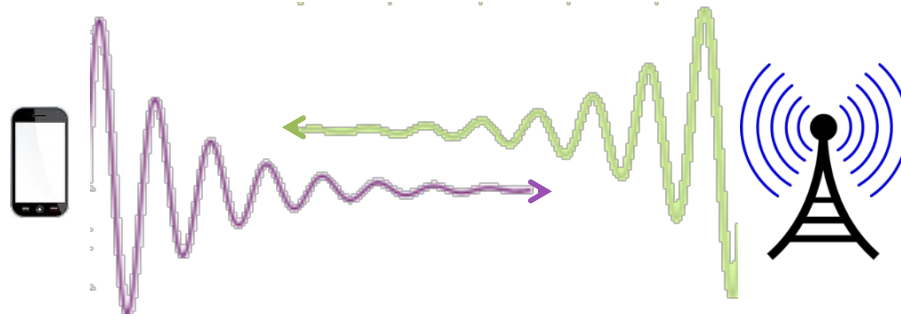# Resource Allocation and Rate Gains in Practical Full-Duplex Systems

Jelena Marašević, Jin Zhou, Harish Krishnaswamy, Yuan Zhong, and Gil Zussman

ACM SIGMETRICS'15, June 2015

Full-Duplex Wireless

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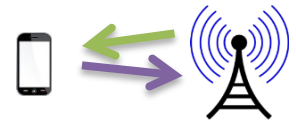- Viability is limited by self-interference

Transmitted signal is over billion times stronger than the received signal!

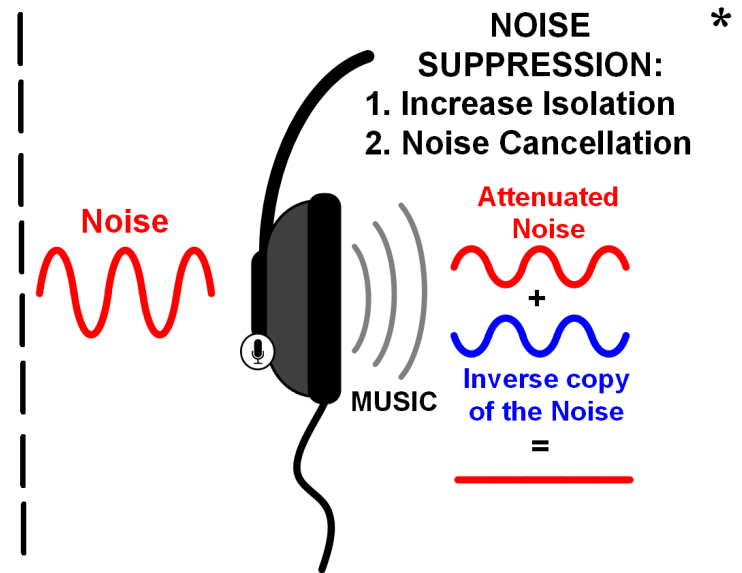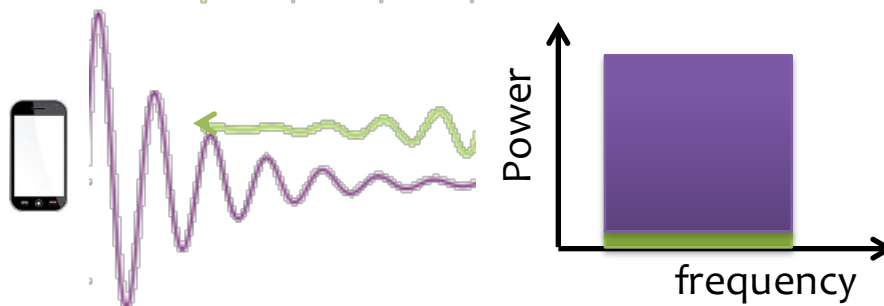Legacy wireless systems separate transmission and reception in either:

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

Full-Duplex Wireless

- Benefits of full-duplex:
  - Increased system throughput
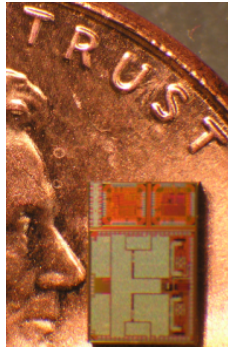 - More flexible use of the wireless spectrum
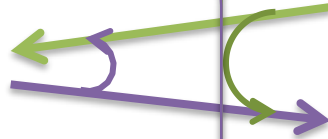
Self-Interference Cancellation (SIC):

NOISE SUPPRESSION: *
1. Increase Isolation
2. Noise Cancellation

Noise

Attenuated Noise

+

Inverse copy of the Noise

=

MUSIC

Power

frequency
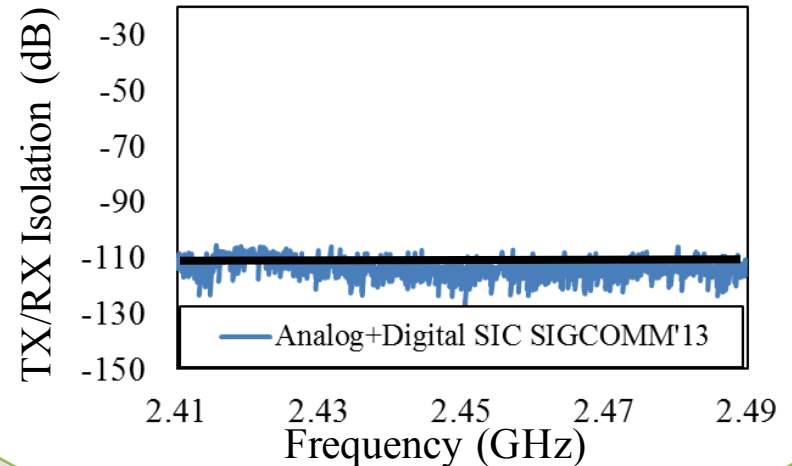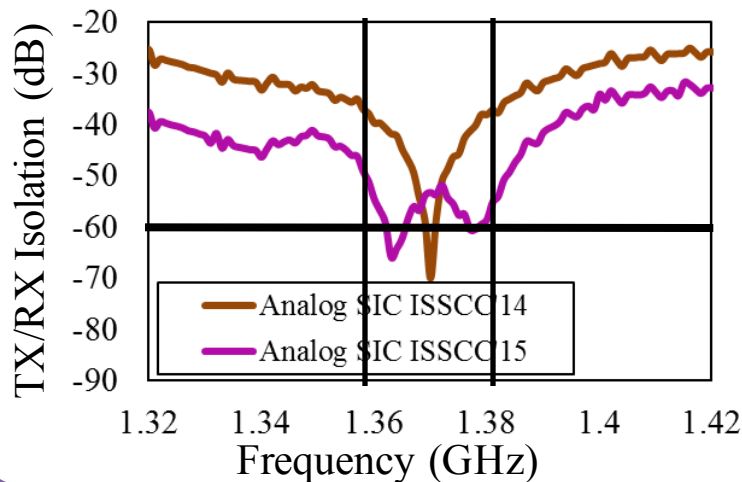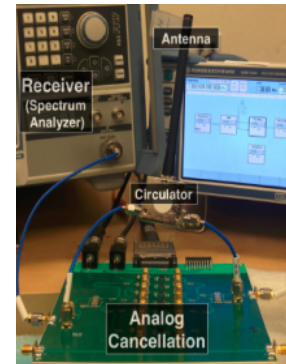
*Image borrowed from Tolga Dinc.

# 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 >0dBm 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 >>20MHz bandwidth self-interference cancellation suitable for FDD, co-existence and full-duplex applications," In Proc. *IEEE ISSCC'15, 2015*.
- D. Bharadia, E. McMilin, and S. Katti. "Full duplex radios." In *Proc. ACM SIGCOMM'13*, 2013.

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:

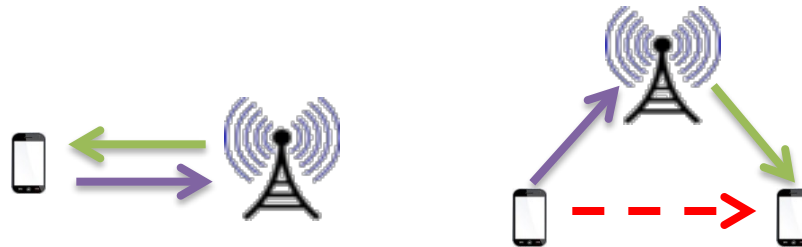 [Sahai et al. 2013], [Xie and Zhang 2014], [Li et al. 2014], [Nguyen et al. 2014]

This Talk

Power allocation and achievable rate gains for realistic hardware models.
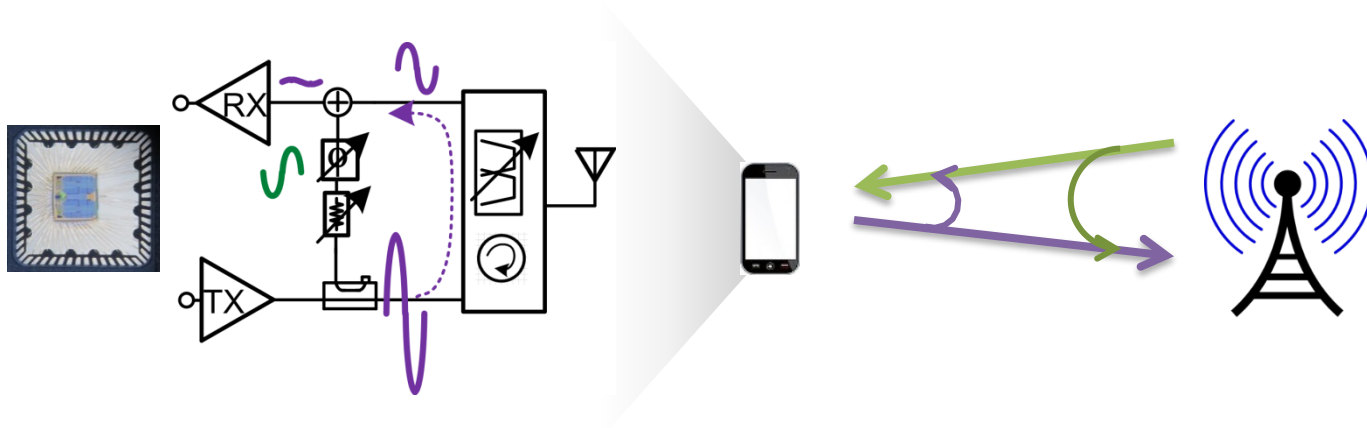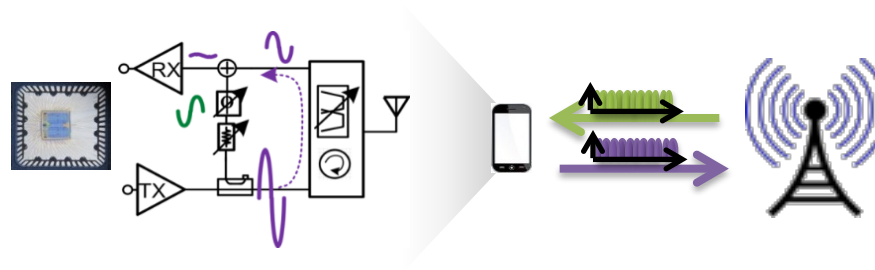
Outline

- Single-channel full-duplex:

- Multi-channel full-duplex:
  - Modeling full-duplex hardware
  - Power allocation and rate gains

Model and Problem Statement

- Self-interference: constant fraction (g_m, g_b) of the transmitted signal

- Goal: maximize the sum of rates on UL and DL

- Variables: transmission power levels P_m and P_b

- Constraints: $\quad P_m \leq \overline{P_m} \qquad P_b \leq \overline{P_b}$

- Remaining notation:

  – Noise: N_m, N_b

  – Wireless channel gain: h_{mb}, h_{bm}

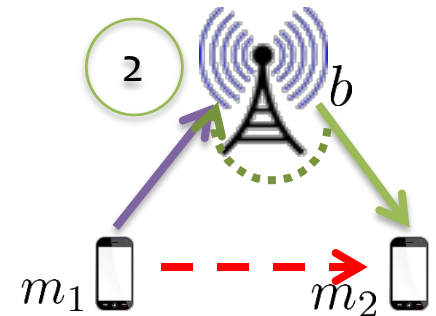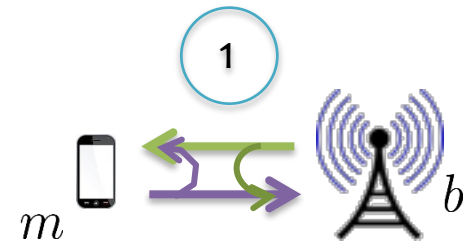Shannon capacity formula: $r = \log\left(1 + \dfrac{\text{received signal}}{\text{noise}+\text{interference}}\right)$

1

$$\overbrace{}^{\text{concave}} \qquad \overbrace{}^{\text{convex}}$$

$$r = \log\left(1 + \frac{h_{mb}P_m}{N_b + g_b P_b}\right) + \log\left(1 + \frac{h_{bm}P_b}{N_m + g_m P_m}\right)$$

self-interference

2

$$r = \log\left(1 + \frac{h_{m_1 b}P_m}{N_b + g_b P_b}\right) + \log\left(1 + \frac{h_{bm_2}P_b}{N_m + h_{m_1 m_2} P_m}\right)$$

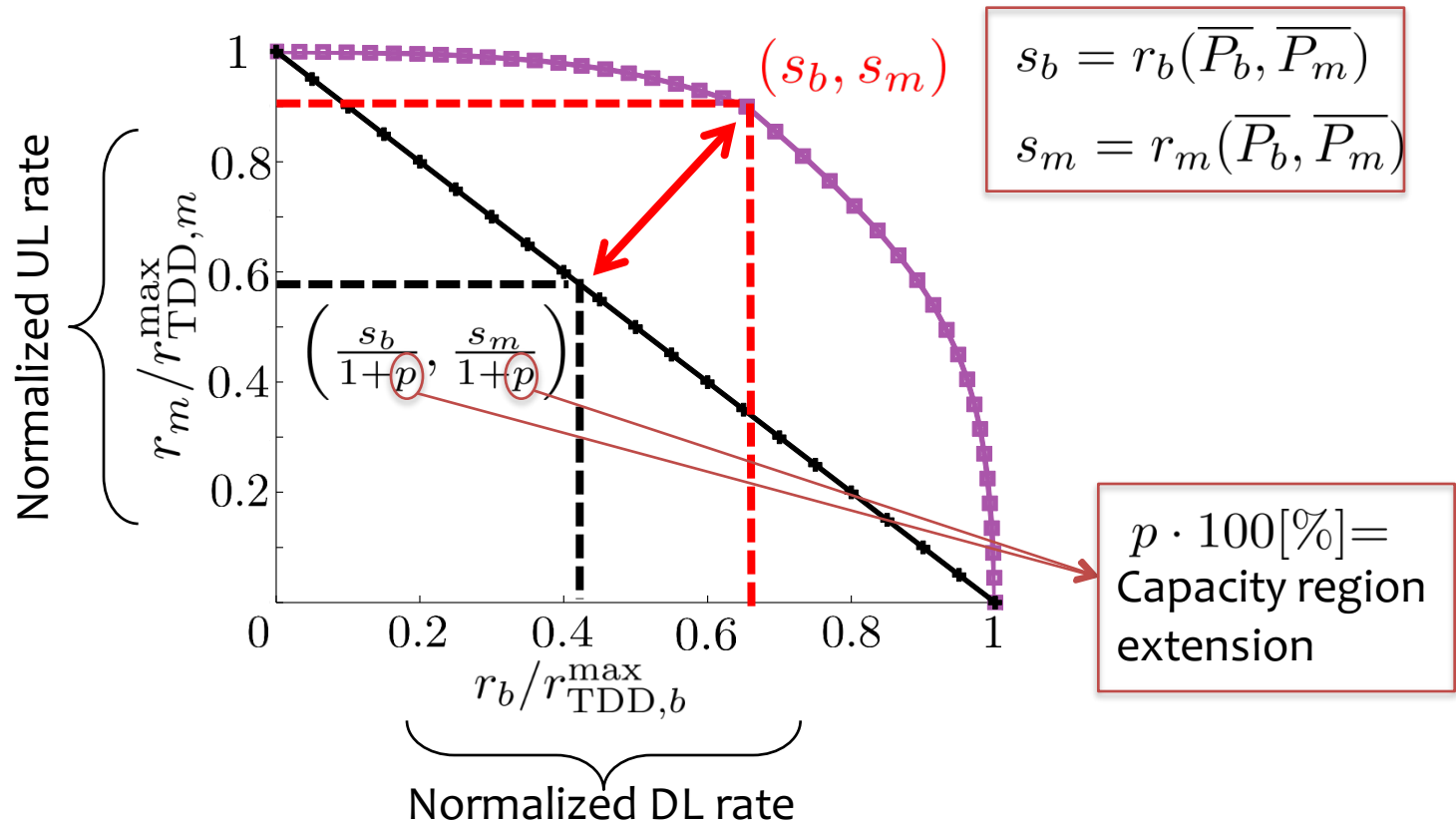$m \qquad b$

1

b

$m_1 \qquad m_2$

2

Maximum Sum-Rate and Rate Gains

Lemma 1. One of the following three power allocations maximizes the sum rate: $(0, \overline{P_m})$, $(\overline{P_b}, 0)$, or $(\overline{P_b}, \overline{P_m})$.

Half-duplex! Full-duplex!

(s_b, s_m)

$s_b = r_b(\overline{P_b}, \overline{P_m})$

$s_m = r_m(\overline{P_b}, \overline{P_m})$

$\left(\dfrac{s_b}{1+p}, \dfrac{s_m}{1+p} \right)$

$p \cdot 100[\%] =$ Capacity region extension

Normalized UL rate

$r_m/r_{\text{TDD},m}^{\max}$

$r_b/r_{\text{TDD},b}^{\max}$
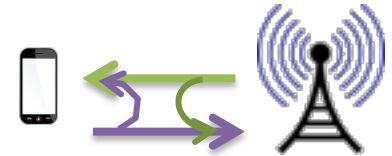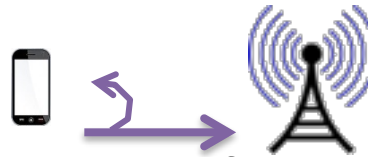
Normalized DL rate

Concavity of the Sum Rate

Lemma 2. If:

(C1) $\dfrac{g_m}{N_m} \leq \dfrac{h_{mb}}{N_b + g_b P_b}$,

the sum rate is concave in P_m. Similarly, if:

(C2) $\dfrac{g_b}{N_b} \leq \dfrac{h_{bm}}{N_m + g_m P_m}$,
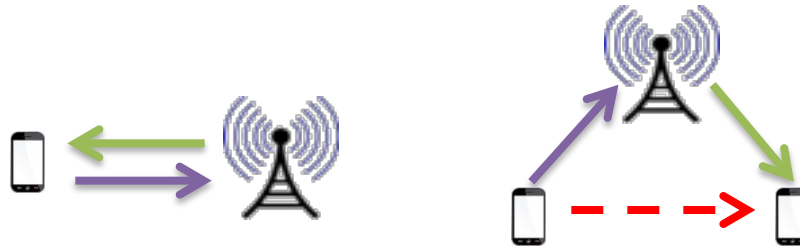
the sum rate is concave in P_b .

If either (C1) or (C2) does not hold, then the maximum improvement of the sum rate as compared to the maximum achievable TDD rate is strictly less than 1b/s/Hz.
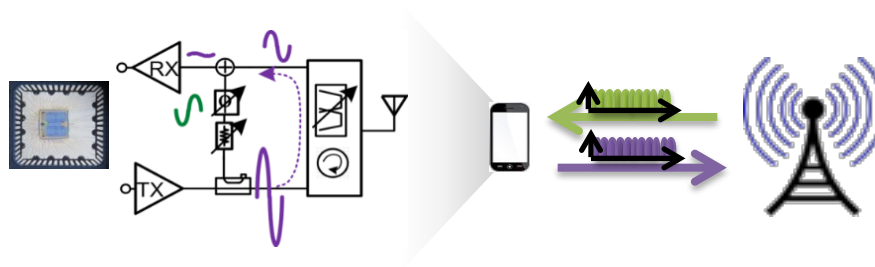
This lemma is essential for designing a power allocation algorithm in the multi-channel case!

Outline

- Single-channel full-duplex:

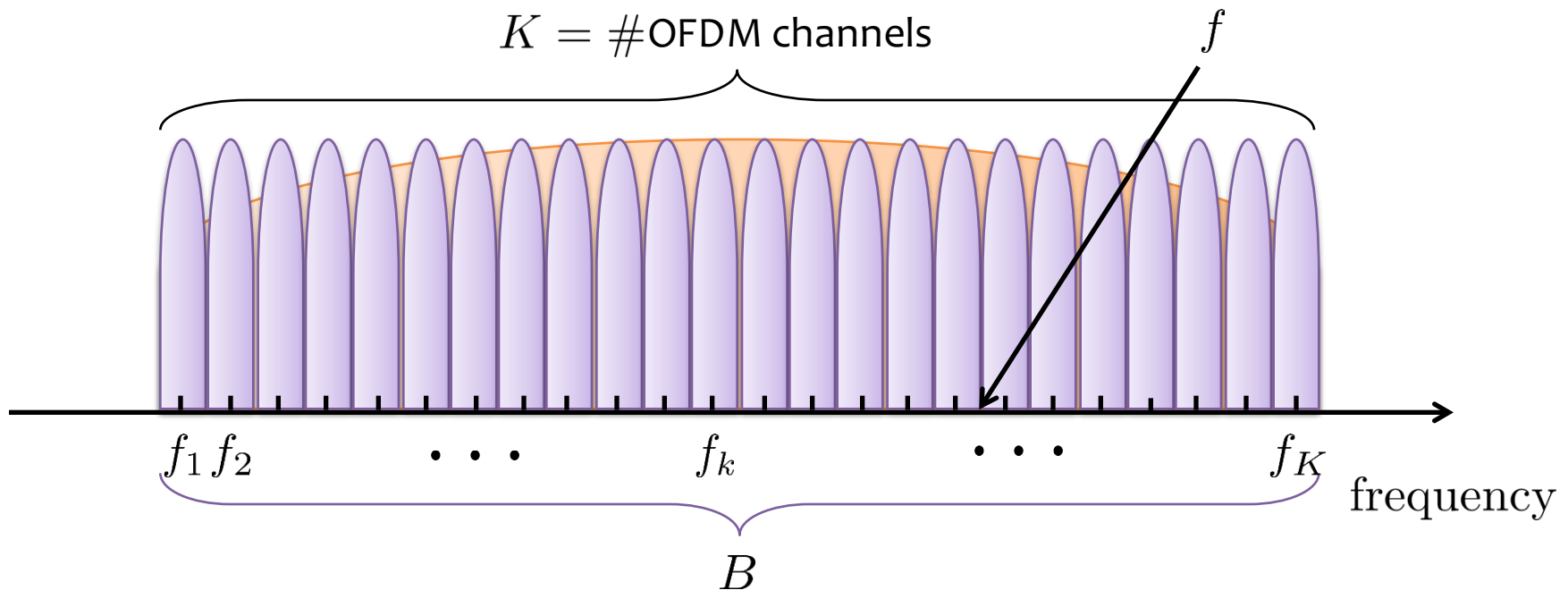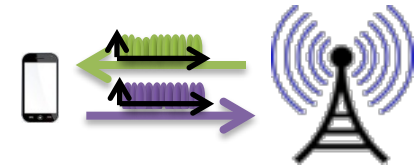- Multi-channel full-duplex:
  - Modeling full-duplex hardware
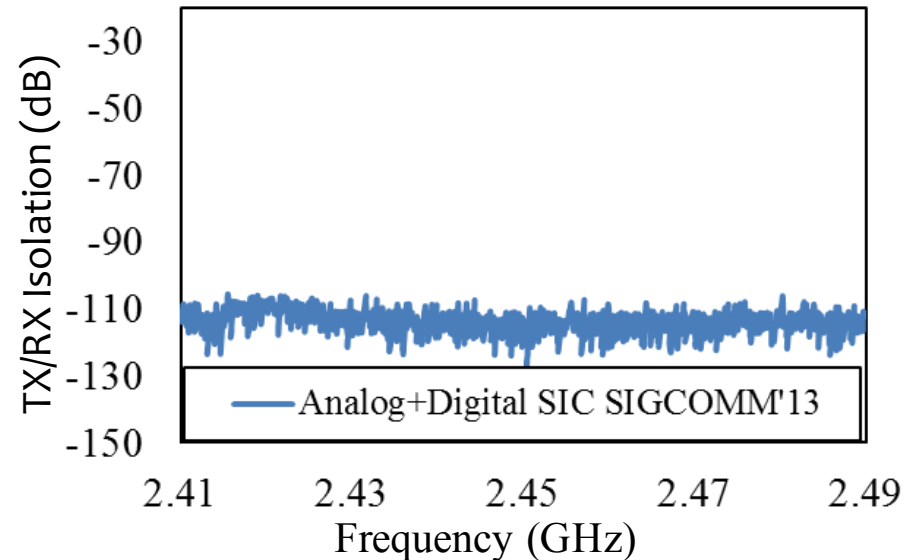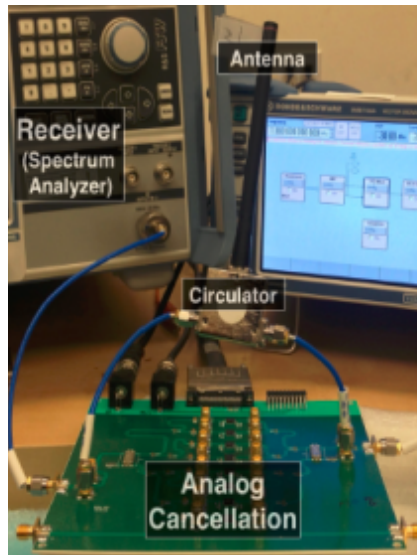 - Power allocation and rate gains

Multi-Channel Full-Duplex

- Orthogonal Frequency Division Multiplexing (OFDM)

- $f_{k+1} - f_k = \frac{B}{K}, \; \forall k$

- $f - f_k = c \cdot \frac{B}{K},$ for some $c \in \mathbb{R}$

$K = \#\text{OFDM channels}$

f

$f_1 \, f_2 \quad \cdots \quad f_k \quad \cdots \quad f_K$

frequency

B

Multi-Channel FD: Cancellation at a BS/AP

- Frequency-flat profile

D. Bharadia, E. McMilin, and S. Katti. "Full duplex radios." In *Proc. ACM SIGCOMM'13*, 2013.

Modeling Cancellation at a (Compact) MS

- Challenging to generate large time delay in RFIC;
- Assuming:

$$H_A(f) = |H_A| \cdot e^{-j2\pi f\tau},$$
$$|H_{C,R}(f)| = |H_{C,R}| = \text{const.},$$
$$\angle H_{C,R} = \text{const.},$$
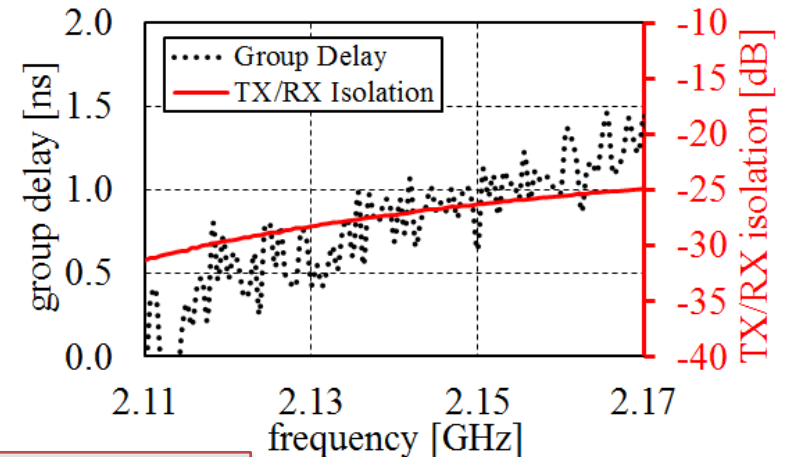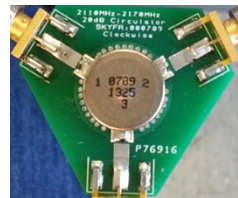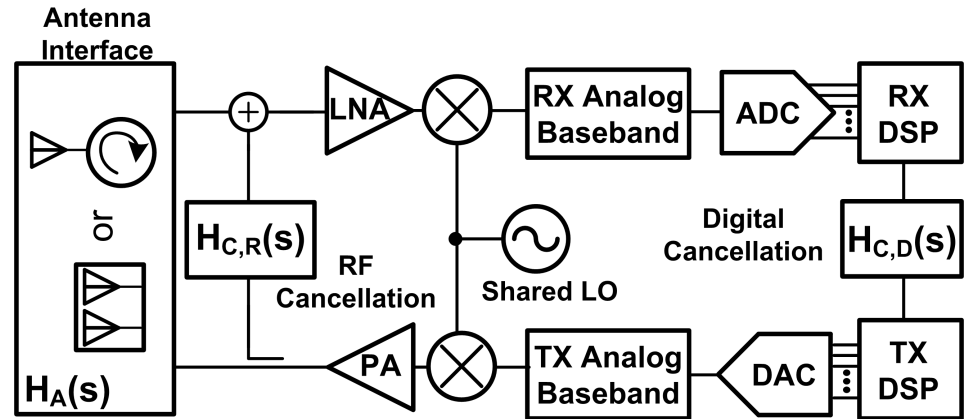$$SIC_D = \text{const.}$$

Setting

$$|H_A| = |H_{C,R}|$$
$$\angle H_{C,R} = \angle H_A(f_c)$$

The remaining self-interference is:

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

Antenna Interface

$H_{C,R}(s)$ — RF Cancellation

LNA — RX Analog Baseband — ADC — RX DSP

Shared LO

Digital Cancellation — $H_{C,D}(s)$

PA — TX Analog Baseband — DAC — TX DSP

$H_A(s)$

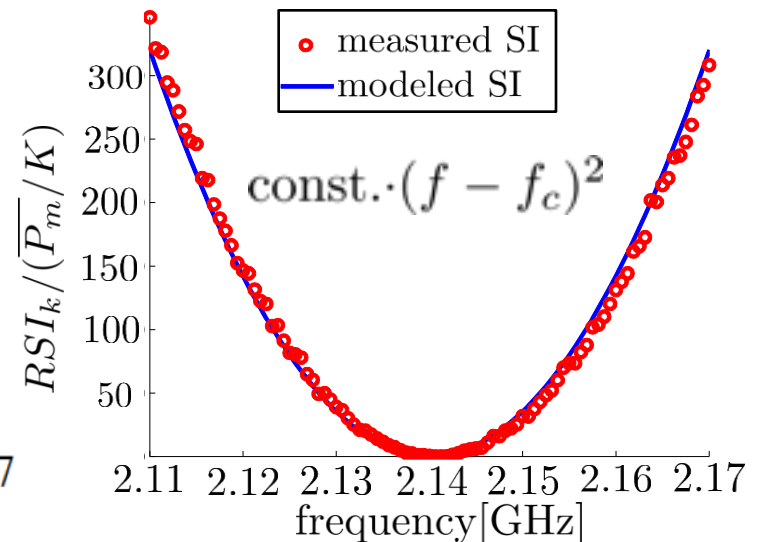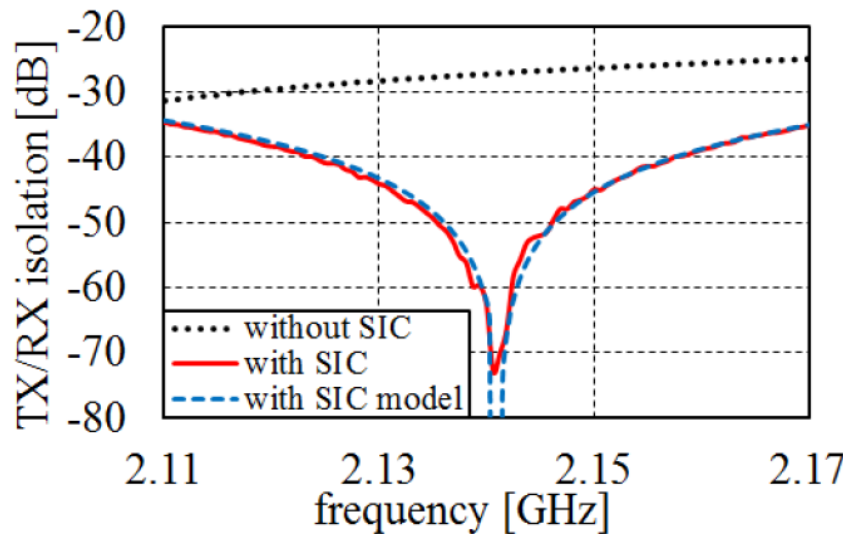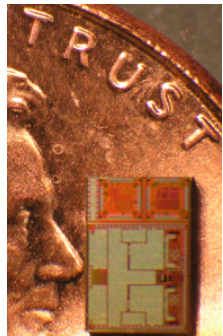- Group Delay
- TX/RX Isolation

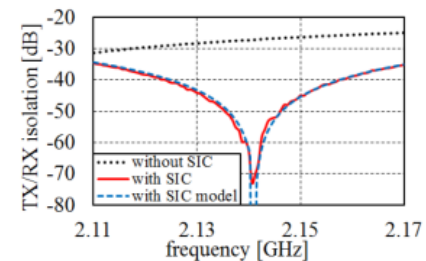# Model vs. Measurements

- Frequency-selective profile

$$RSI_{m,k} = \text{const.} \cdot (f_k - f_c)^2 \cdot P_{m,k}$$

- Measurements done using a circuit developed by Zhou et al. (presented at IEEE ISSCC'14).
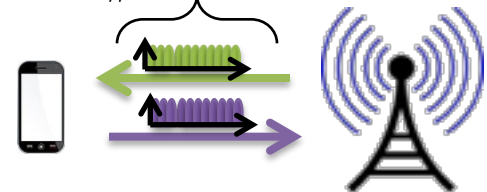
Remaining Self-Interference

- At the base station, channel k: $RSI_{b,k} = \boxed{g_b} \cdot \boxed{P_{b,k}}$ TX power on ch. k

  a constant

  TX power on ch. k

- At the mobile station, channel k: $\boxed{RSI_{m,k} = \boxed{g_m} \cdot \boxed{(k-c)^2} \cdot \boxed{P_{m,k}}}$

  a constant square-distance from max SIC

$$r = \sum_{k=1}^{K} \left(\log \left(1 + \frac{h_{mb,k} P_{m,k}}{N_b + g_b P_{b,k}} \right) + \log \left(1 + \frac{h_{bm,k} P_{b,k}}{N_m + g_m (k-c)^2 P_{m,k}} \right) \right)$$

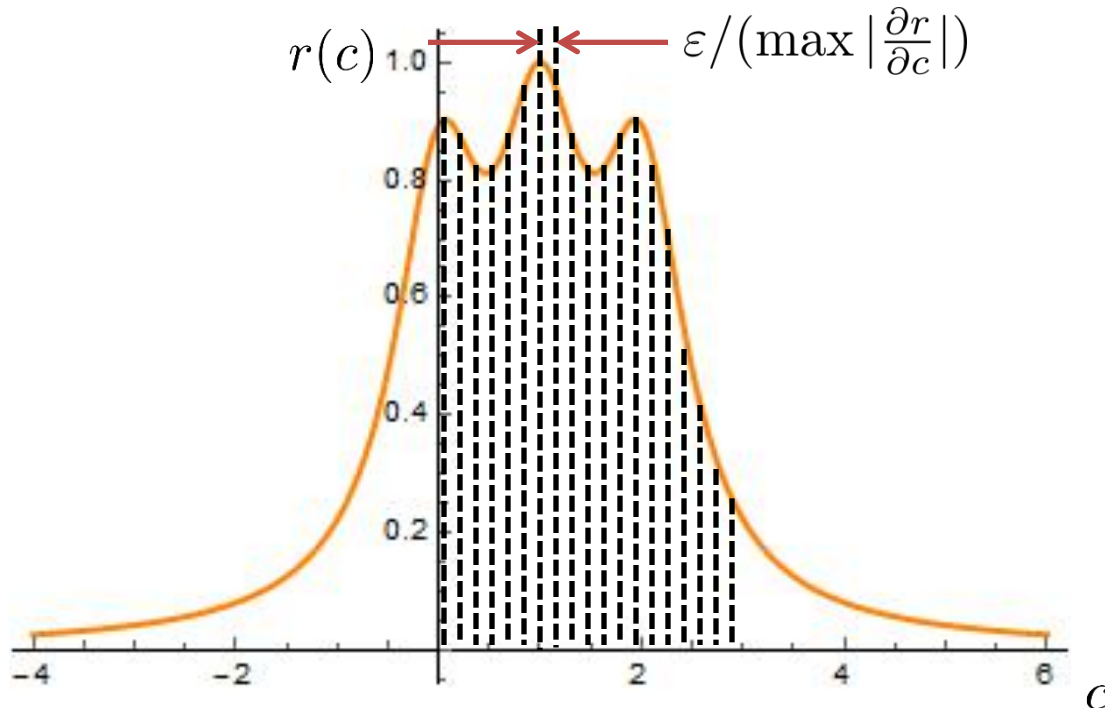$$\sum_{k=1}^{K} P_{m,k} \le \overline{P_m} \qquad \sum_{k=1}^{K} P_{b,k} \le \overline{P_b}$$

$K = \#$ OFDM channels

Parameter Selection

- The problem of determining $(\{P_{m,k}, P_{b,k}\}, c)$ that maximize the sum of rates is hard in general:
  - The sufficient conditions for concavity in power levels extend for any fixed c
  - … but the dependence on c is not "nice"
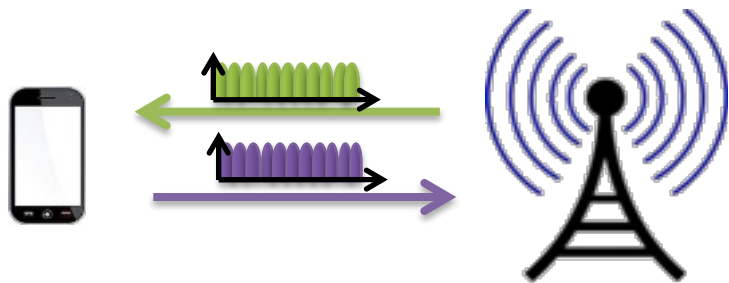- However, the problem has "enough" structure

High SINR Approximation

- Dependence on c is still "hard" in general.

- But:

> *Lemma 4.* If $(\{P_{m,k}, P_{b,k}\}, c)$ maximizes r, then $c = \frac{K+1}{2}$.
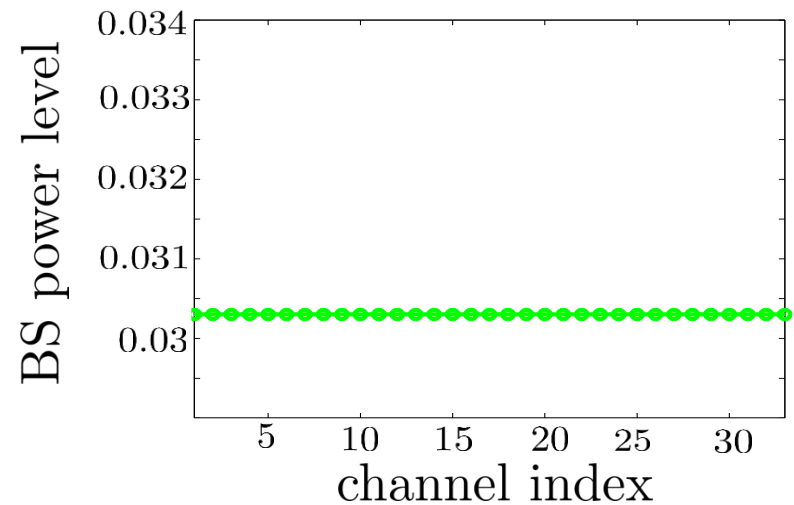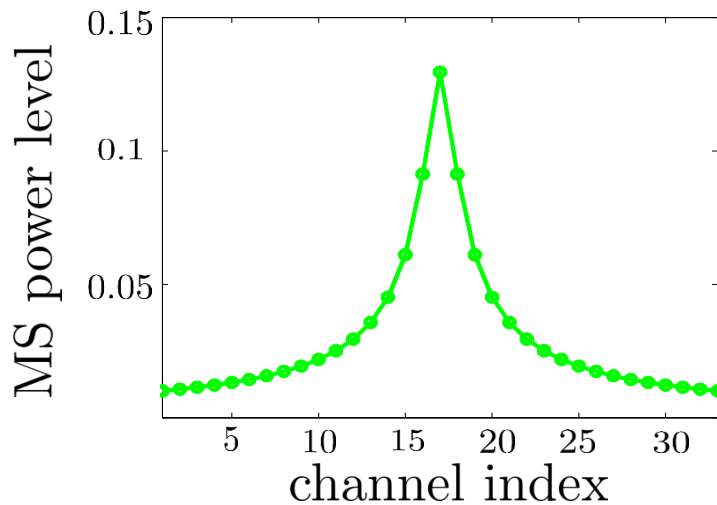
Numerical Results

Setting

- $K = 33$ channels on a 20MHz bandwidth;

- Additional 50dB cancellation from the digital;

- 110dB difference between the max TX signal and the noise floor;

- Flat frequency fading;

- Average SNR : SNR observed in the half-duplex mode with max TX power, when the transmission power levels are equally allocated over channels

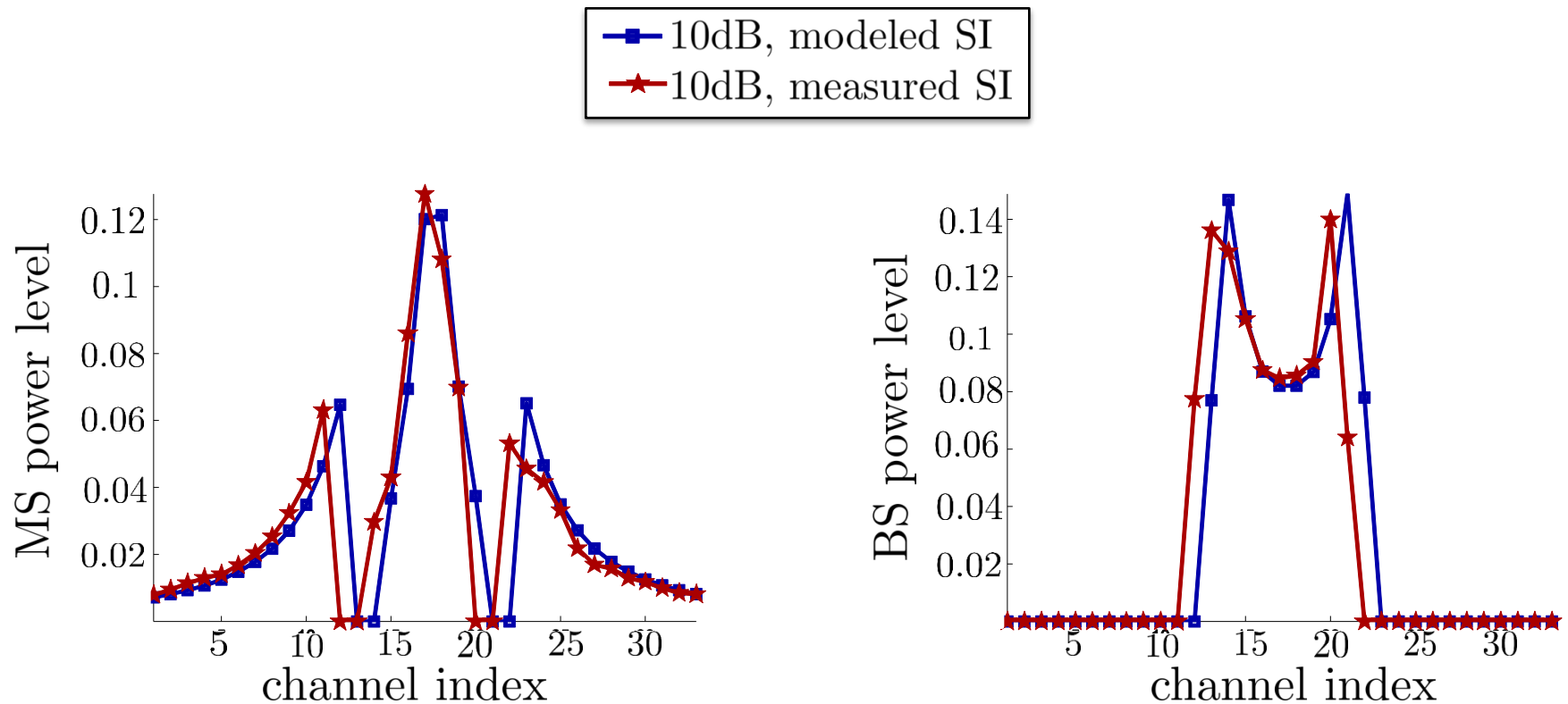- Self-interference: measured and modeled profile
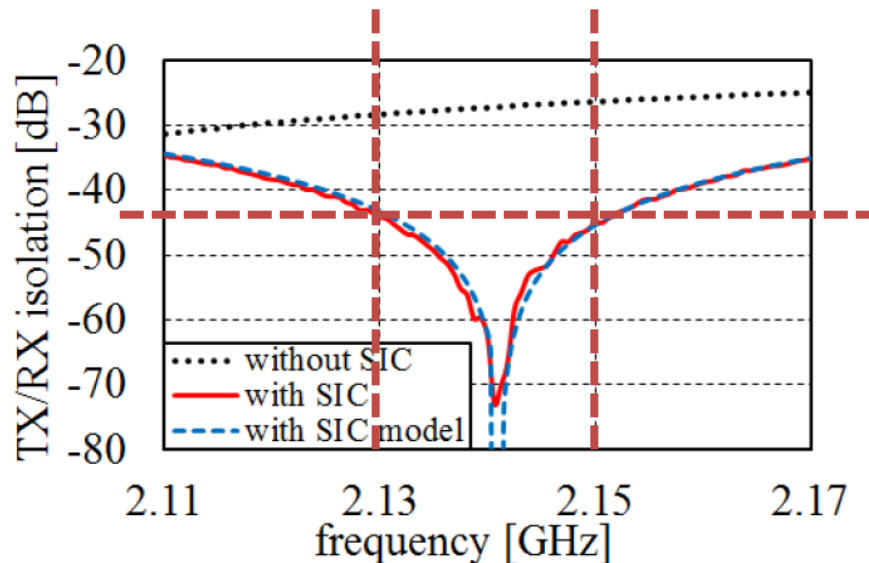
Power Allocation: Low SINR

Most channels are half-duplex – only one stations is transmitting at a time.
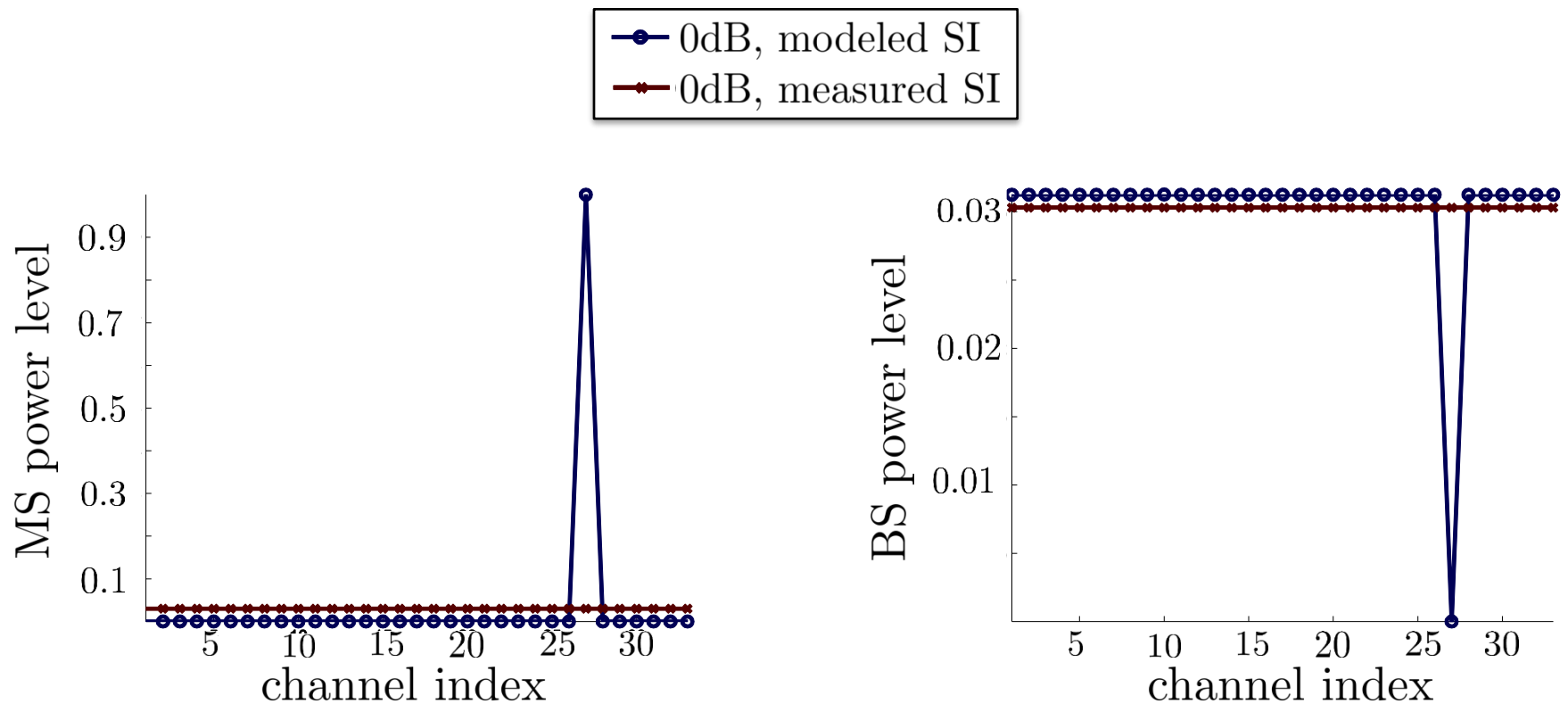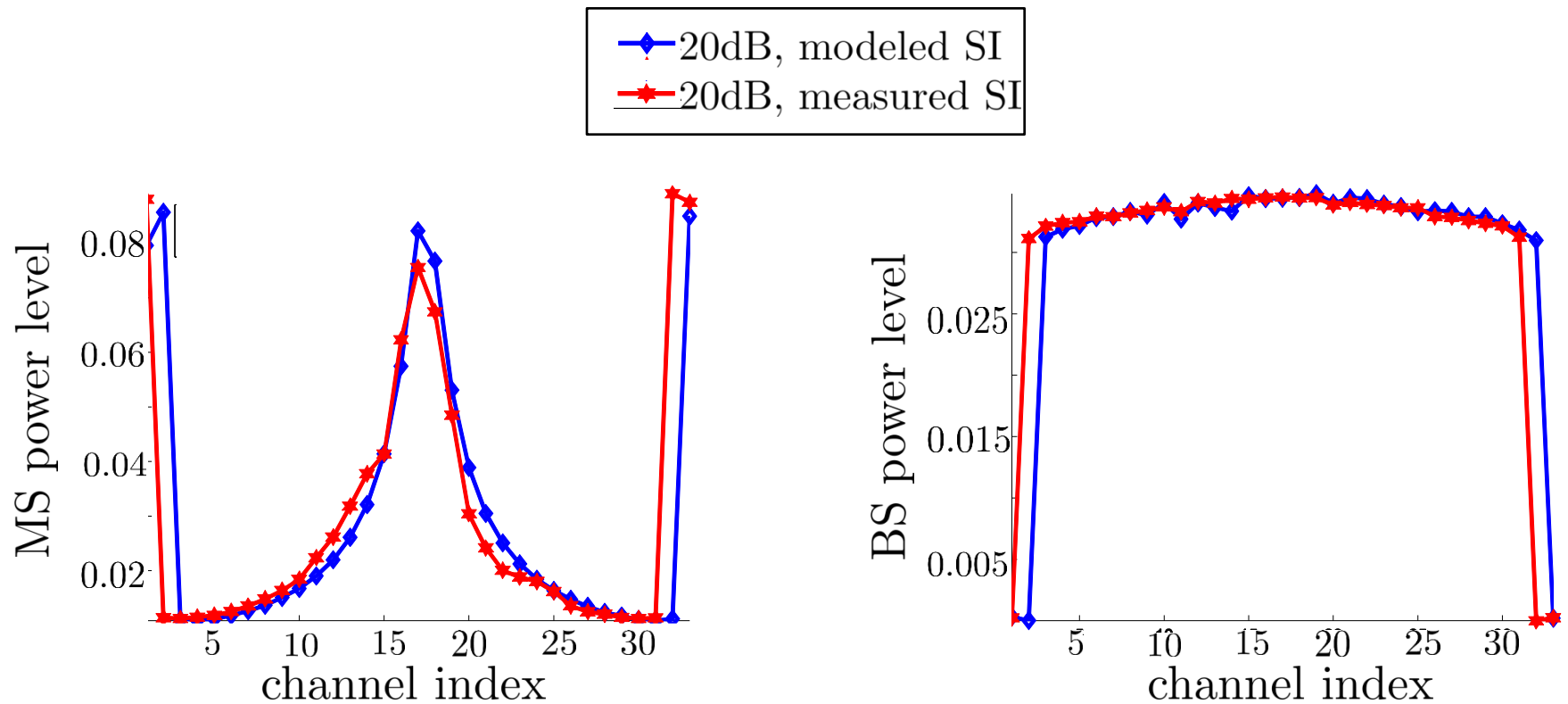
Low-Medium SINR

Most channels are half-duplex, but about 1/5 of the channels are full-duplex.
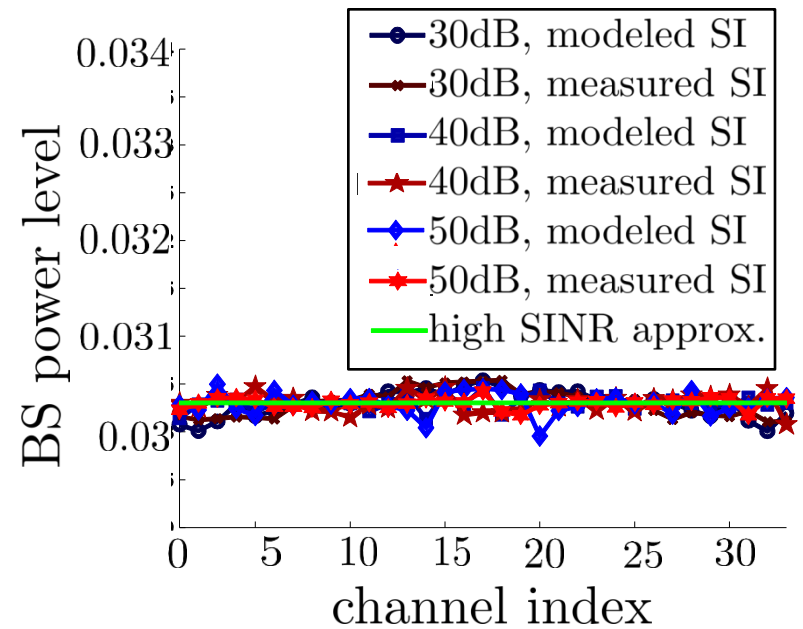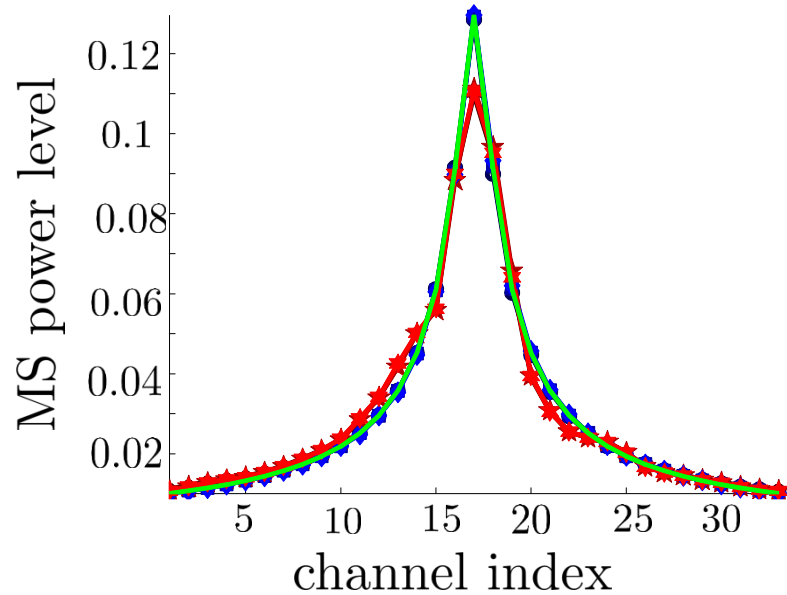
Medium SINR

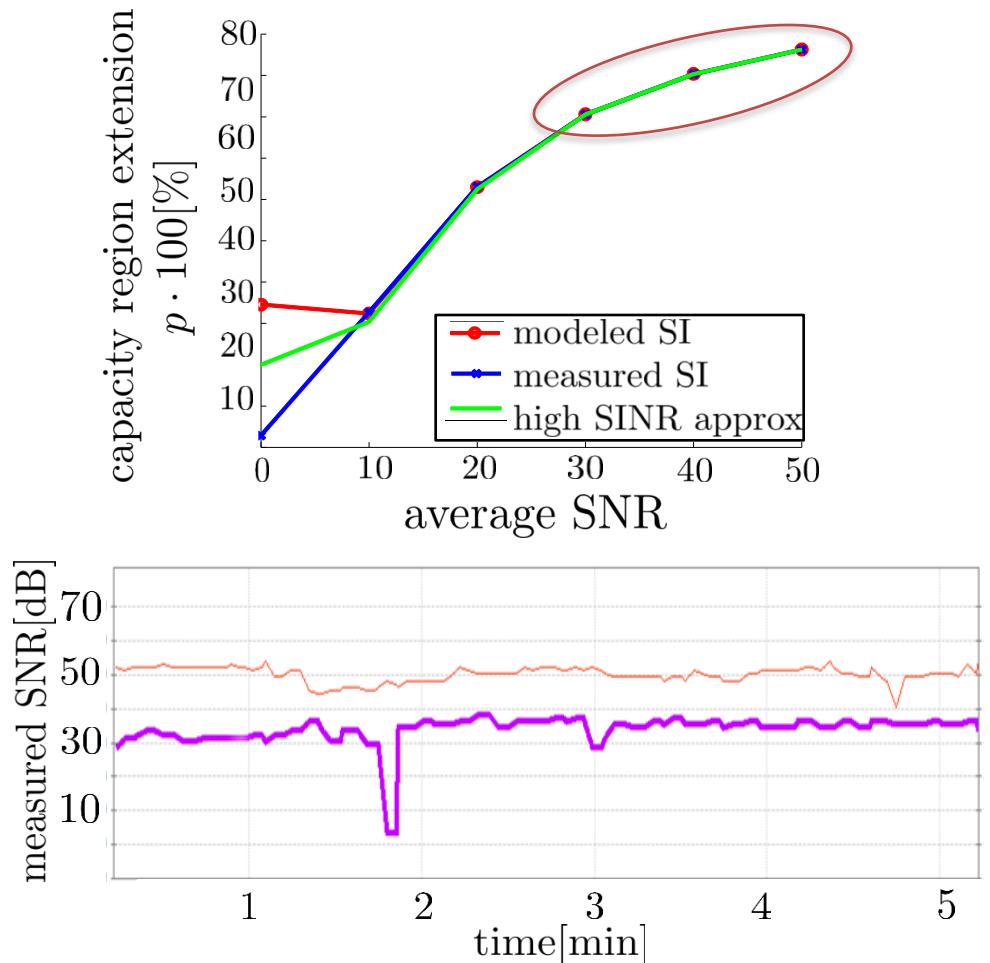Most channels are full-duplex.

High SINR

All channels are full-duplex, and the power allocation matches closely the power allocation in high SINR approximation.

Rate Improvements

Significant rate improvements are mainly observed when the high SINR approximation holds.

Summary and Future Directions

- Characterized throughput gains and properties of the sum rate for 3 representative use cases of full-duplex

- Used realistic models of the hardware

- The results are analytical and provide insights into properties of the achievable rates

- Future directions:

  - Wi-Fi (CSMA) MAC with fairness guarantees

  - Cellular OFDMA MAC
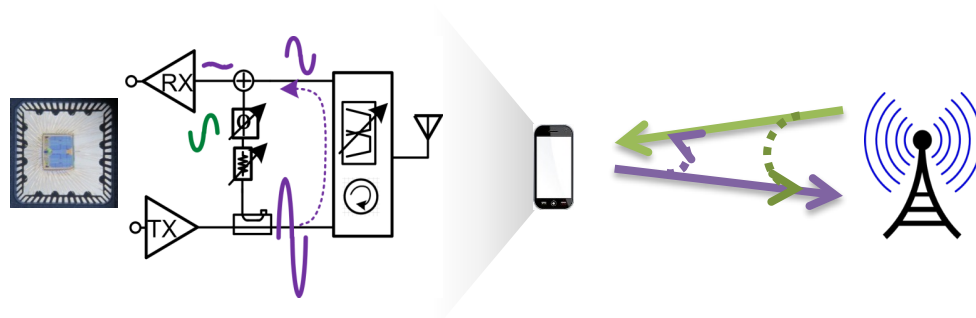
Thanks!

jelena@ee.columbia.edu

www.ee.columbia.edu/~jelena

J. Marašević , J. Zhou, H. Krishnaswamy, Y. Zhong, G. Zussman,
"Resource Allocation and Rate Gains in Practical Full-Duplex Systems"