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Wireless & Mobile Networking Lab

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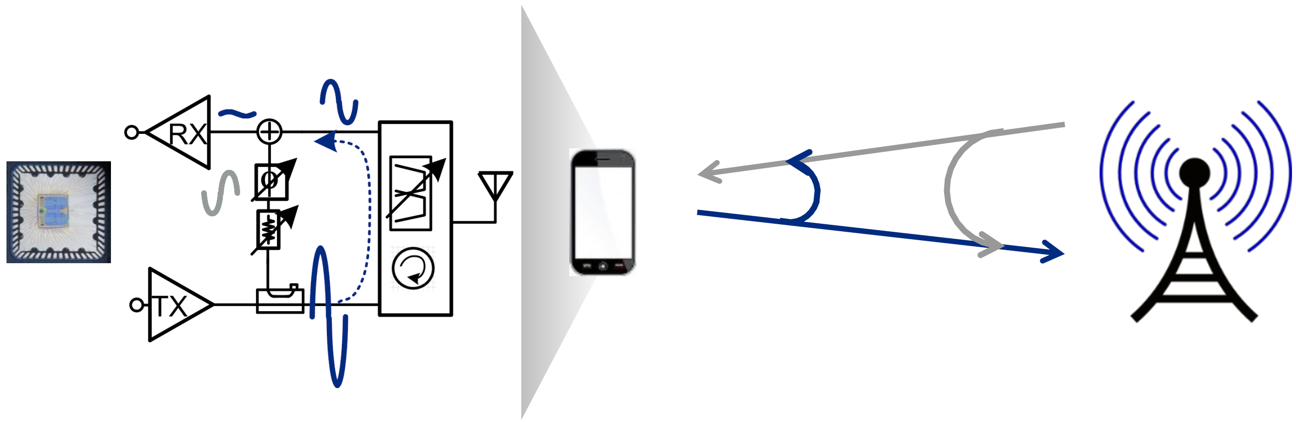

On the Capacity Regions of Single-Channel and Multi-Channel Full-Duplex Links

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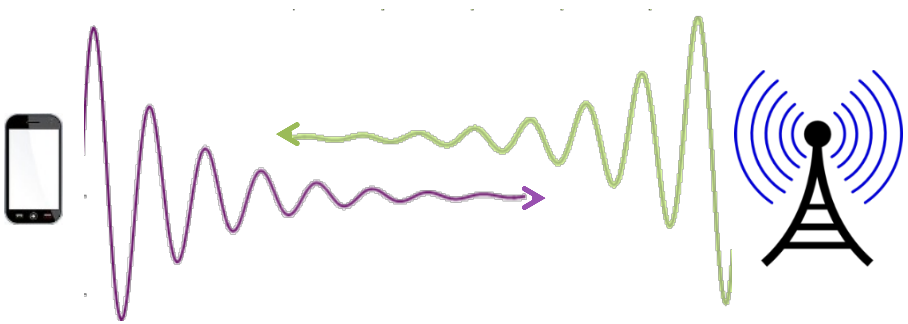
MobiHoc'16, July 2016

Full-Duplex Wireless

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



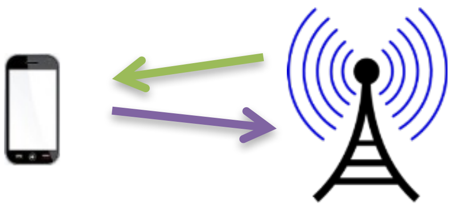
Transmitted signal is billions of times stronger than the received signal!

Legacy wireless systems separate transmission and reception in either:

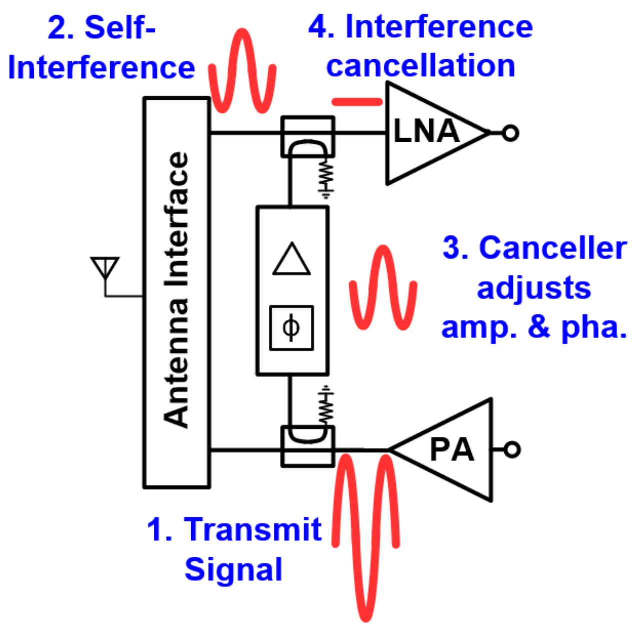
- Time – Time Division Duplex (TDD)
- Frequency – Frequency Division Duplex (FDD)

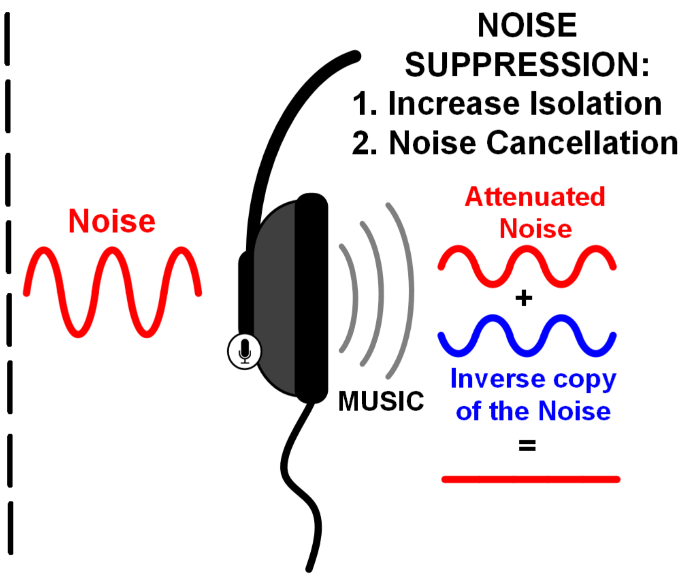
Full-Duplex Wireless

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

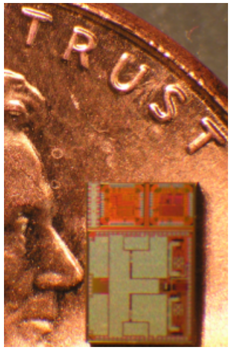


Self-Interference Cancellation (SIC):

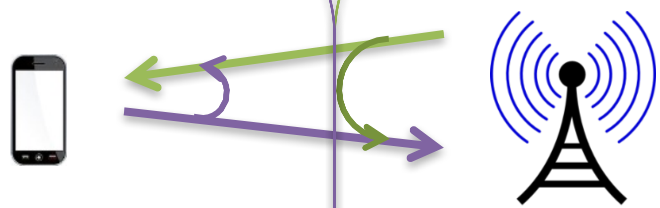




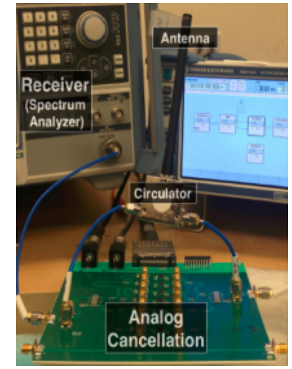
Imperfect Self-Interference Cancellation

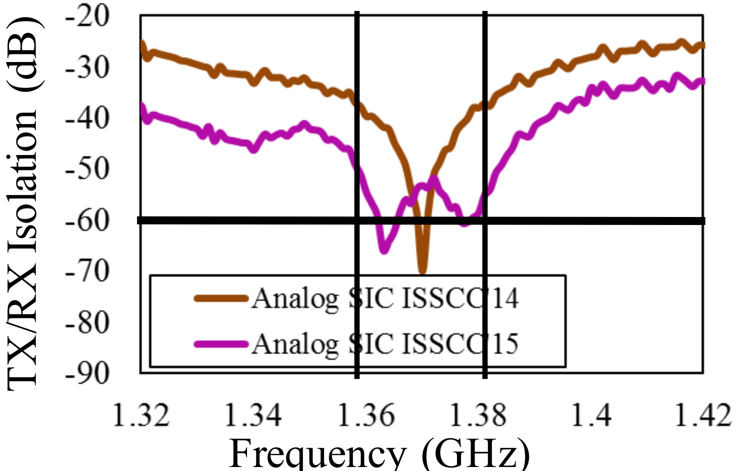


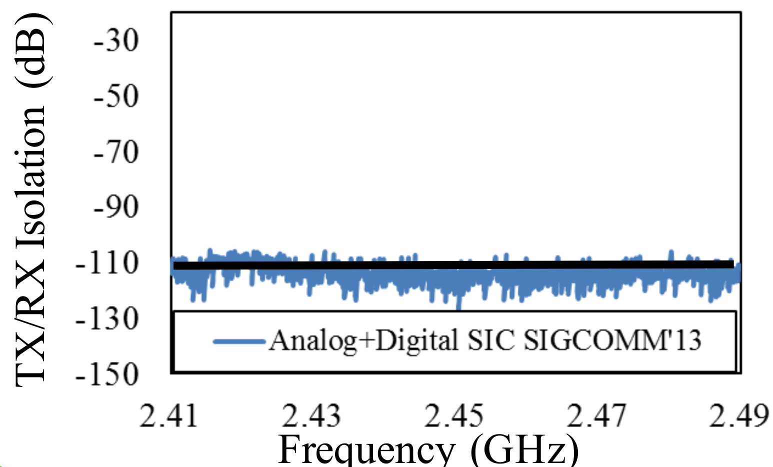
Columbia



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], [Korpi et al. 2015]

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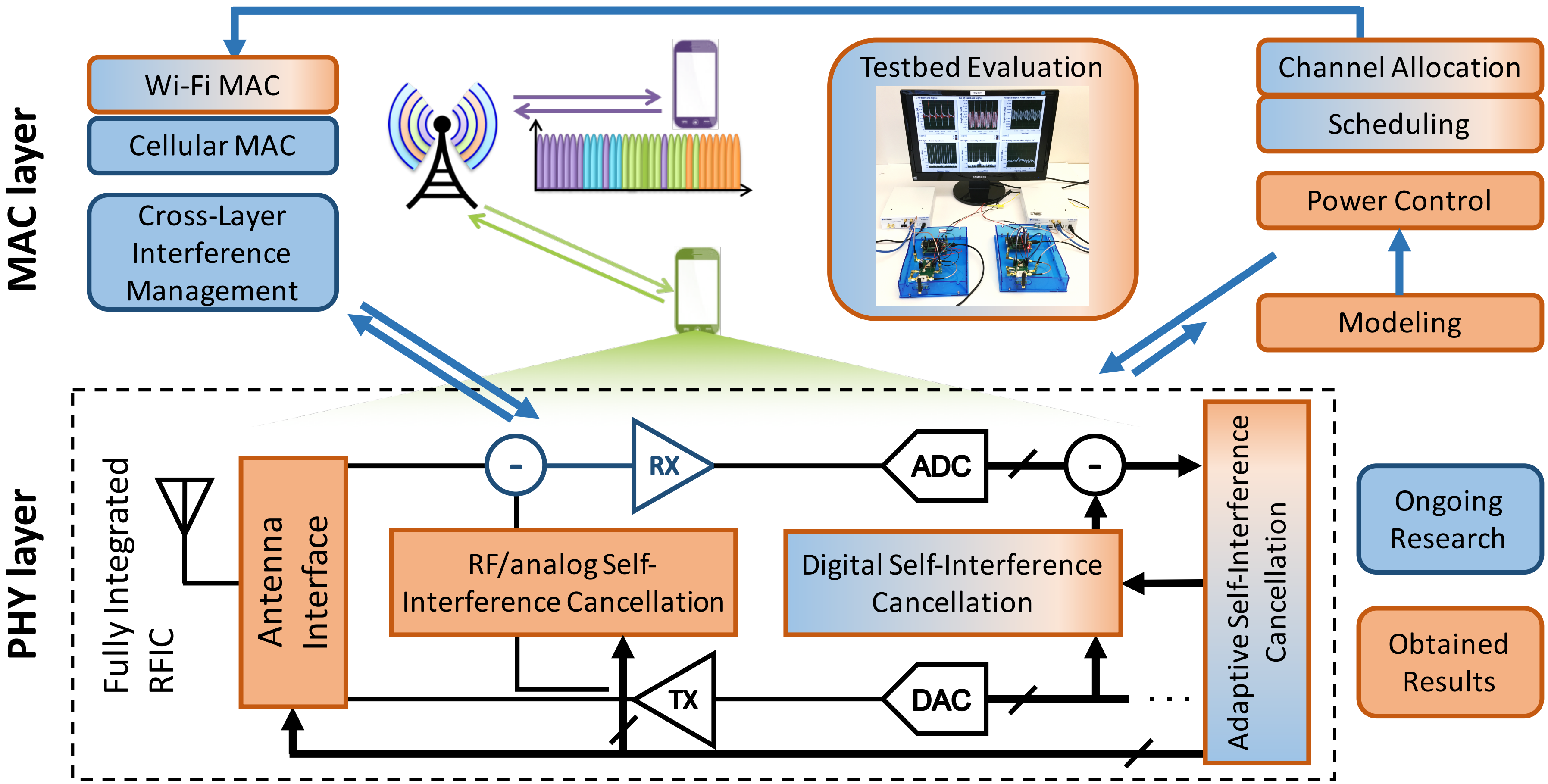
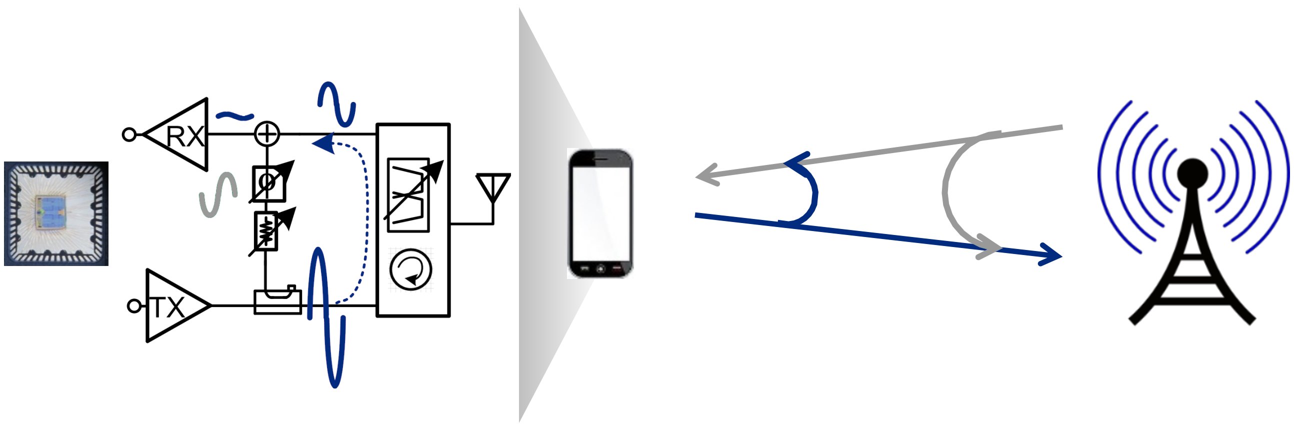
Full Duplex wireless – from Integrated Circuits to Networks



This Talk

How much can we gain from full-duplex and under what conditions?

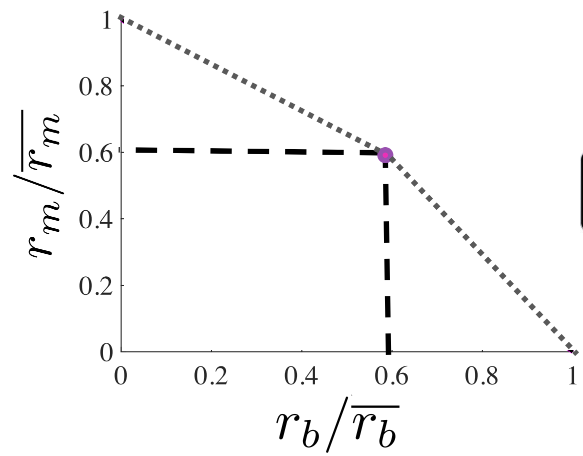


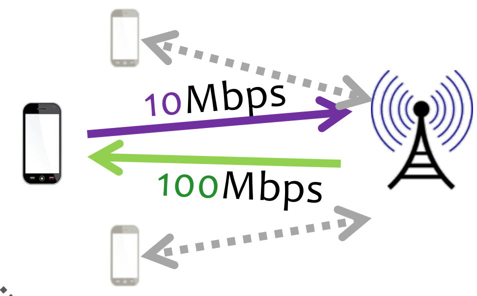
Outline

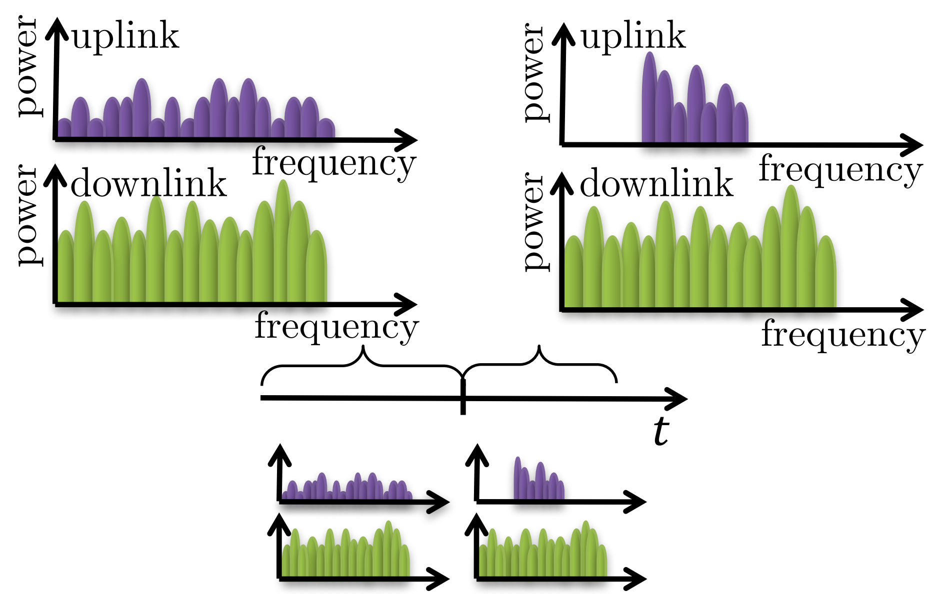
- Motivation and Problem Statement
- Single Channel FD
  - Structural Results
  - Determining FD + TDD Capacity Region
- Multi-Channel FD
  - Fixed Power Allocation
  - General Power Allocation

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)







*J. Marašević, J. Zhou, H. Krishnaswamy, Y. Zhong, G. Zussman, "Resource Allocation and Rate Gains in Practical Full-Duplex Systems", *to appear in* IEEE/ACM Transactions on Networking, 2016

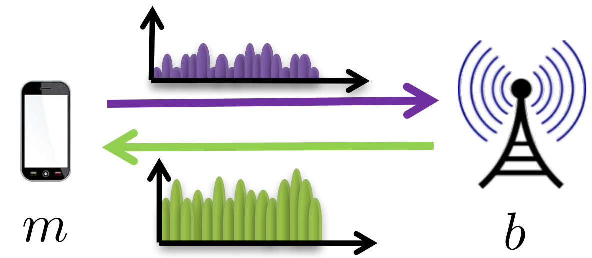
Model and Problem Statement (I)

- k: channel index; K: # of channels
- Self-interference on channel k: constant fraction of the transmission power on channel k
- $\alpha_{i,k} = \frac{\text{TX power of } i \text{ on ch } K}{\text{max total TX power of } i}, \; i \in \{m, b\}$
- Signal-to-noise-ratio (SNR):

$$\gamma_{mb,k} = \alpha_{m,k}\overline{\gamma_{mb,k}} \qquad \gamma_{bm,k} = \alpha_{b,k}\overline{\gamma_{bm,k}}$$

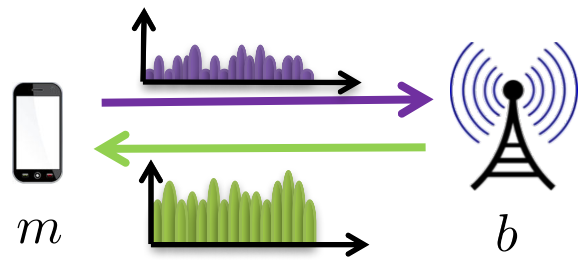
- Self-interference-to-noise-ratio (XINR):

$$\gamma_{bb,k} = \alpha_{b,k}\overline{\gamma_{bb,k}} \qquad \gamma_{mm,k} = \alpha_{m,k}\overline{\gamma_{mm,k}}$$



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

Model and Problem Statement (II)



The UL and DL rates:

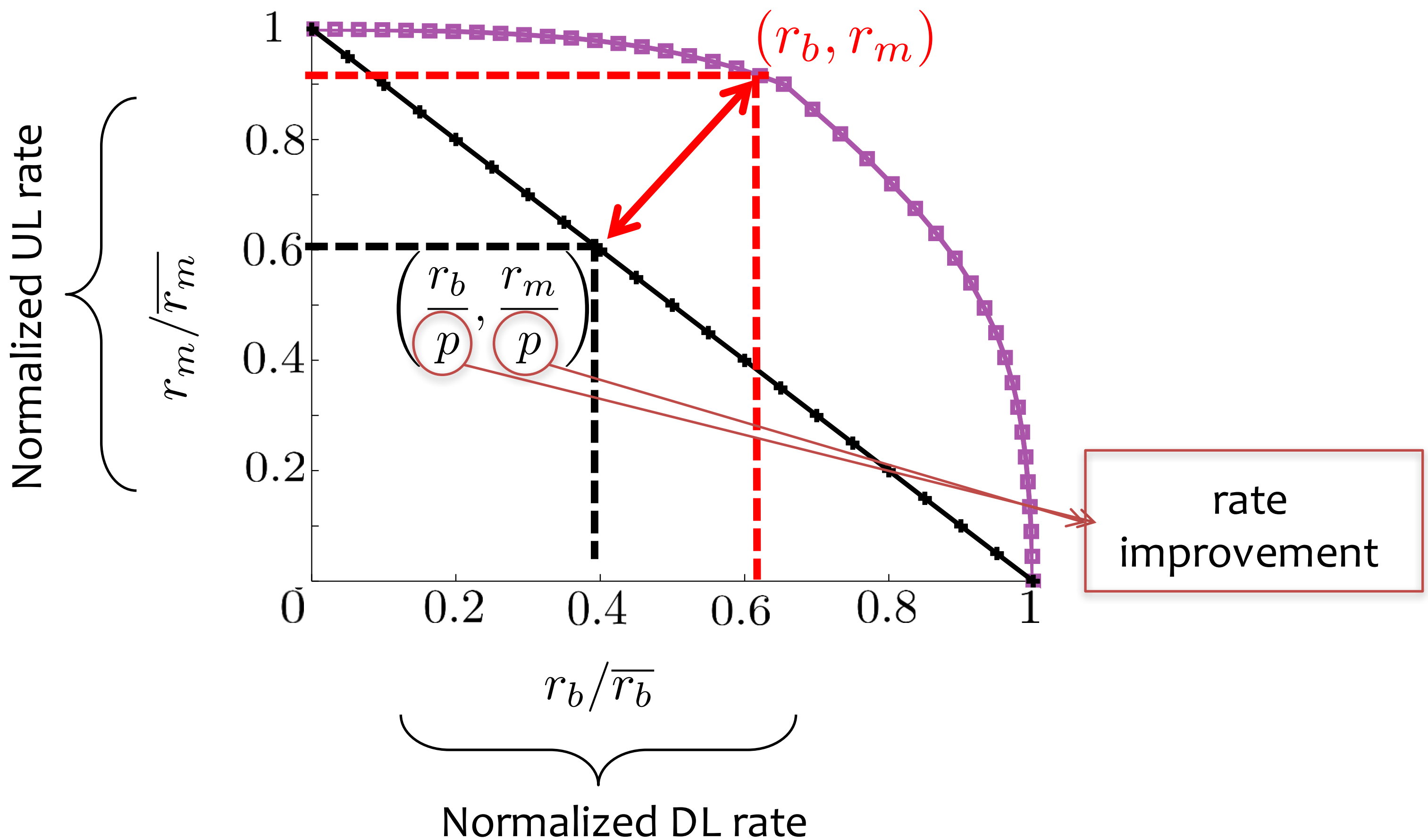
$$r_m = \sum_{k=1}^{K} \log\left(1 + \frac{\alpha_{m,k}\overline{\gamma_{mb,k}}}{1 + \alpha_{b,k}\overline{\gamma_{bb,k}}}\right)$$

$$r_b = \sum_{k=1}^{K} \log\left(1 + \frac{\alpha_{b,k}\overline{\gamma_{bm,k}}}{1 + \alpha_{m,k}\overline{\gamma_{mm,k}}}\right)$$

The problem:

$$\begin{aligned} \max \quad & r_m \\ \text{s.t.} \quad & r_b = r_b^* \\ & \sum_{k=1}^{K} \alpha_{b,k} \leq 1, \ \sum_{k=1}^{K} \alpha_{m,k} \leq 1 \\ & \alpha_{b,k} \geq 0, \ \alpha_{m,k} \geq 0, \ \forall k \end{aligned}$$

Rate Improvement



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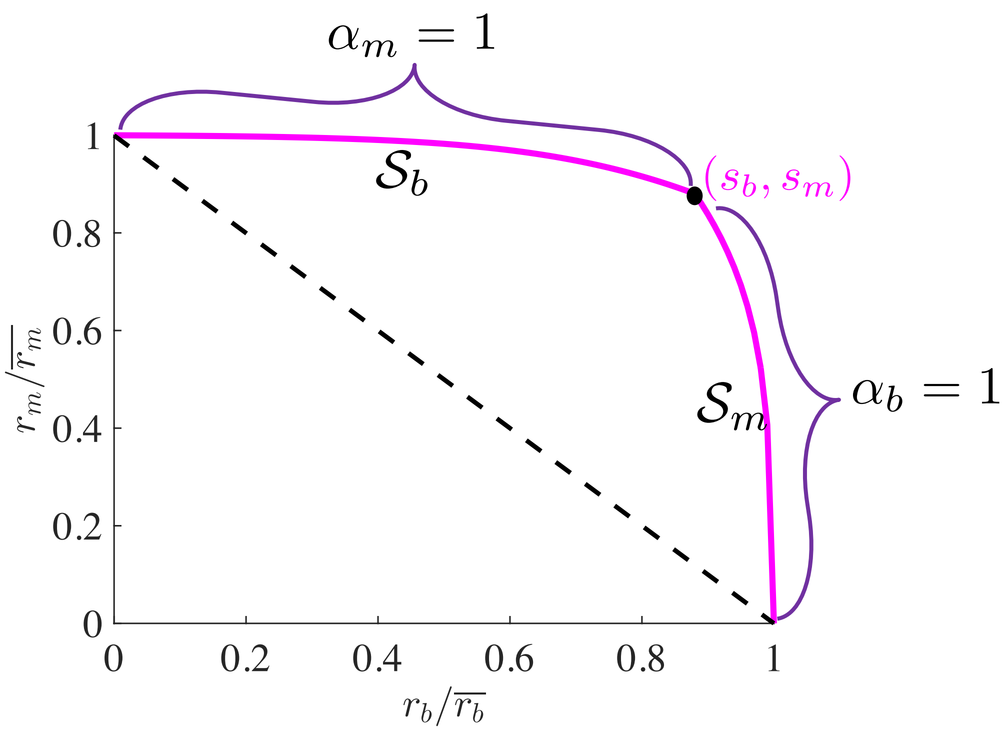
Structural Results (I)

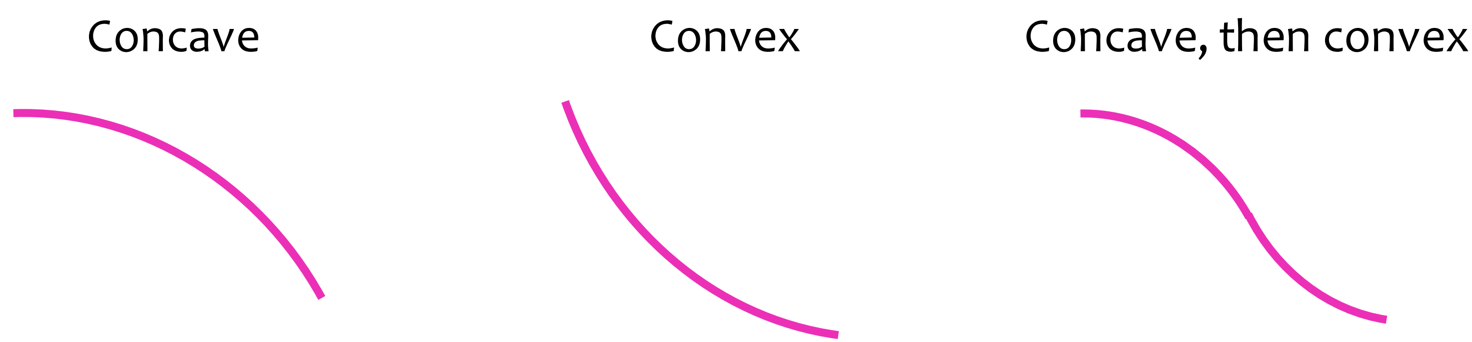
- FD Capacity Region:

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



Structural Results (II)

Lemma. $\mathcal{S}_b$ can take only one of the following three shapes:



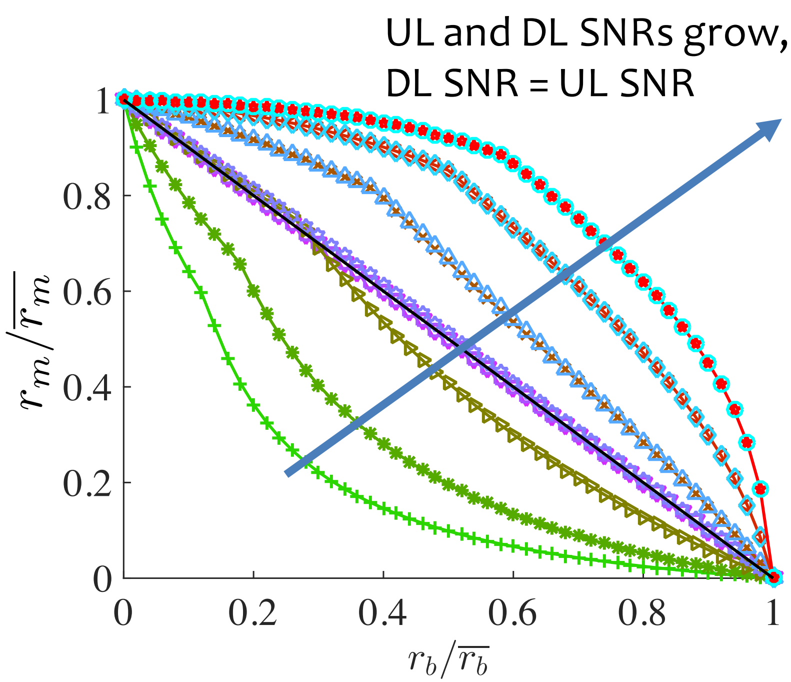
Proposition.

1. If both $\mathcal{S}_b$ and $\mathcal{S}_m$ are concave, FD capacity region is convex.
2. If (s_b, s_m) maximizes the sum of the uplink and downlink rates, then (s_b, s_m) is outside the convex hull of the FD capacity region.
3. If $s_b + s_m \leq r_m$, then $\mathcal{S}_b$ is convex.

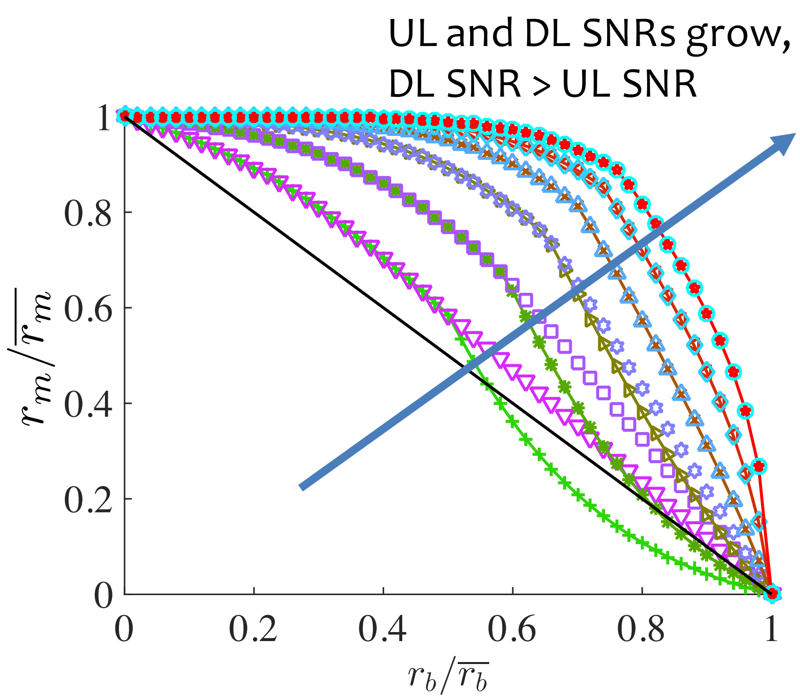
FD+TDD Capacity Region

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

Symmetric UL/DL SNR



Asymmetric UL/DL SNR



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

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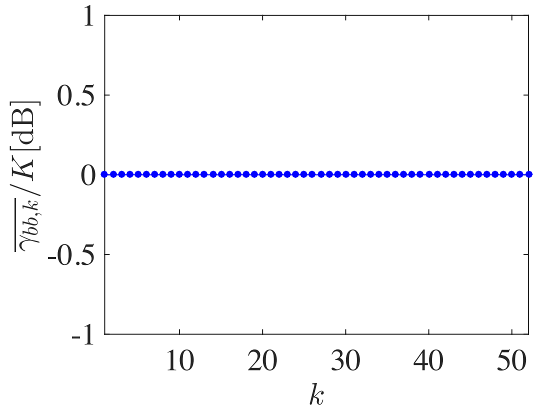
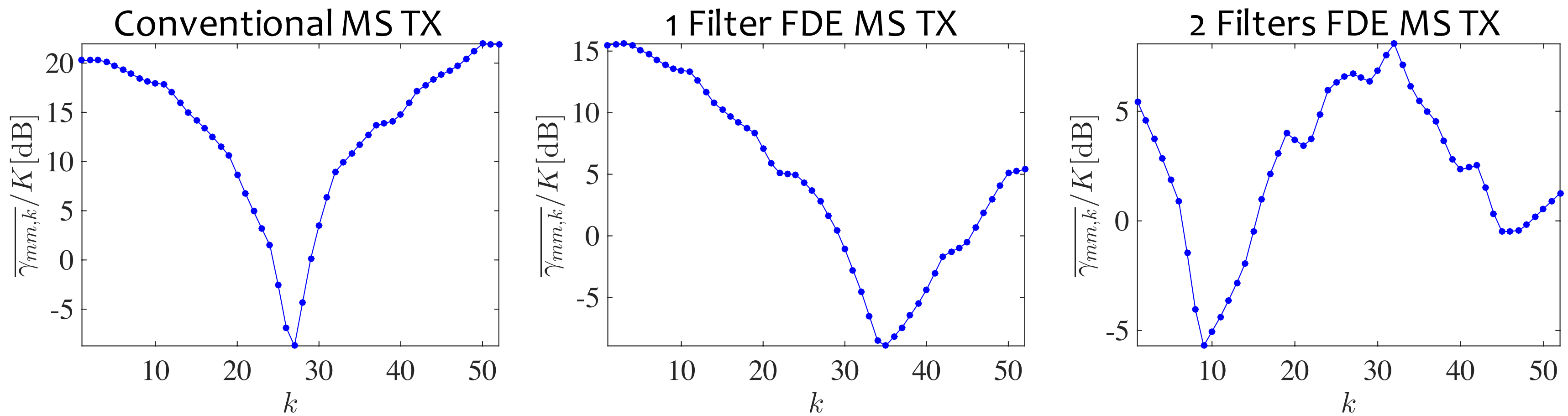
Cancellation Profiles

- Base Station/Access Point



- Mobile Station



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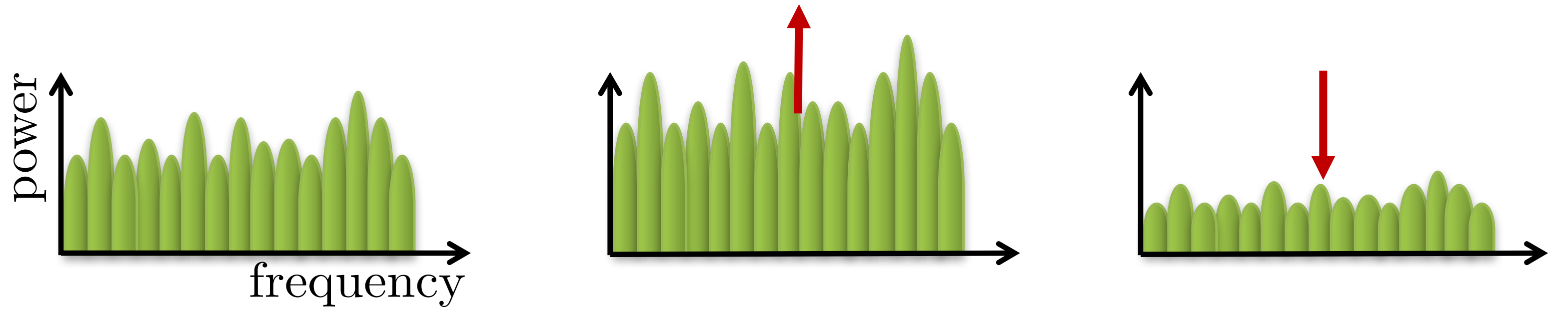
Fixed Power Allocation

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

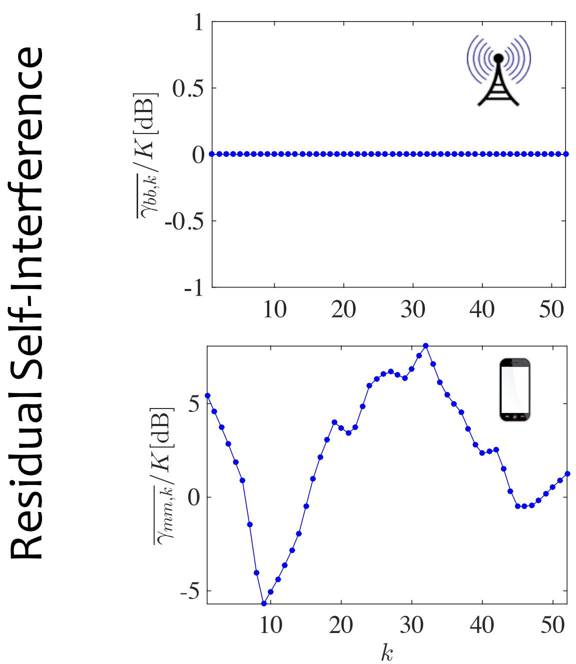


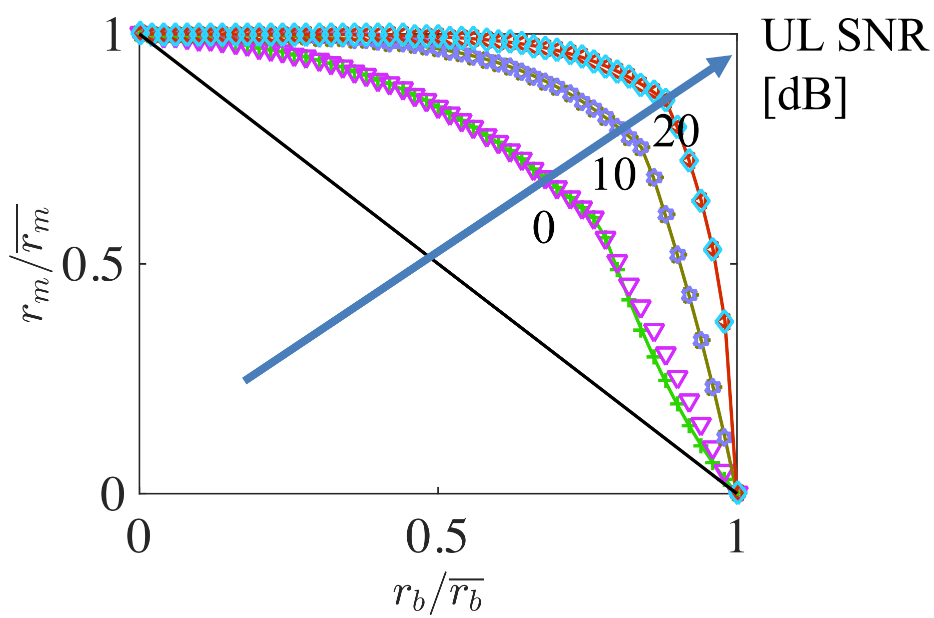
Lemma: At the boundary of the capacity region, either uplink or downlink sum of the power levels must be equal to its maximum value

- Equivalent to the result for the single channel
- Every point on the boundary of FD capacity region can be found via bisection

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





(avg DL SNR) - (avg UL SNR) = 20dB

General Power Allocation (I)

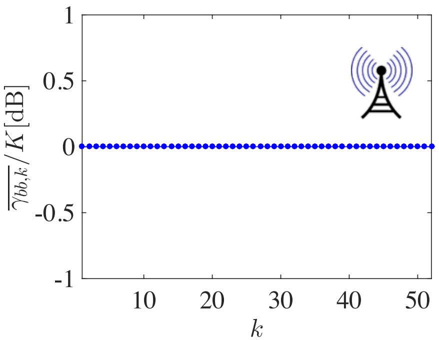
$$\max \quad r_m$$
$$\text{s.t.} \quad r_b = r_b^*$$

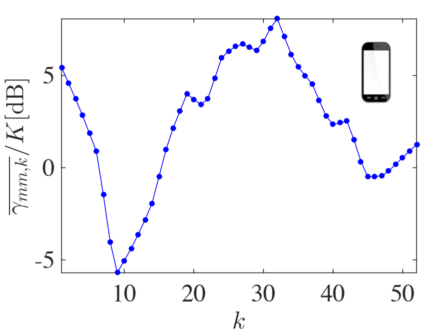
- Can assign any TX power to any channel, as long as

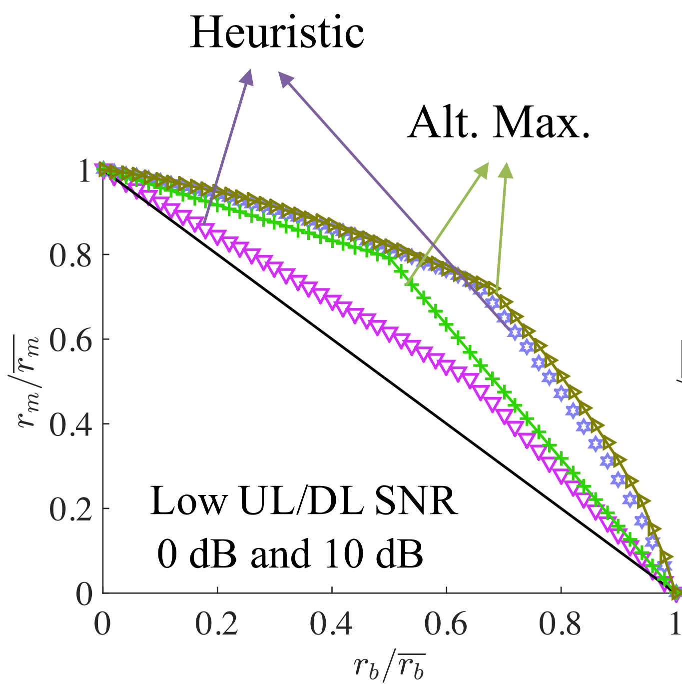
$$\sum_{k=1}^{K} \alpha_{b,k} \leq 1, \quad \sum_{k=1}^{K} \alpha_{m,k} \leq 1$$

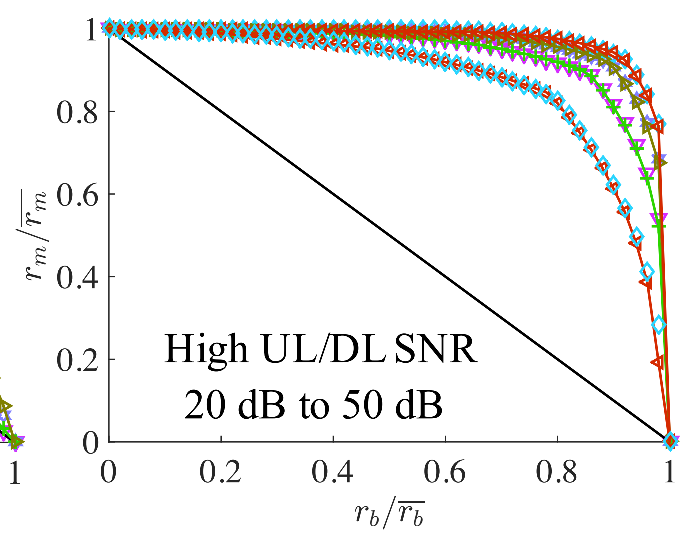
- A non-convex problem
- We show how to, under mild restrictions, solve this problem with an alternating minimization (maximization) method
- The algorithm converges to a stationary point that is a global max in practice
- We also design a simple heuristic that has similar performance
- Intuition for the heuristic:
  - Half-duplex power allocation when one of the rates is close to zero
  - High-SINR approximation power allocation around the point that maximizes the sum of the uplink and downlink rates over channels
  - Turning some of the channels off may increase the rate

General Power Allocation (II)





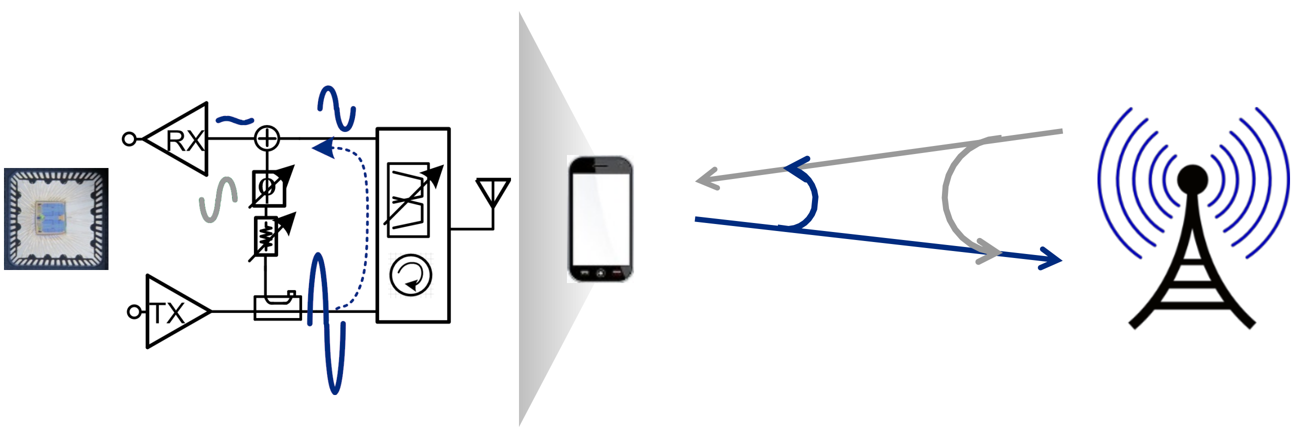




avg DL SNR = avg UL SNR

Summary

- Characterized rate improvements and properties of the capacity regions for full-duplex links
- Used realistic models of the hardware
- The results are analytical and insightful
- Bottom line: simple policies and algorithms are enough
- Future work:
  - Wi-Fi and cellular MAC: (fair) resource allocation and scheduling



Questions?

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