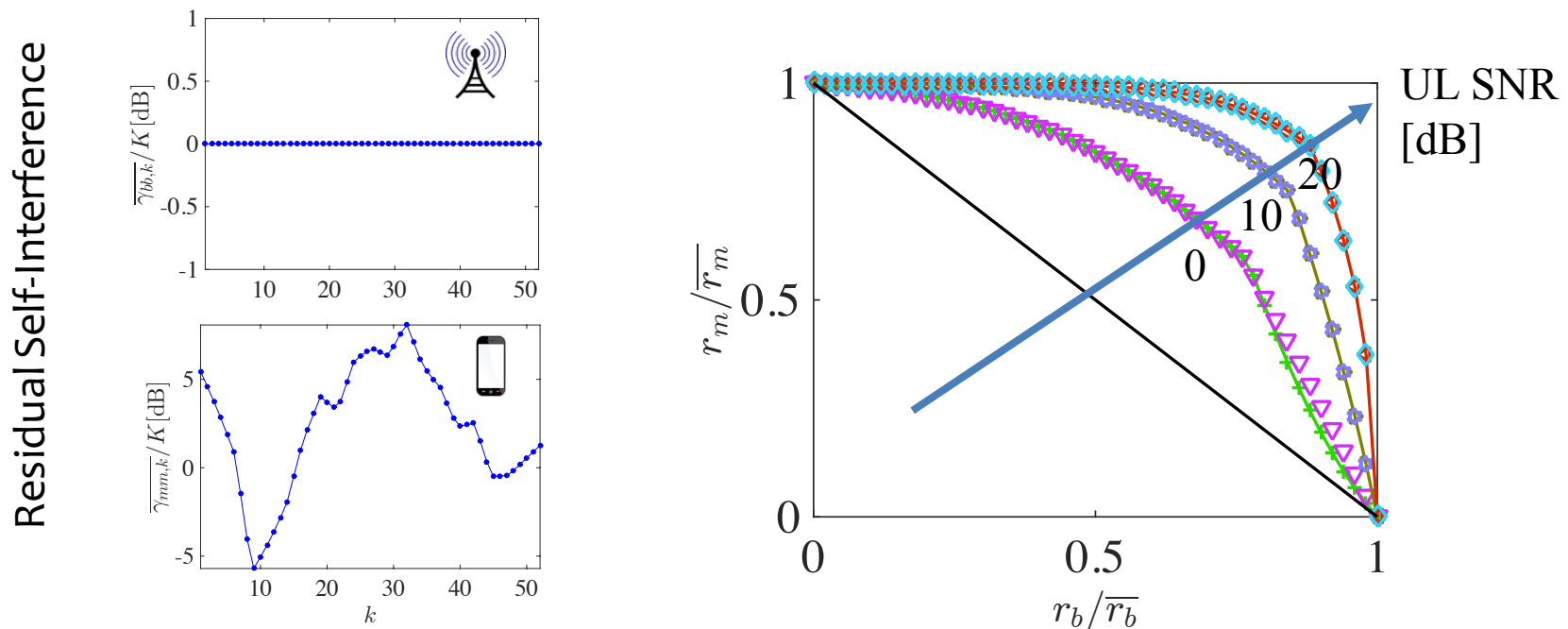
- The shape of the power allocation is fixed, but the sum TX power over channels can be varied



Lemma: At the boundary of the capacity region, either uplink or downlink sum of the power levels must be equal to its maximum value

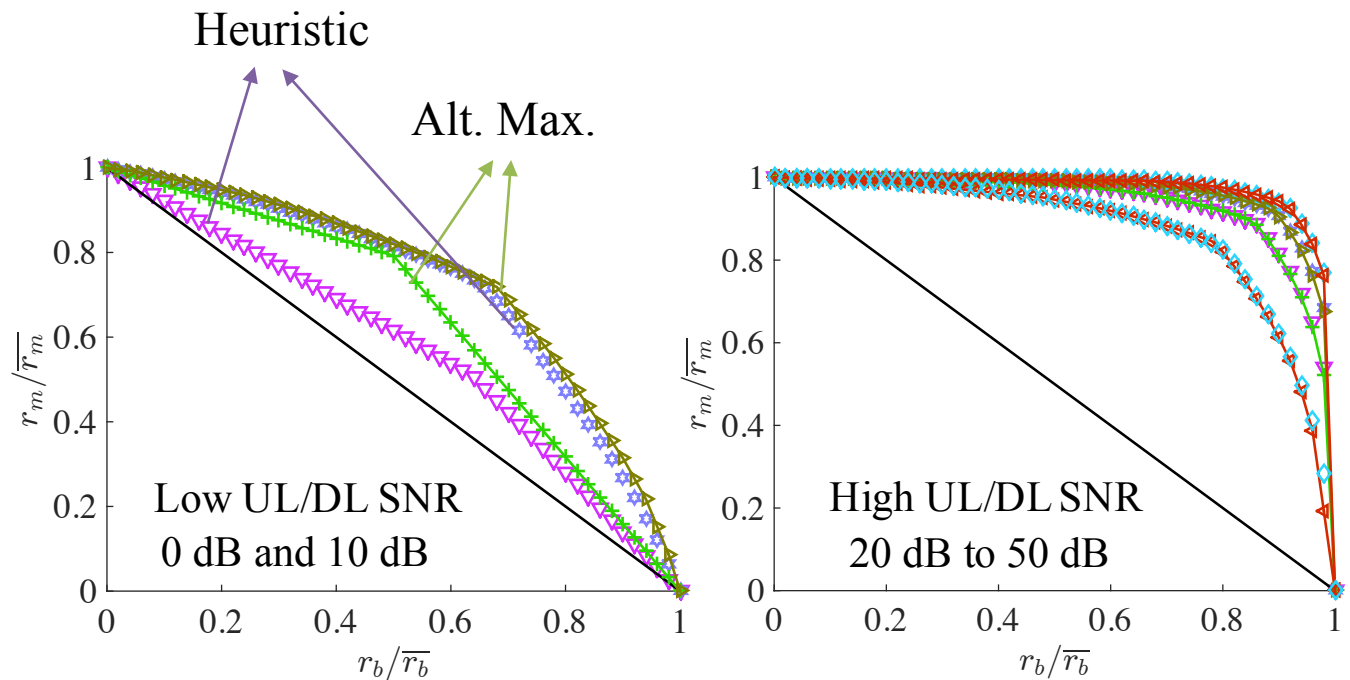
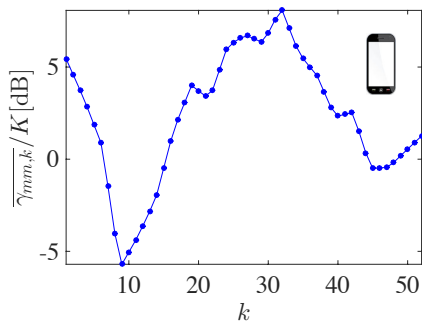
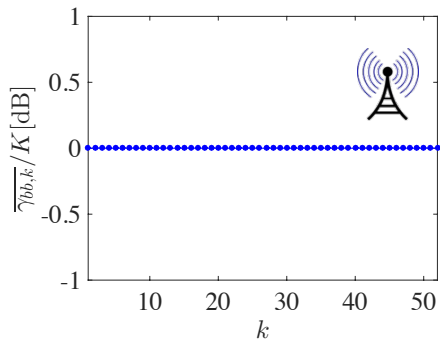
Fixed Power Allocation (cont.)

- Do not have the same structural properties for the shape of the FD capacity region as in the single channel case
- However, the convex hull (TDFD capacity region) can still be determined in reasonable time



$$(\text{avg DL SNR}) - (\text{avg UL SNR}) = 20\text{dB}$$

General Power Allocation



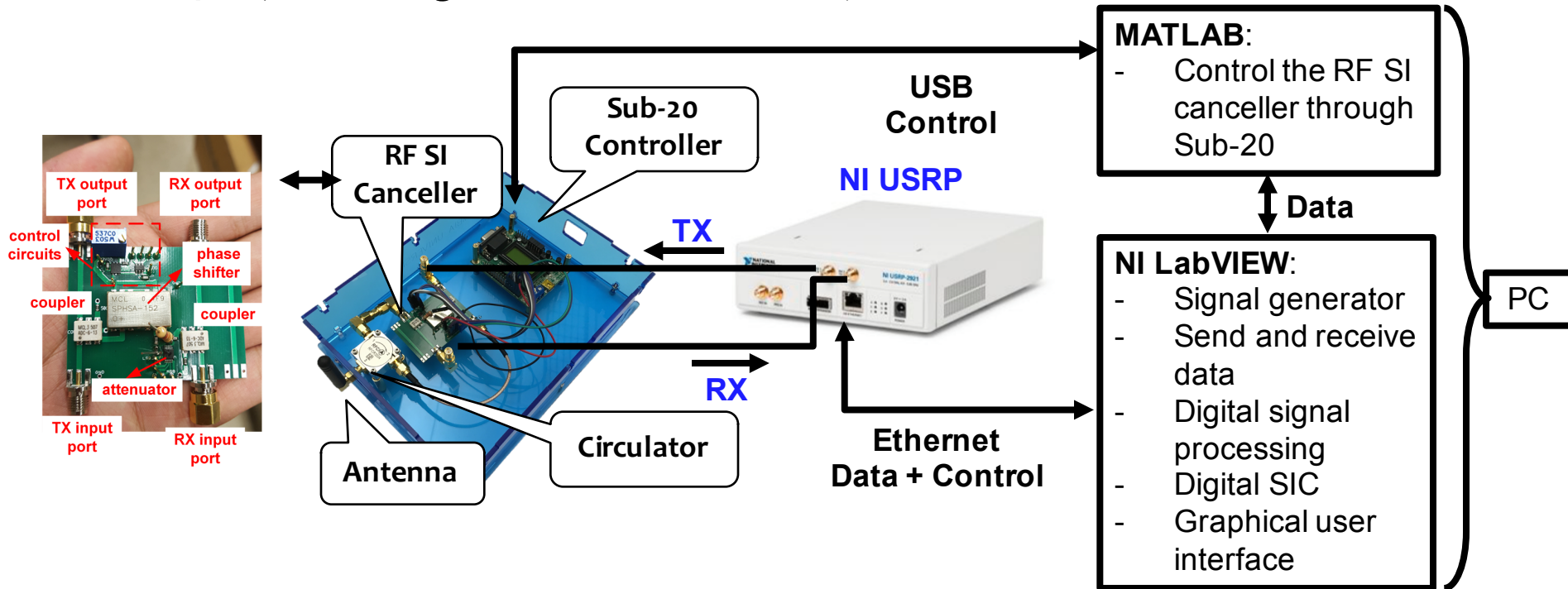
$$\text{avg DL SNR} = \text{avg UL SNR}$$

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Full-Duplex Testbed Based on USRP

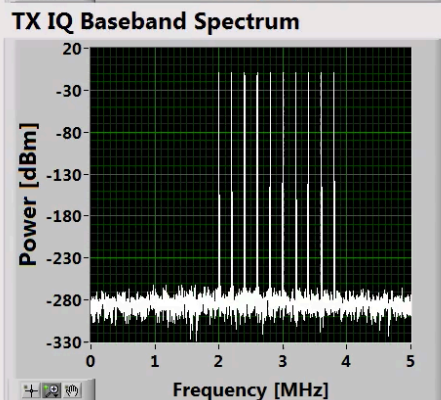
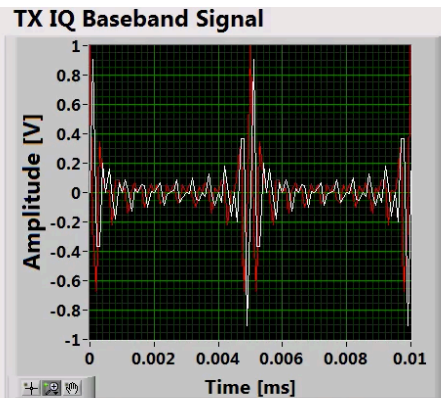
Prototype (emulating the RFIC SI canceller):



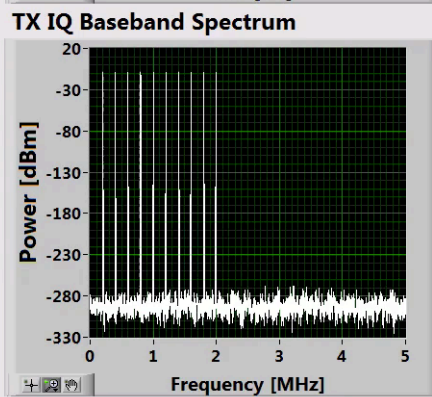
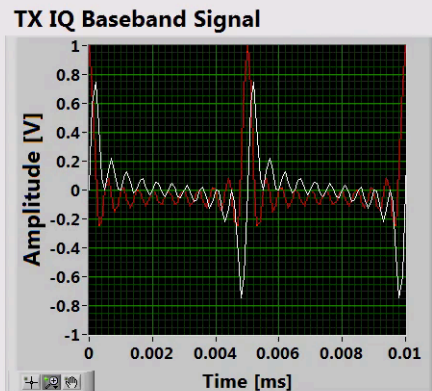
FD link:



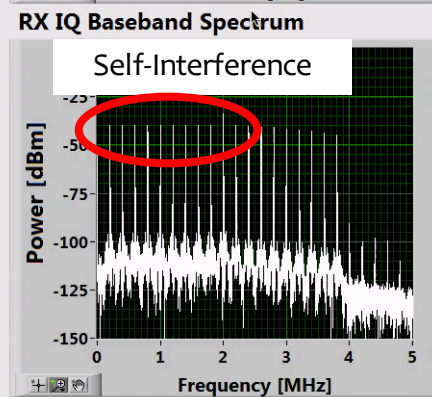
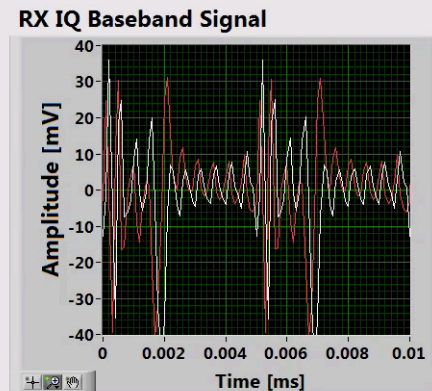
Full-Duplex Demo Video



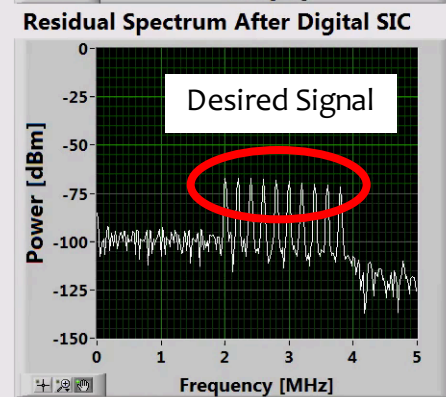
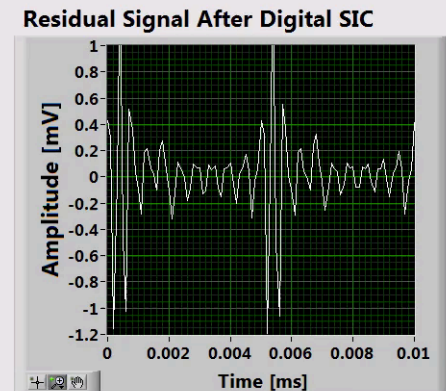
Transmitted signal
at Radio 1



Transmitted signal at
Radio 2



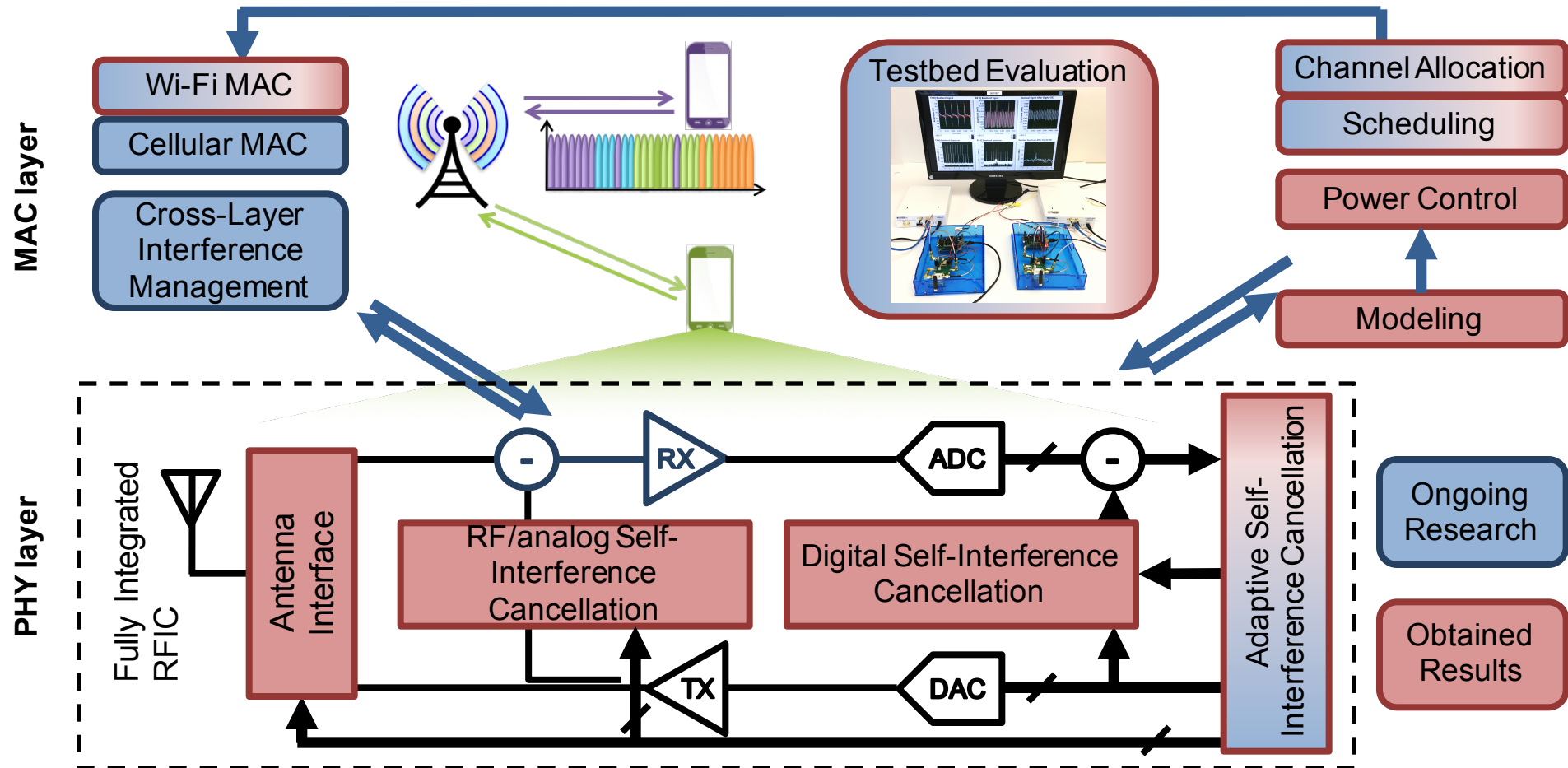
Received signal after
analog SIC at Radio 2



Received signal after
digital SIC at Radio 2

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

Back to the Big Picture



flexicon.ee.columbia.edu

References

1. Jelena Marašević and Gil Zussman, “On the Capacity Regions of Single-Channel and Multi-Channel Full-Duplex Links”, under submission to IEEE/ACM Transactions on Networking.
2. Jin Zhou, Negar Reiskarimian, Jelena Marašević, Tolga Dinc, Tingjun Chen, Gil Zussman, Harish Krishnaswamy, “Integrated Full Duplex Radios,” **invited** and submitted to IEEE Communications Magazine.
3. Negar Reiskarimian, Jin Zhou, Harish Krishnaswamy, “A CMOS Passive LPTV Non-Magnetic Circulator and Its Application in a Full-Duplex Receiver”, submitted to the IEEE Journal of Solid-State Circuits.
4. Jelena Marašević, Tingjun Chen, Jin Zhou, Negar Reiskarimian, Harish Krishnaswamy, and Gil Zussman, “Full-Duplex Wireless: Algorithms, Rate Improvement Bounds, and Integrated Circuit Implementations” **invited** and to appear in the 3rd ACM Workshop on Hot Topics in Wireless (ACM HotWireless 2016).
5. Harish Krishnaswamy, Gil Zussman, Jin Zhou, Jelena Marašević, Tolga Dinc, Negar Reiskarimian, and Tingjun Chen, “Full-Duplex in a Hand-held Device - From Fundamental Physics to Complex Integrated Circuits, Systems and Networks: An Overview of the Columbia FlexICoN project,” **invited** and to appear in the 2016 Asilomar Conference on Signals, Systems, and Computers, November 2016.
6. Jelena Marašević, Jin Zhou, Harish Krishnaswamy, Yuan Zhong, and Gil Zussman, “Resource allocation and rate gains in practical full-duplex systems,” accepted and to appear in IEEE/ACM Transactions on Networking, 2016.
7. Jelena Marašević, “Resource Allocation in Wireless Networks: Theory and Applications”, Ph.D. thesis, Columbia University, 2016
8. Harish Krishnaswamy and Gil Zussman, “1 Chip 2x Bandwidth,” IEEE Spectrum, July 2016.
9. Jelena Marašević and Gil Zussman, “On the Capacity Regions of Single-Channel and Multi-Channel Full-Duplex Links”, in Proc. ACM MobiHoc'16, July 2016.
10. Tingjun Chen, Jin Zhou, Nicole Grimwood, Rel Fogel, Jelena Marašević, Harish Krishnaswamy, and Gil Zussman, “Demo: Full-duplex Wireless based on a Small-Form-Factor Analog Self-Interference Canceller,” in Proc. ACM MobiHoc'16, July 2016.
11. Jin Zhou, Negar Reiskarimian, and Harish Krishnaswamy, “Receiver with integrated magnetic-free N-path-filter-based non-reciprocal circulator and baseband self-interference cancellation for full-duplex wireless,” in Proc. IEEE International Solid-State Circuits Conference (ISSCC'16), February 2016.
12. Jin Zhou*, Jelena Marašević *, Gil Zussman, and Harish Krishnaswamy, “Co-design of Full-duplex RFIC and Resource Allocation Algorithms,” in IEEE Power Amplifier Symposium, September 2015. (* both authors contributed equally to this work.)