Experiment-Driven Characterization of Full-Duplex Wireless Systems

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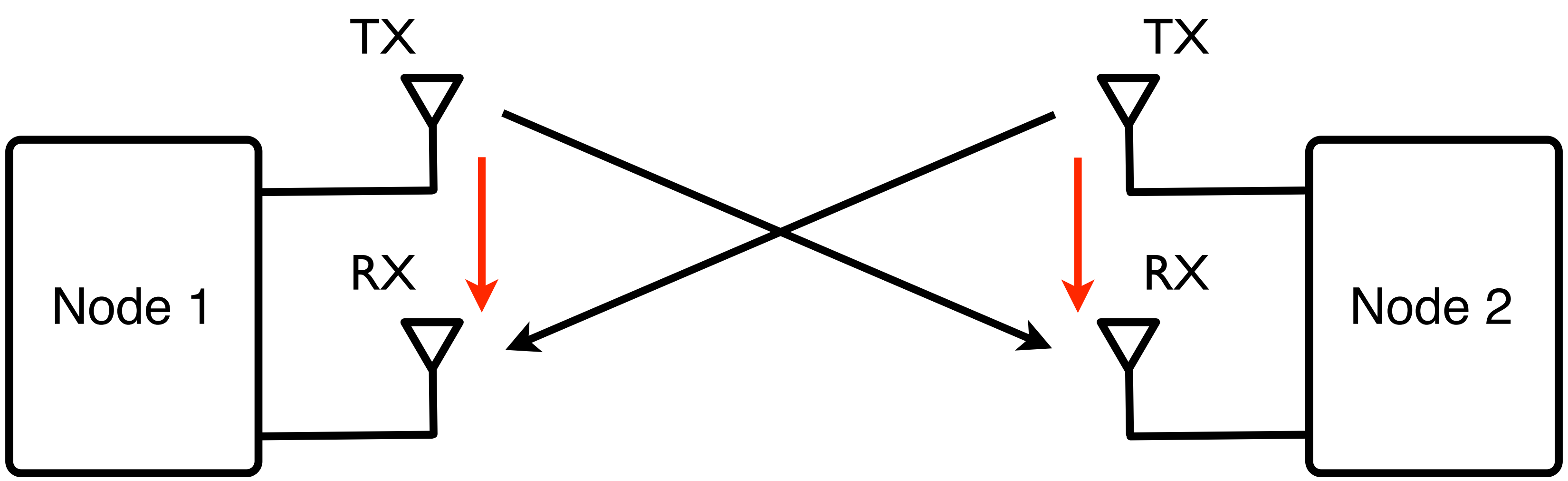
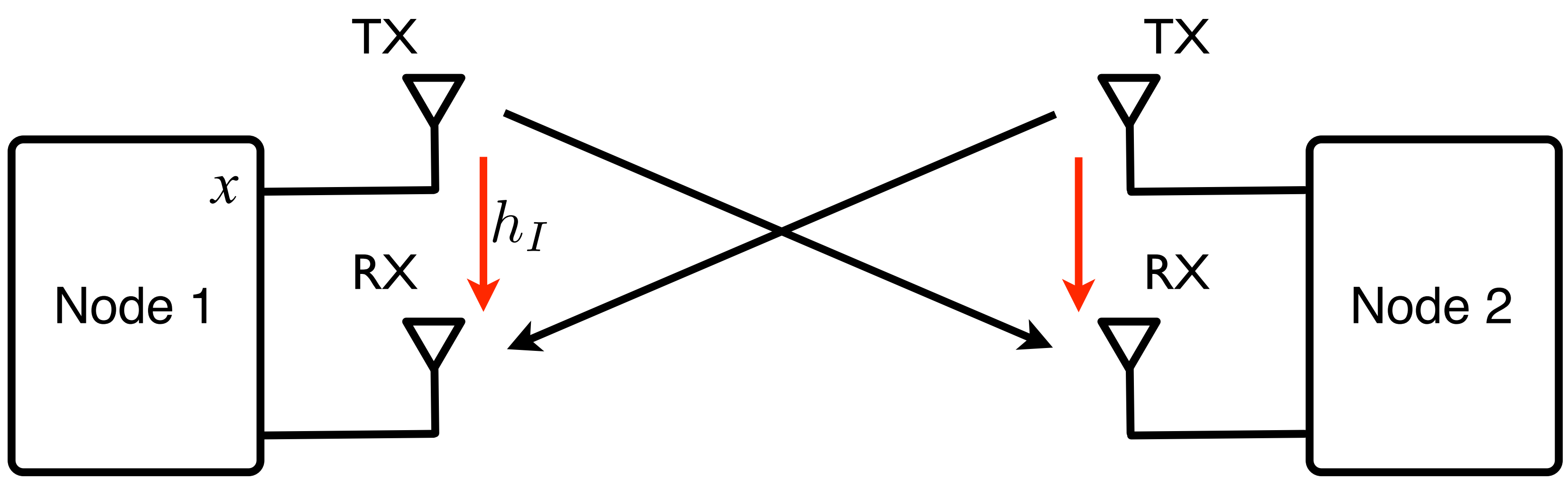
Full-Duplex Wireless



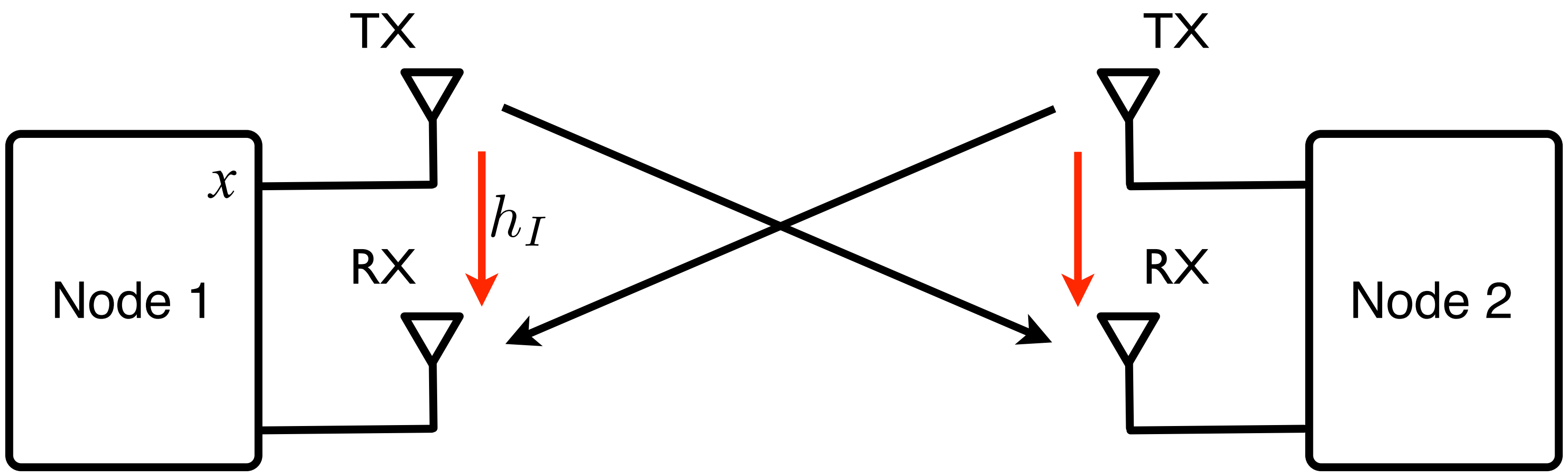
- Same time same frequency band
- Assumed to be impossible due to large self interference
- Revisit this assumption using techniques for interference cancellation
- Can full-duplex achieve higher data rates than half-duplex ?
- Characterize amount of cancellation and achievable rate performance

Interference Problem



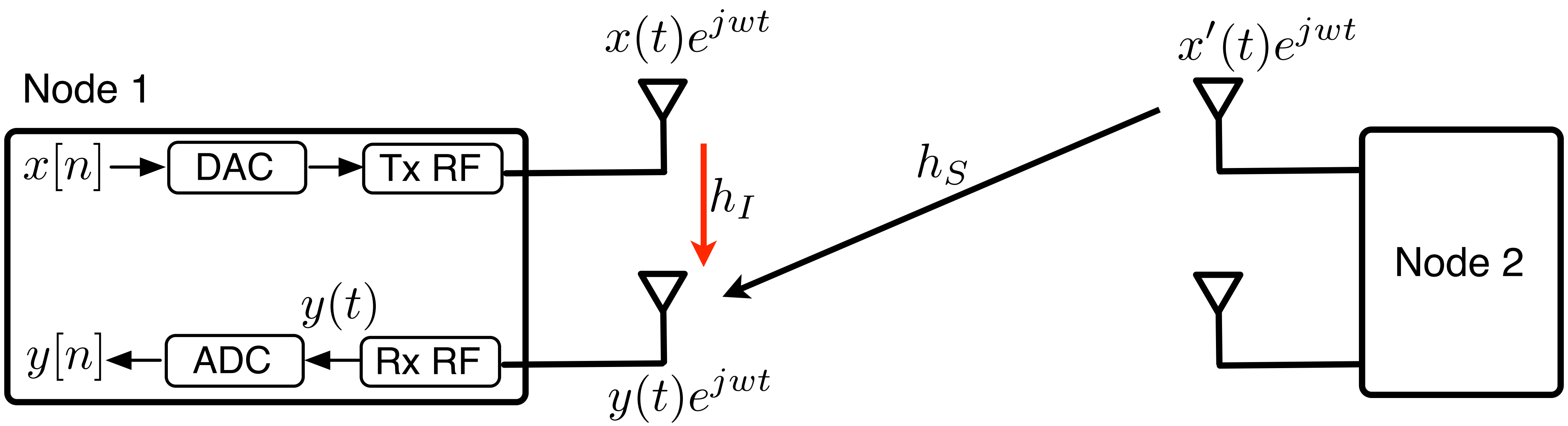
- Theory
  - Interference >> Signal
  - Strong interference regime
  - Interference is known, estimate channel, cancel, done

Interference Problem



- Implementation

Interference Problem



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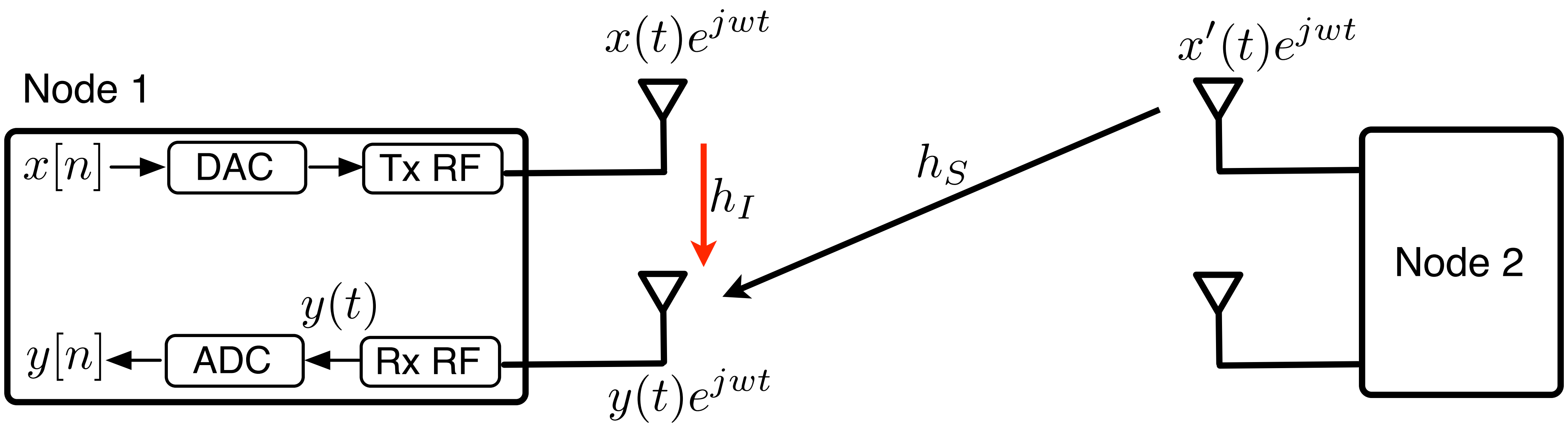
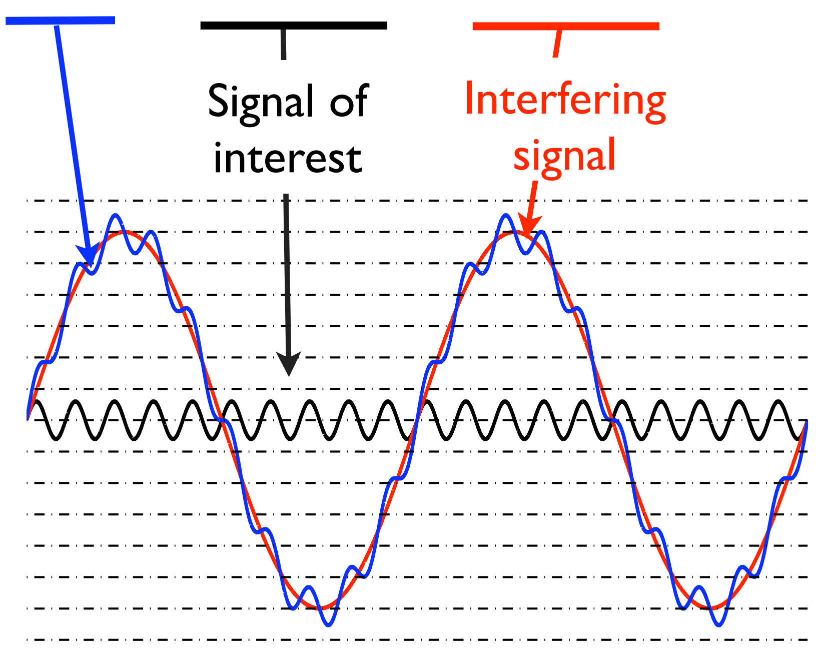


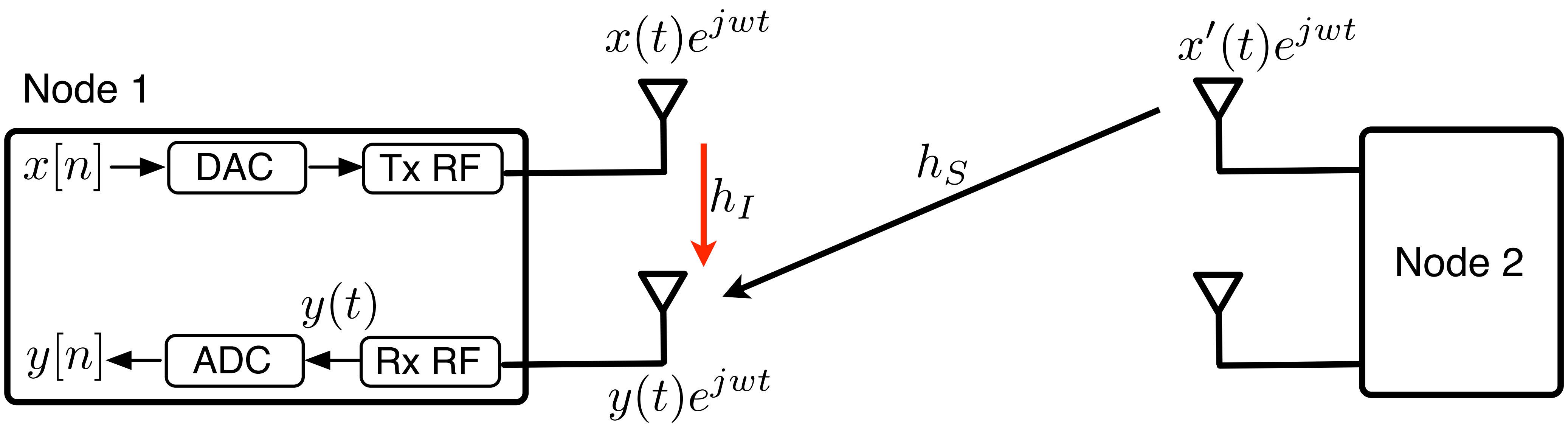
- Implementation

- Received signal

$$y(t) = h_S x'(t) + h_I x(t) + z(t)$$



Interference Problem



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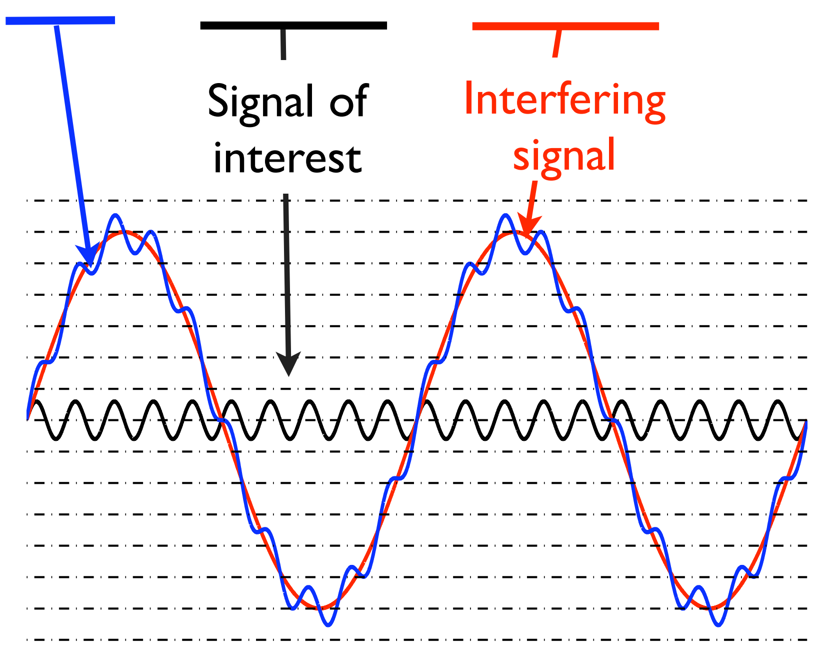
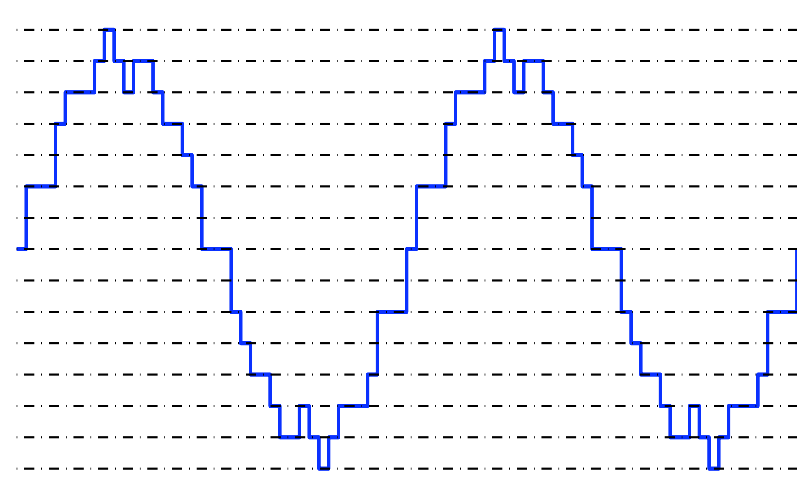


- Quantized received signal

$$y[n] = h_S x'[n] + h_I x[n] + z[n]$$



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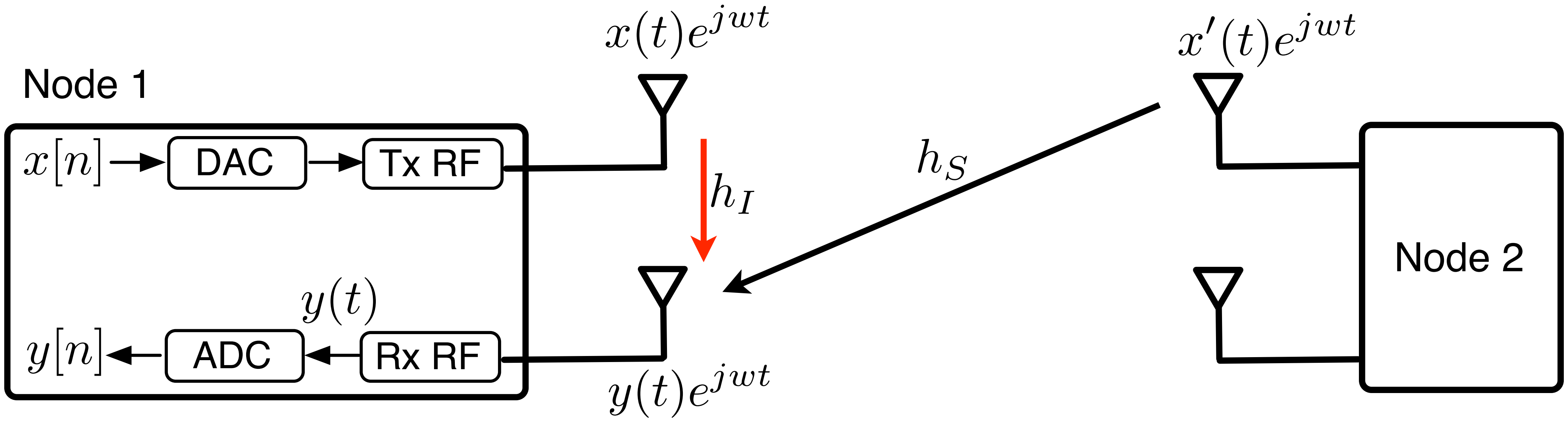

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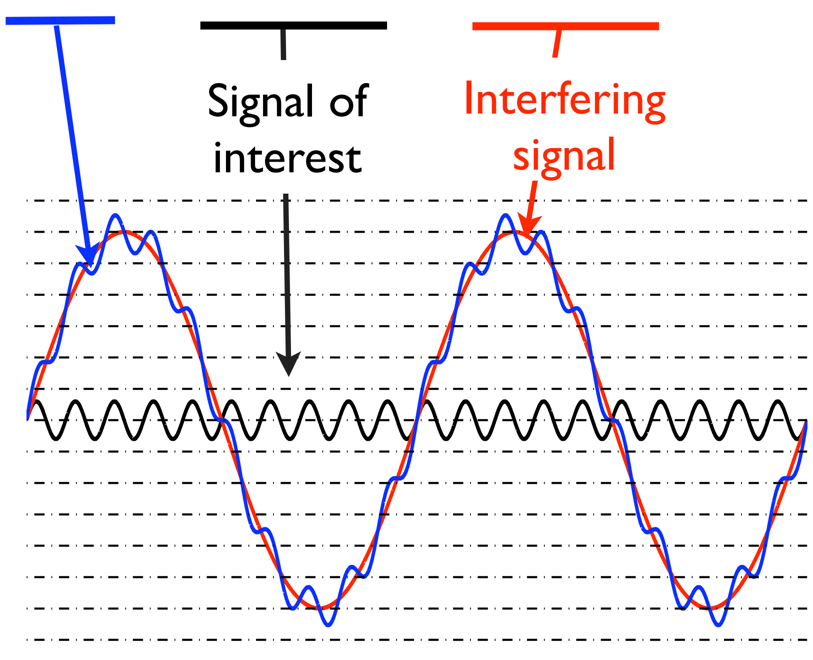

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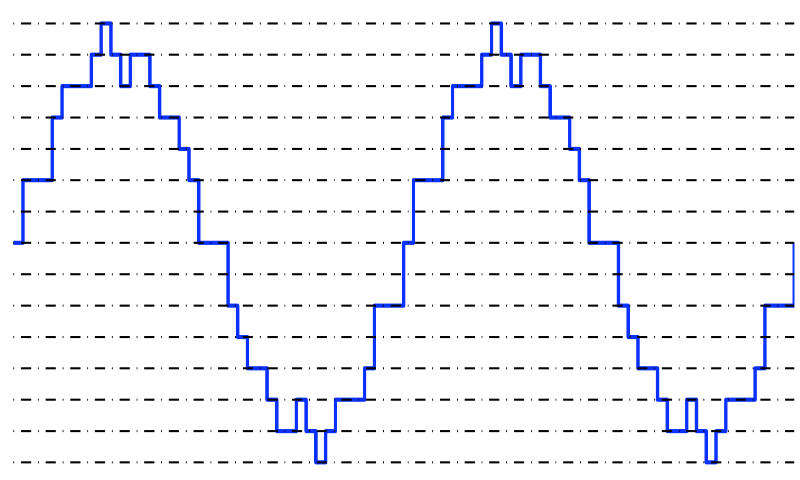
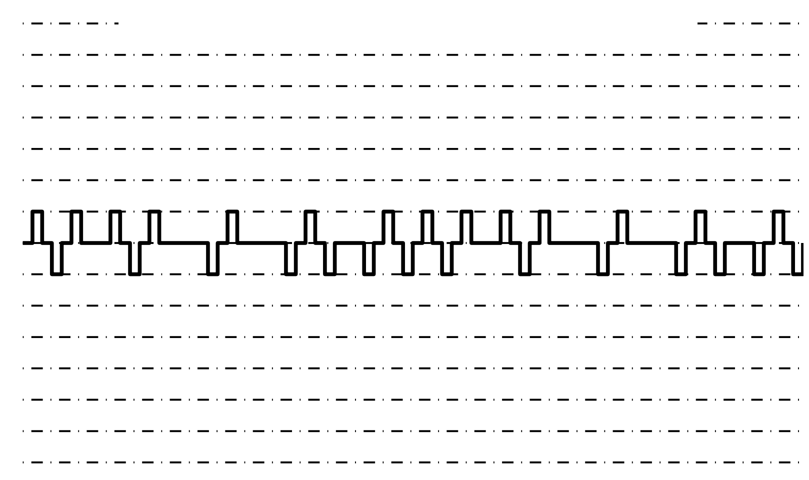


- After removing interference

$$y[n] = h_S x'[n] + z[n]$$

Quantization noise



Interference Problem

- Implementation
  - Interference >> Signal : Quantization noise
  - Full-duplex assumed to be impossible due to large self interference

- Real systems SIR

-100 dB → -20 dB

Outdoor
Cellular

Distance between nodes decreases

Indoor
Bluetooth, WiFi

- More than 20 dB cancellation has been reported in radar systems

- Revisit this assumption using passive and active techniques for interference cancellation

Passive Cancellation

- Antenna Separation

- Antenna Directionality

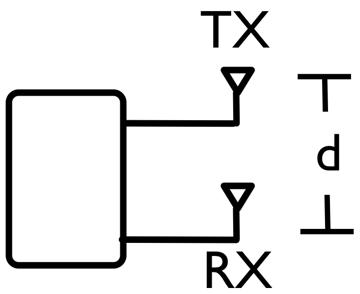
- Antenna Cancellation

- Device Cancellation

Passive Cancellation

- Antenna Separation

  Separation d between same node Tx and Rx antennas



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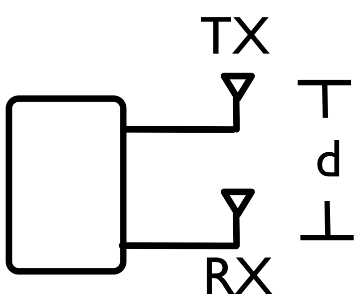
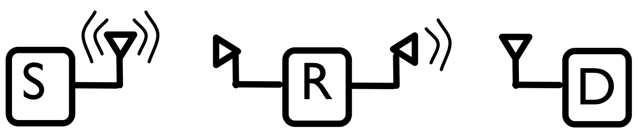


- Antenna Directionality

  Used in Full-duplex Relays



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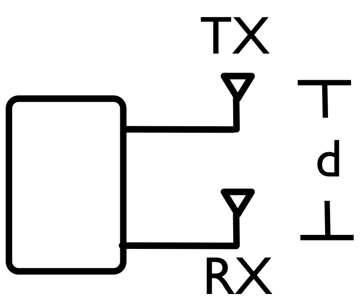

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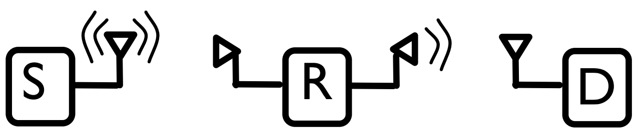

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  2 Tx and 1Rx per node, Tx at d and d+λ/2

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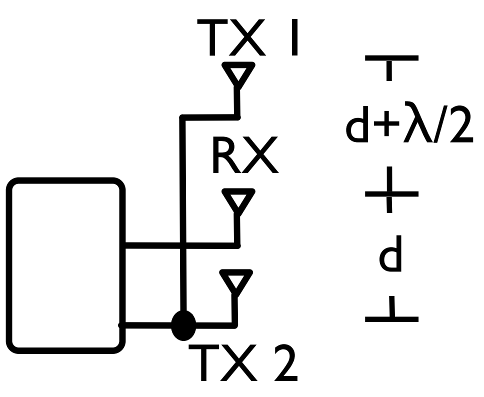

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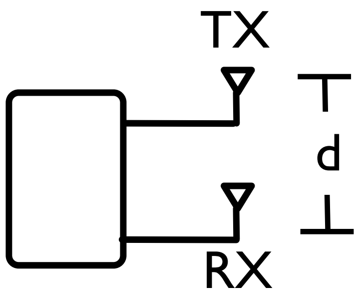

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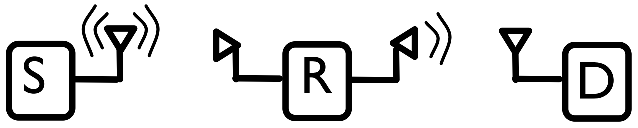

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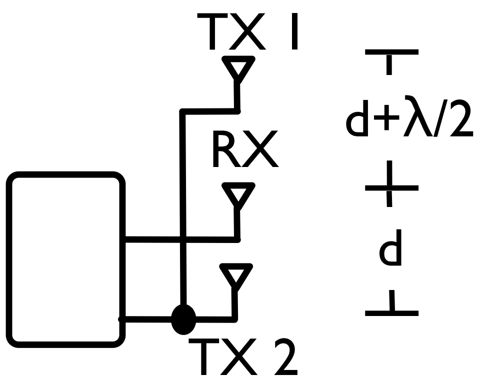
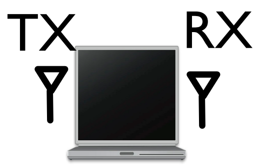


- Device Cancellation

  Place antennas at opposite sides of the device

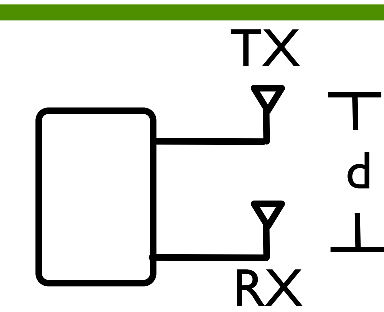


Sahai et al. *Pushing the Limits of Full-Duplex: Design and Real-Time Implementation.* Tech. Report 2011. Rice University.

Passive Cancellation

- Antenna Separation

  Separation d between same node Tx and Rx antennas
  - We use antenna separation with d = 10cm, 20cm, 40cm
  - Worse case interference
  - Minimum resources for passive cancellation



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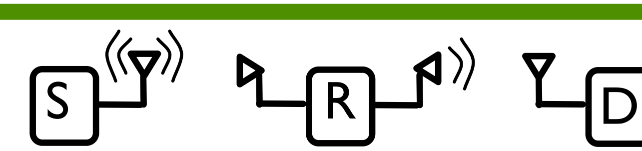

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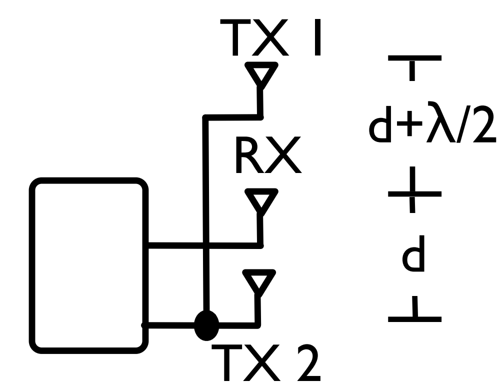

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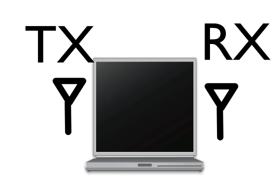


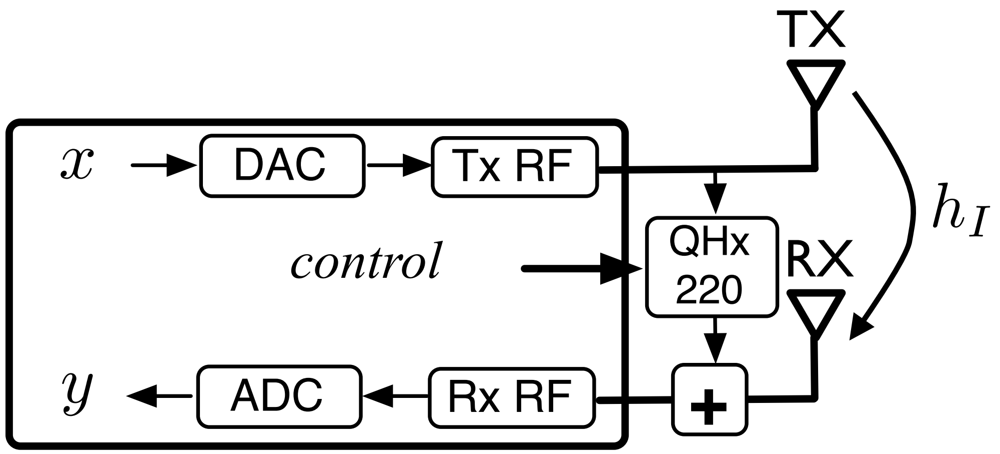
Active Analog Cancellation

- Using QHx220 chip

- Using extra Tx RF chain (without a power amplifier)

Active Analog Cancellation

- Using QHx220 chip
  - Tuning algorithm to control gain and delay that chip applies to its input
  - Suitable for wideband frequency flat h_I



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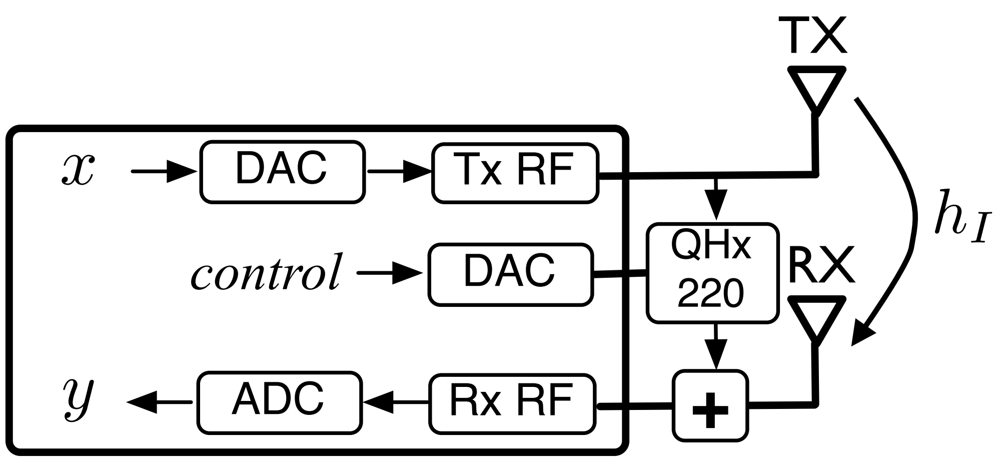

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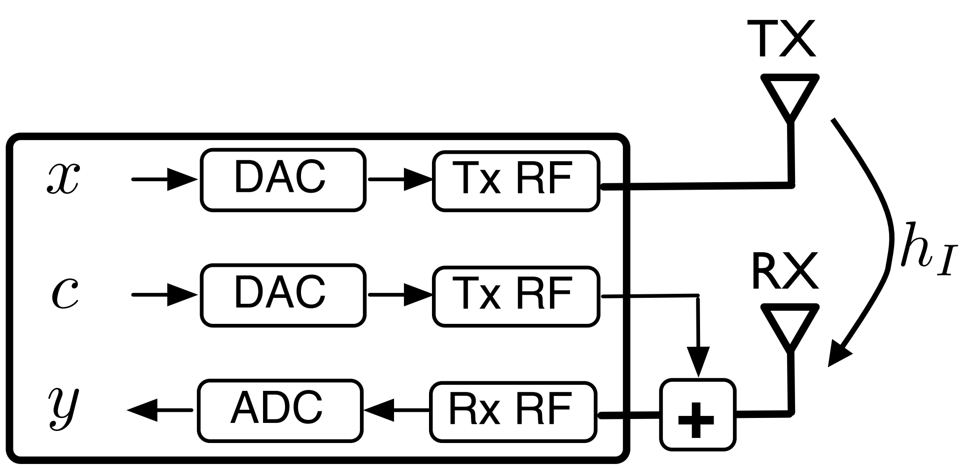
- Using extra Tx RF chain (without a power amplifier)
  - Estimate h_I and design c for analog cancellation
  - Suitable for wideband frequency flat ***and frequency selective*** h_I
  - ***Uses off-the-shelf MIMO radios***



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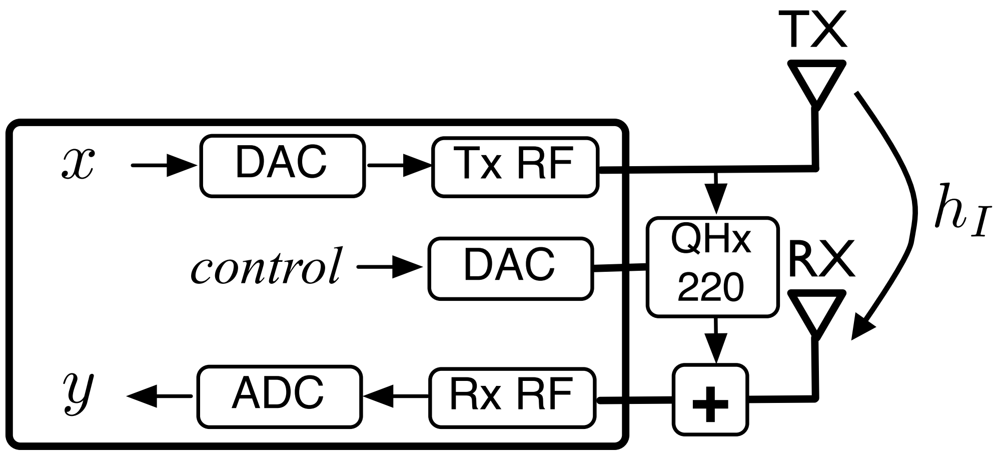

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- Used in our experiments

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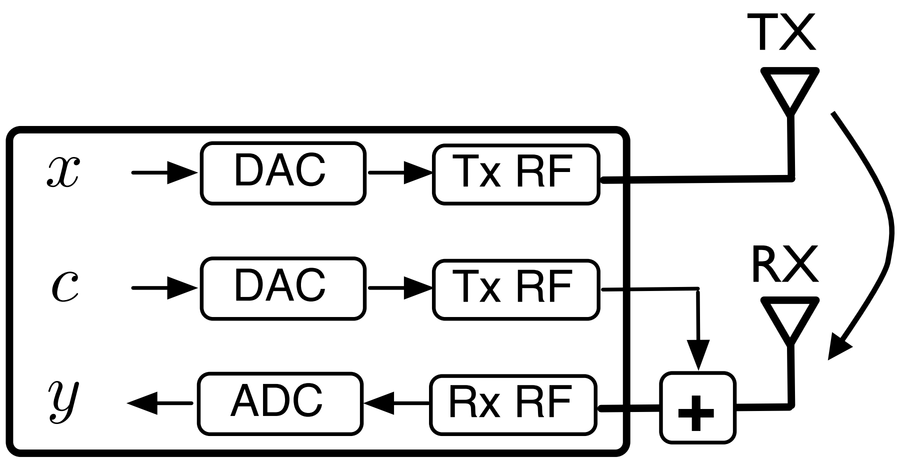

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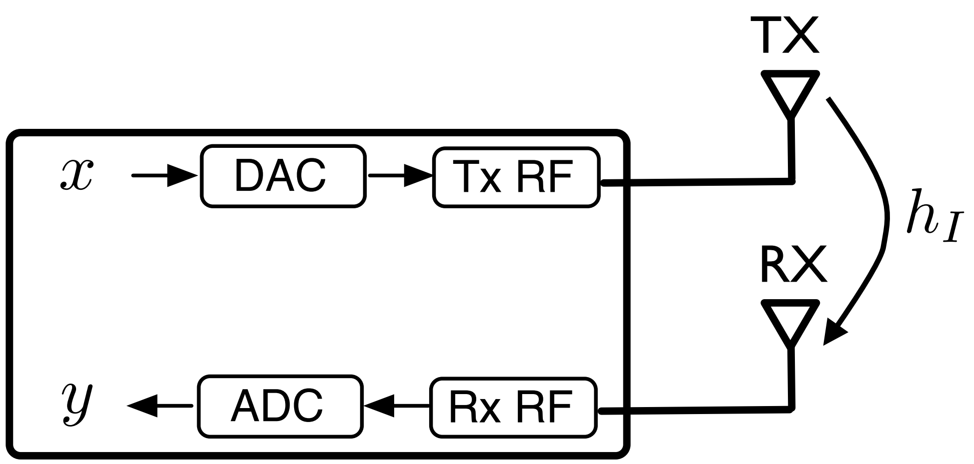
Active Digital Cancellation

- Without analog cancellation

- Combined with analog cancellation

Active Digital Cancellation

- Without analog cancellation
  - Estimate h_I and cancel $h_I x$ in the digital domain



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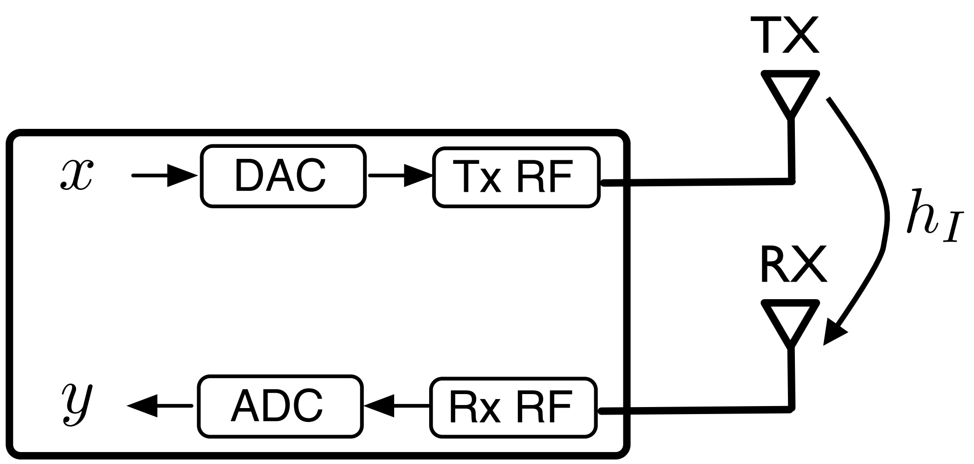
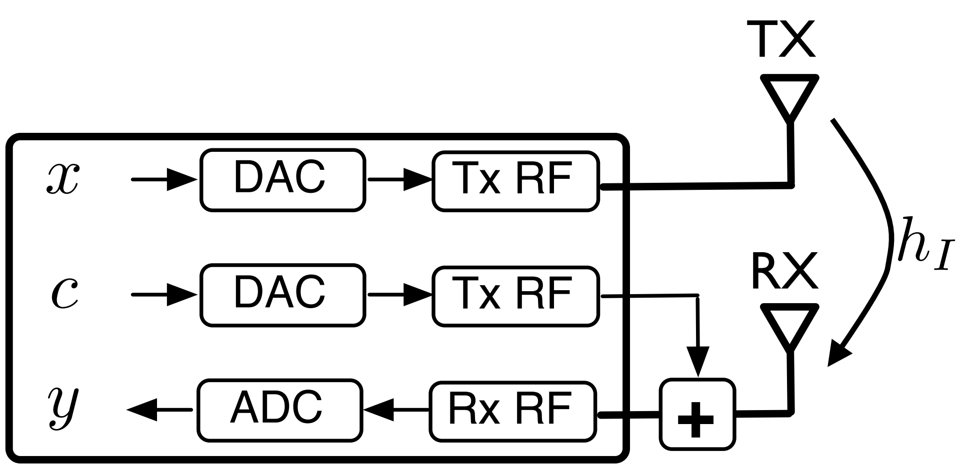


- Combined with analog cancellation
  - Estimate residual interference and cancel in the digital domain



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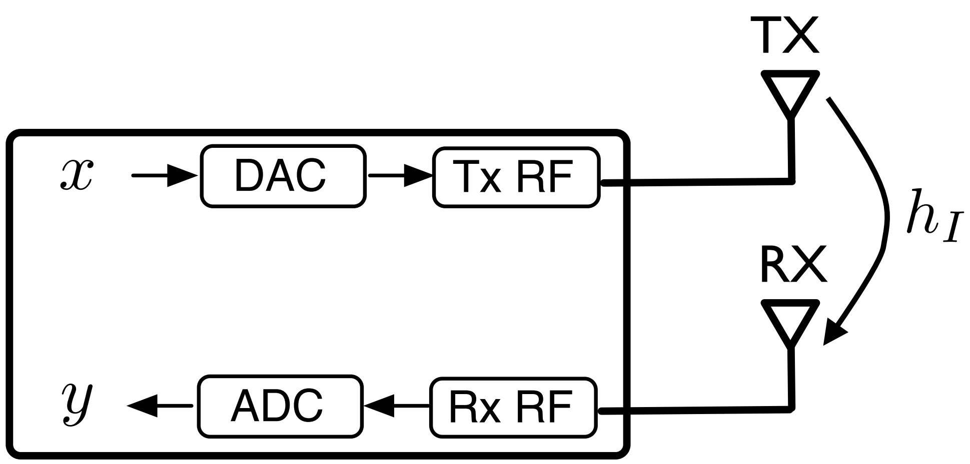

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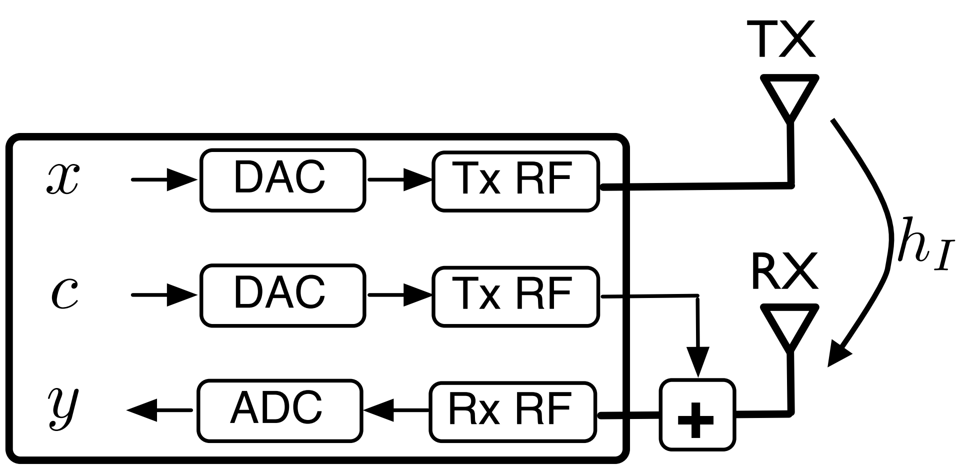

- We have considered the two options above
  - Allows us to characterize the effect in total cancellation when concatenating cancellation mechanisms
  - Duarte et al. *Experiment-Driven Characterization of Full-duplex Wireless Systems*. Submitted to IEEE Trans. Wireless 2011.

Full-Duplex Systems Considered

- We have implemented the following full-duplex systems
  - Antenna Separation + Digital Cancellation
  - Antenna Separation + Analog Cancellation
  - Antenna Separation + Analog Cancellation + Digital Cancellation

Summary of Results

- Characterization of self-interference cancellation mechanisms
  - Amount of cancellation
  - Impact on full-duplex achievable rate performance

- Comparison with half-duplex systems
  - Demonstrated that full-duplex can achieve higher rates than half-duplex

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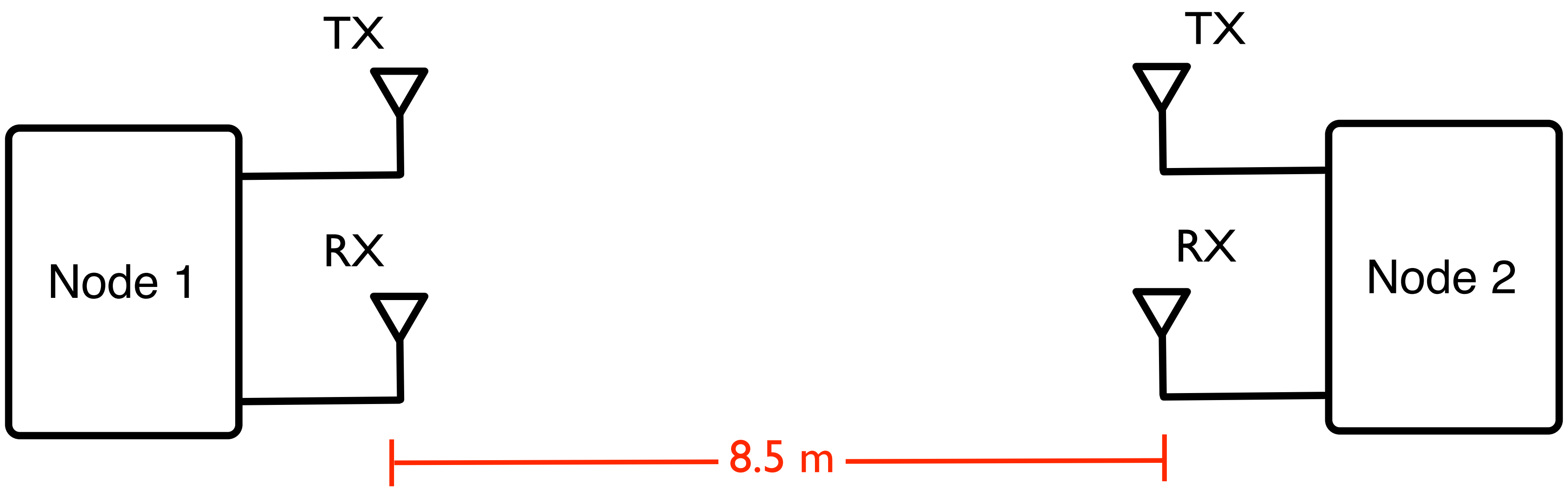

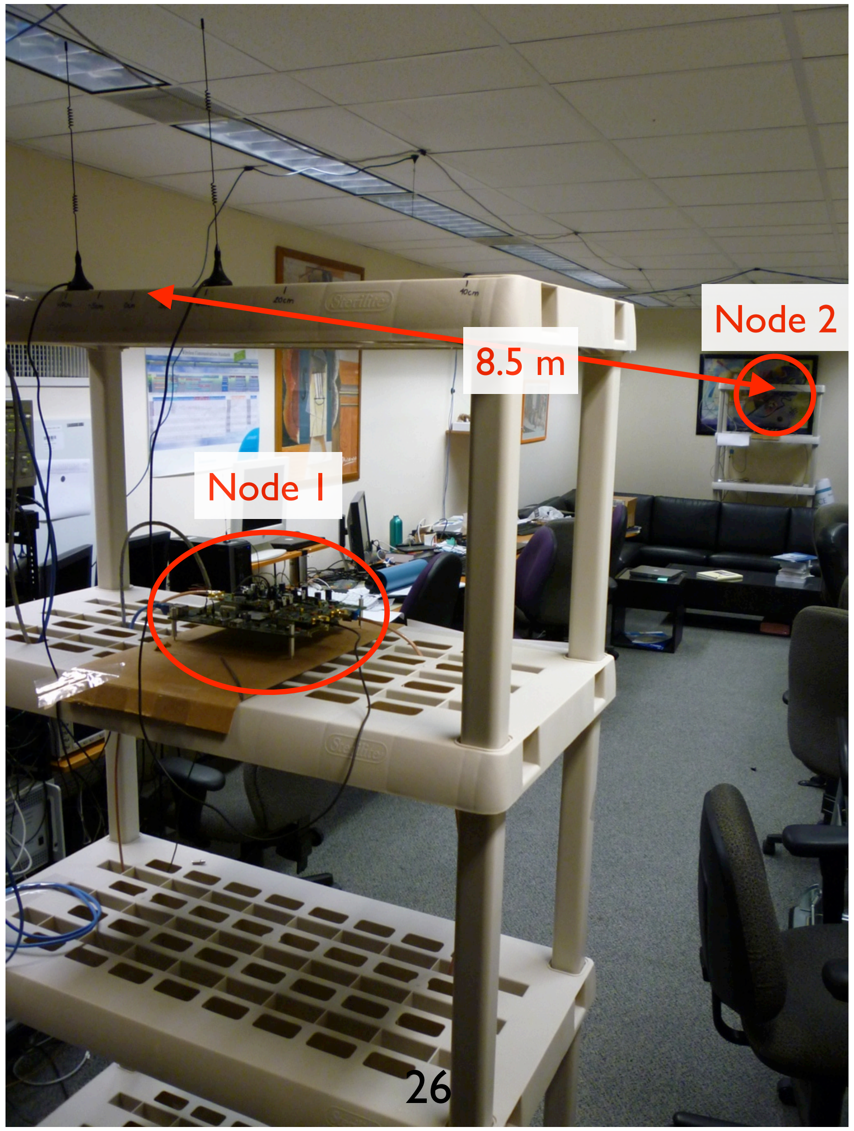

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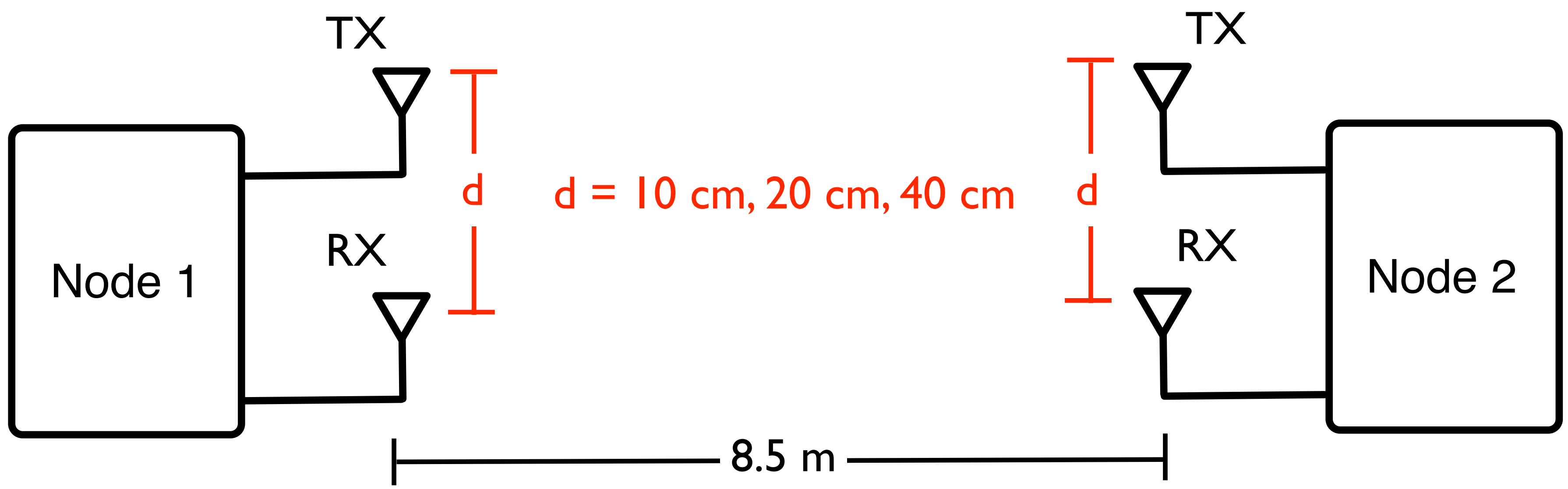

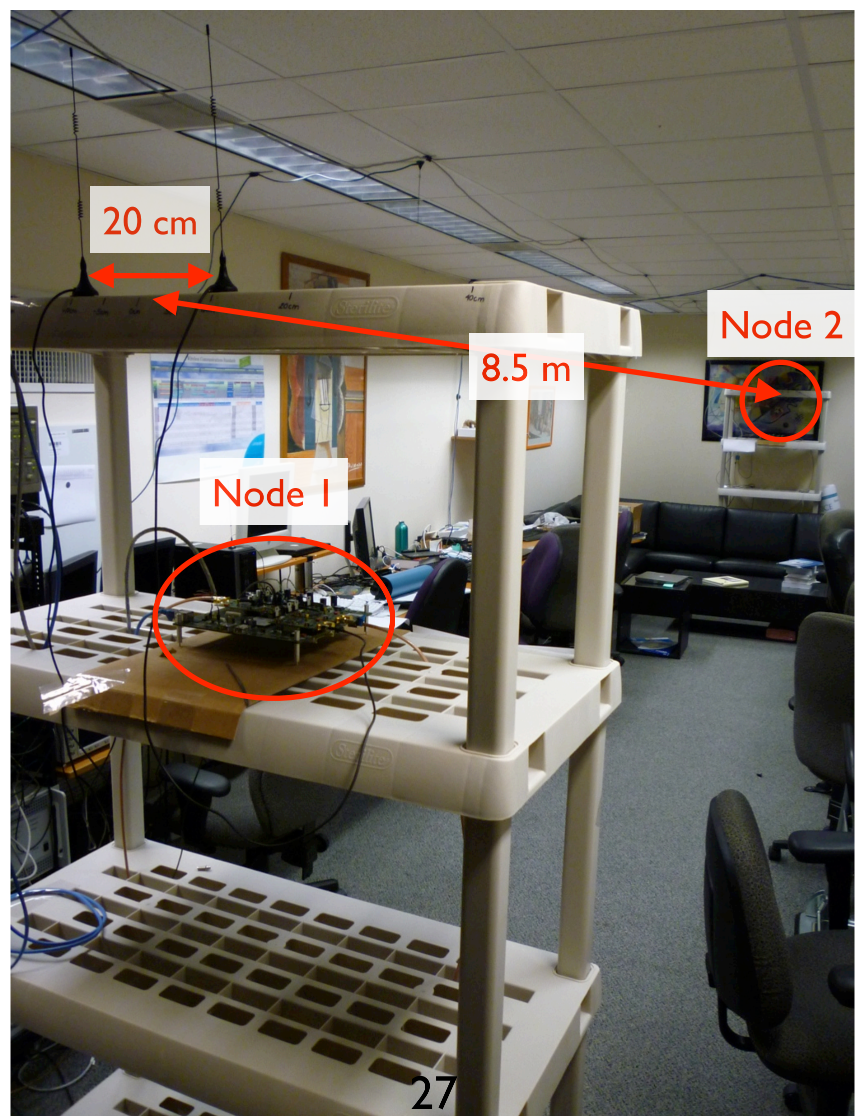

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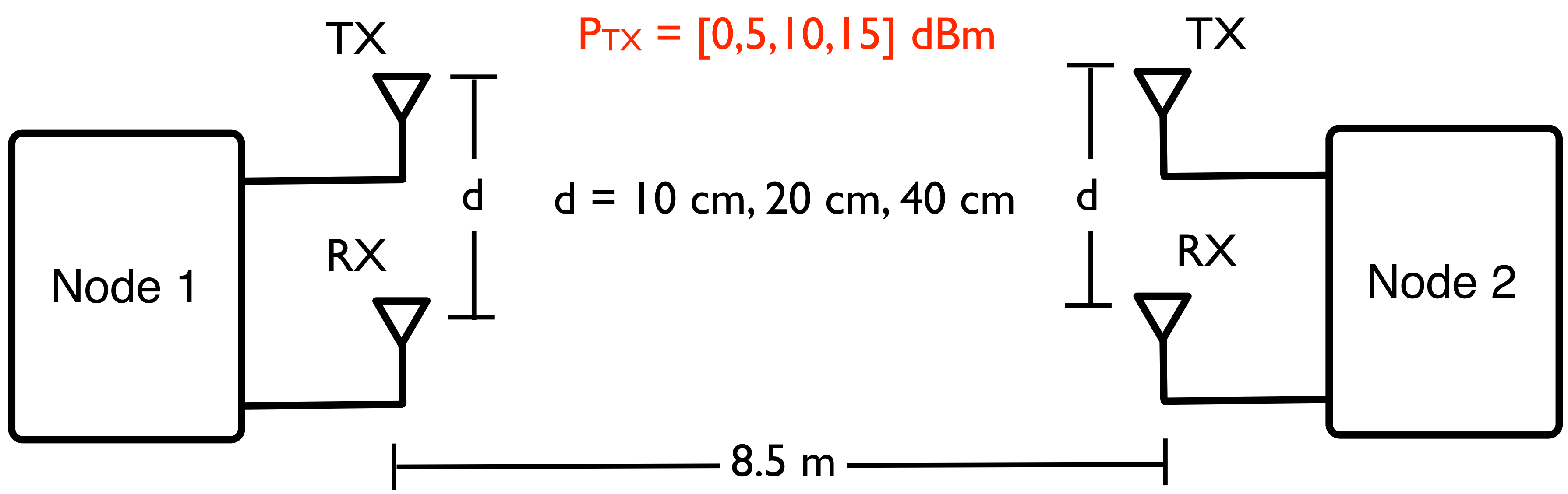

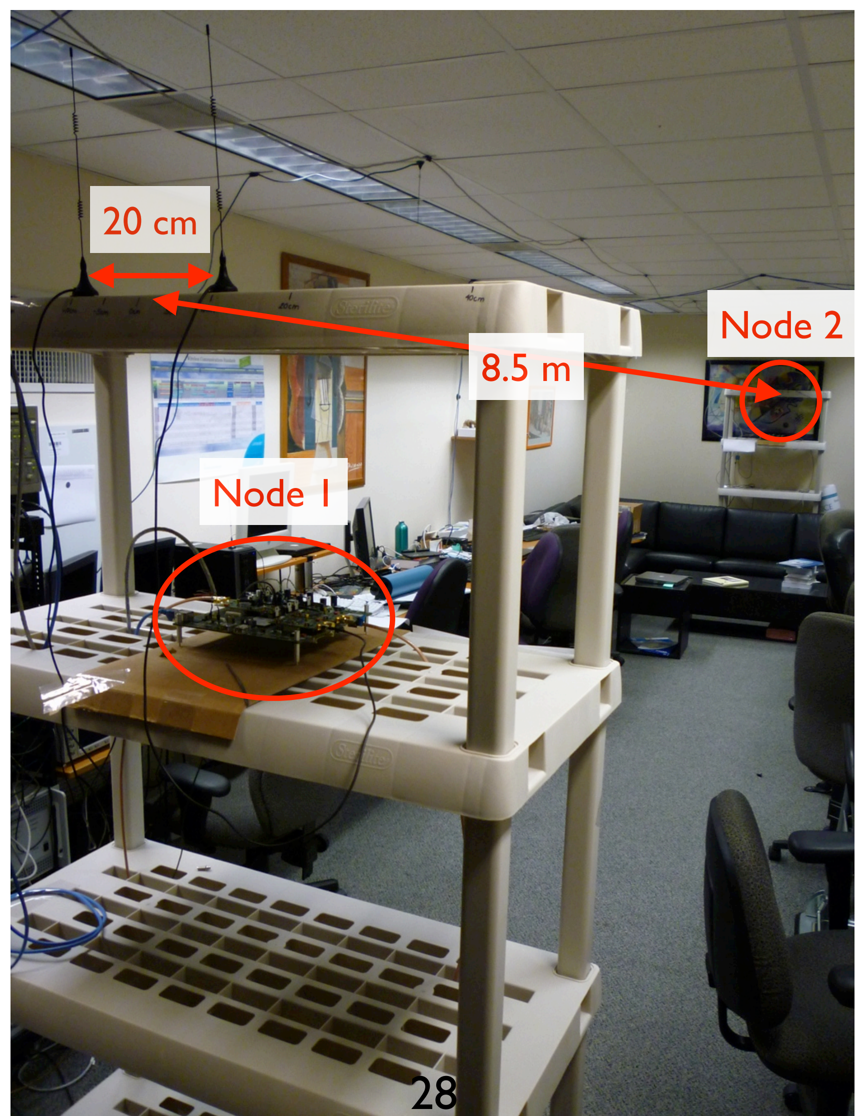

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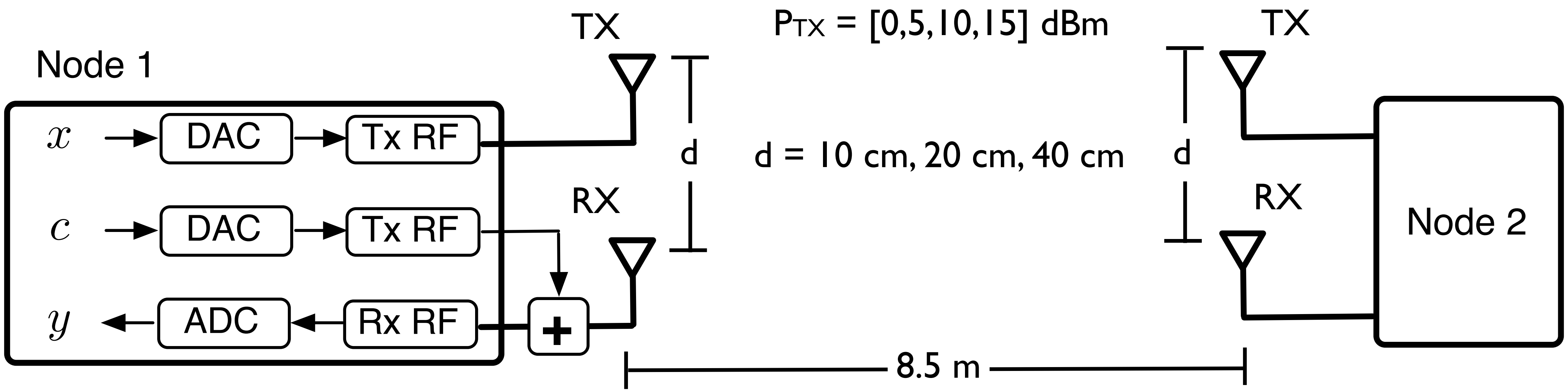
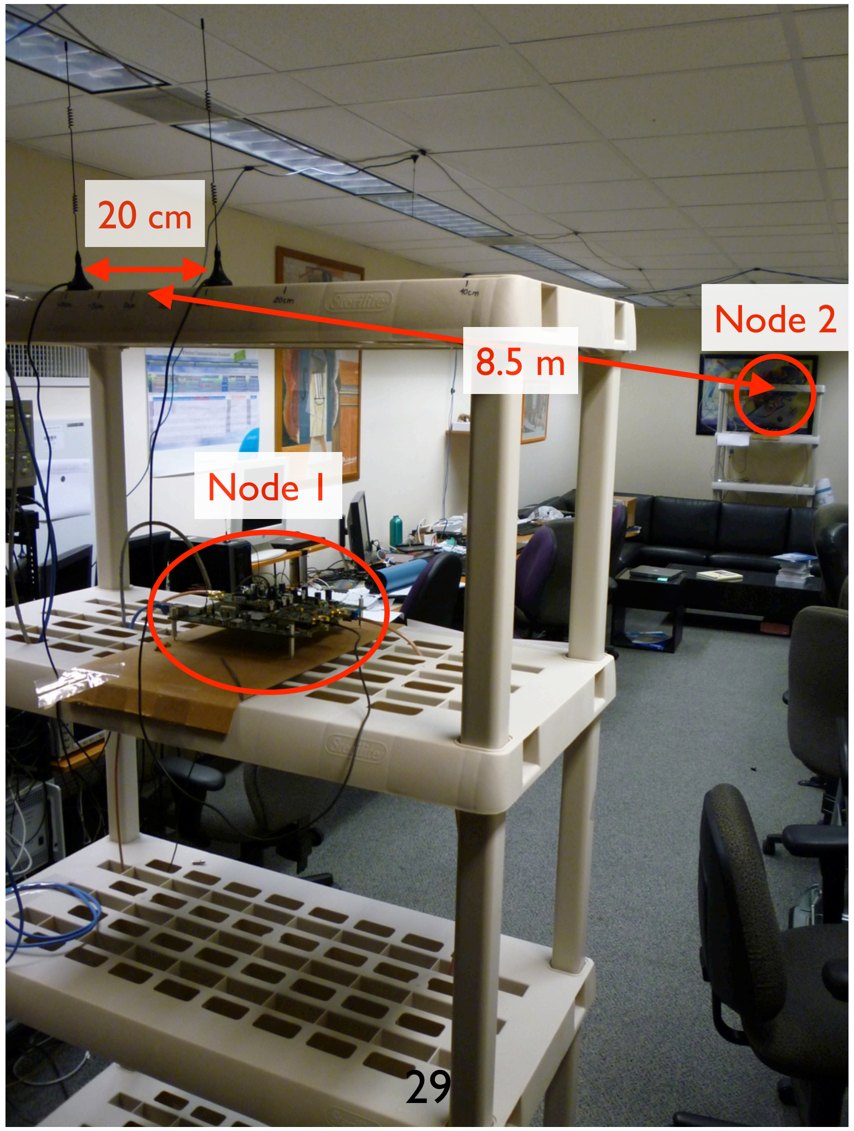


- WARP with 3 radios
- WARPLab = WARP + Matlab, to generate/analyze signals
- Narrowband tests, 0.65 MHz
- Recent extension to OFDM 10MHz @ Rice
  - Sahai et al. *Pushing the Limits of Full-Duplex: Design and Real-Time Implementation.* Tech. Report 2011. Rice University.



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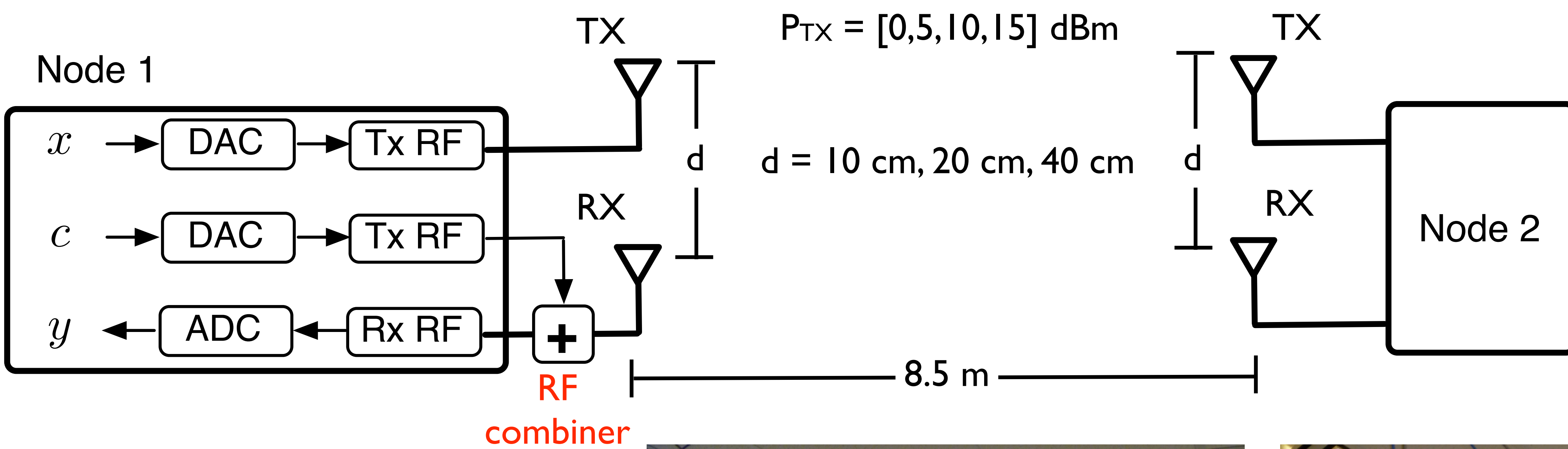

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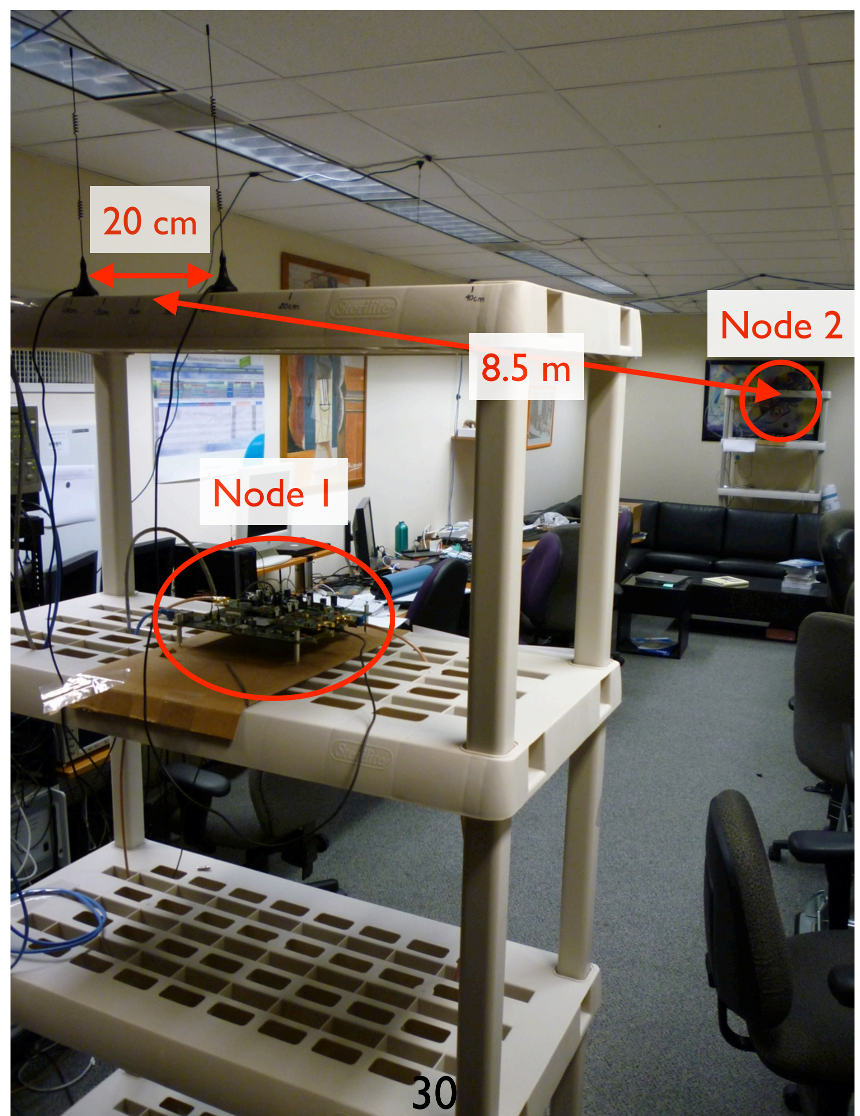

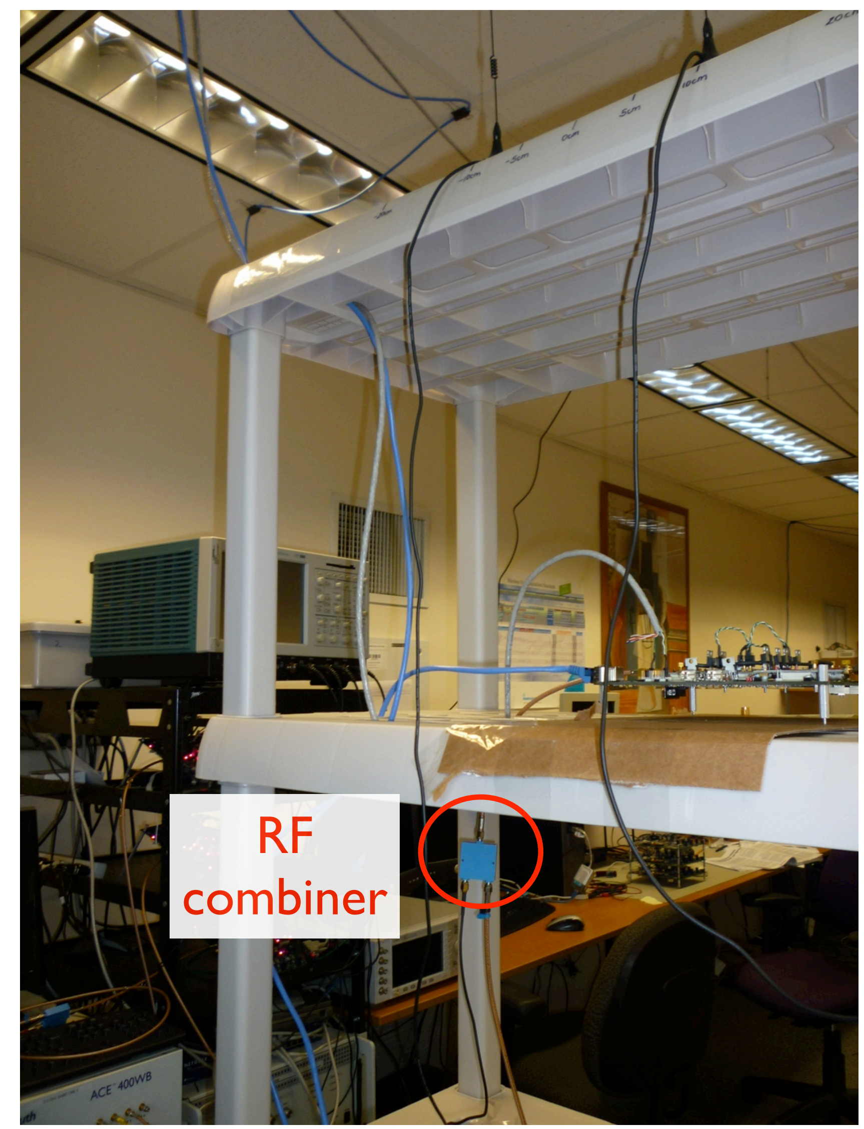

Characterization of Average Cancellation

- Digital cancellation
- Analog cancellation
- Analog and digital cancellation

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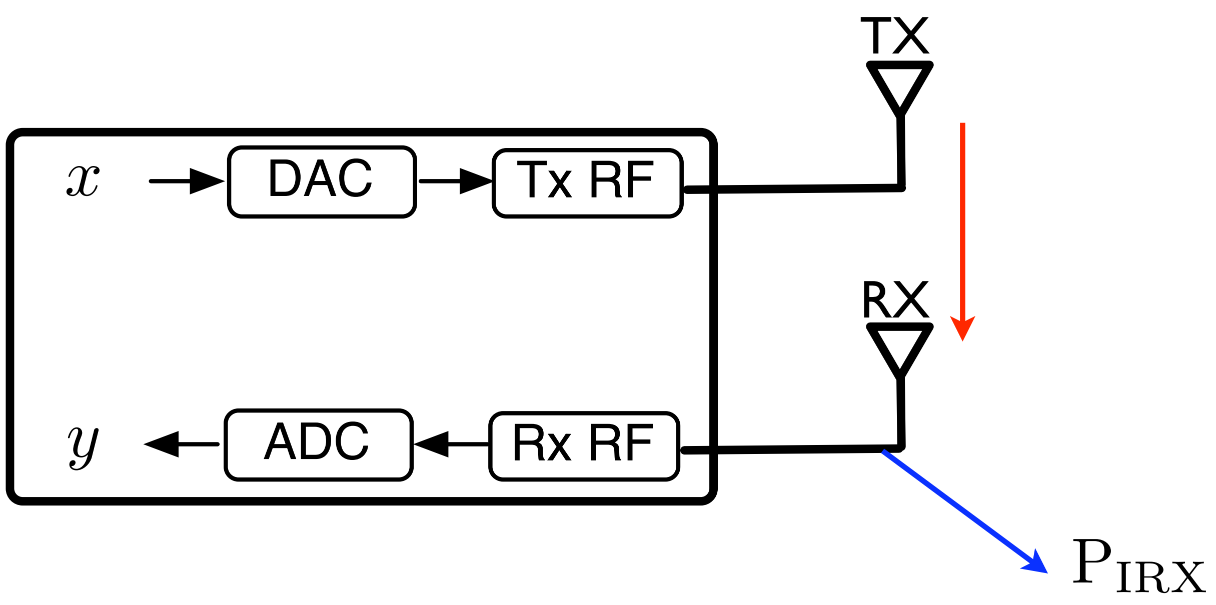

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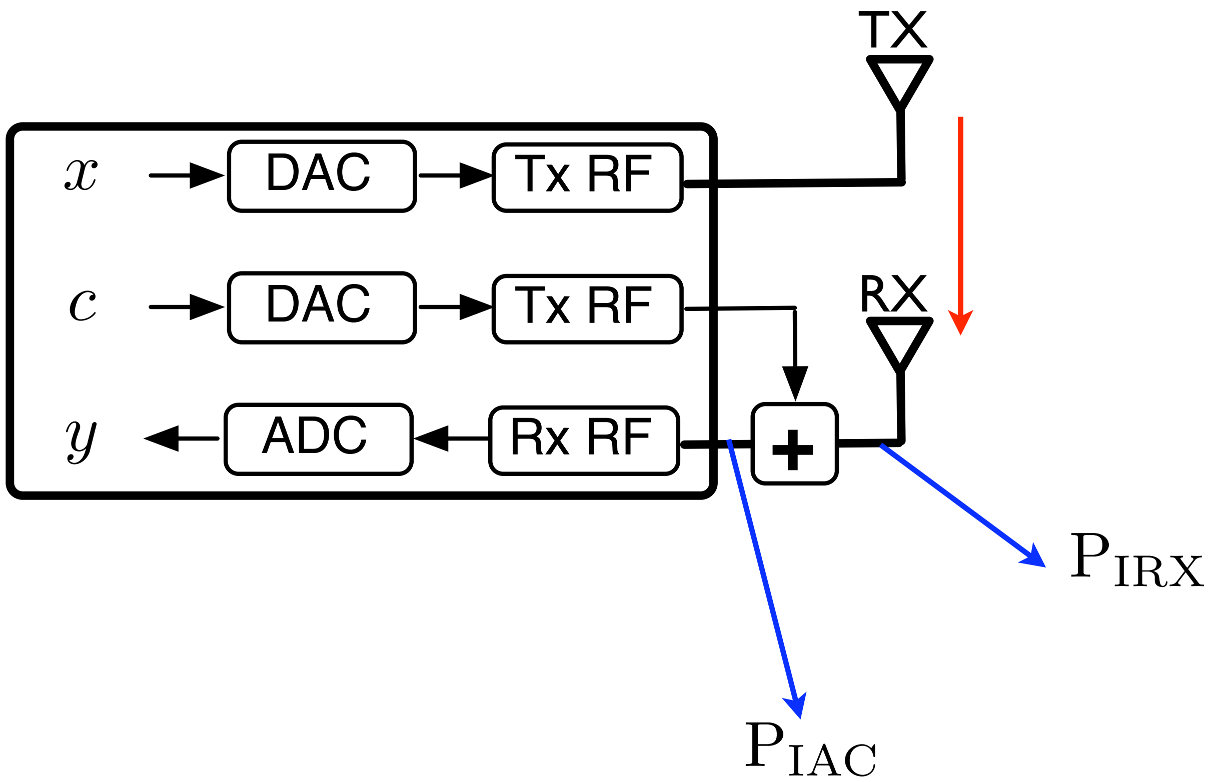
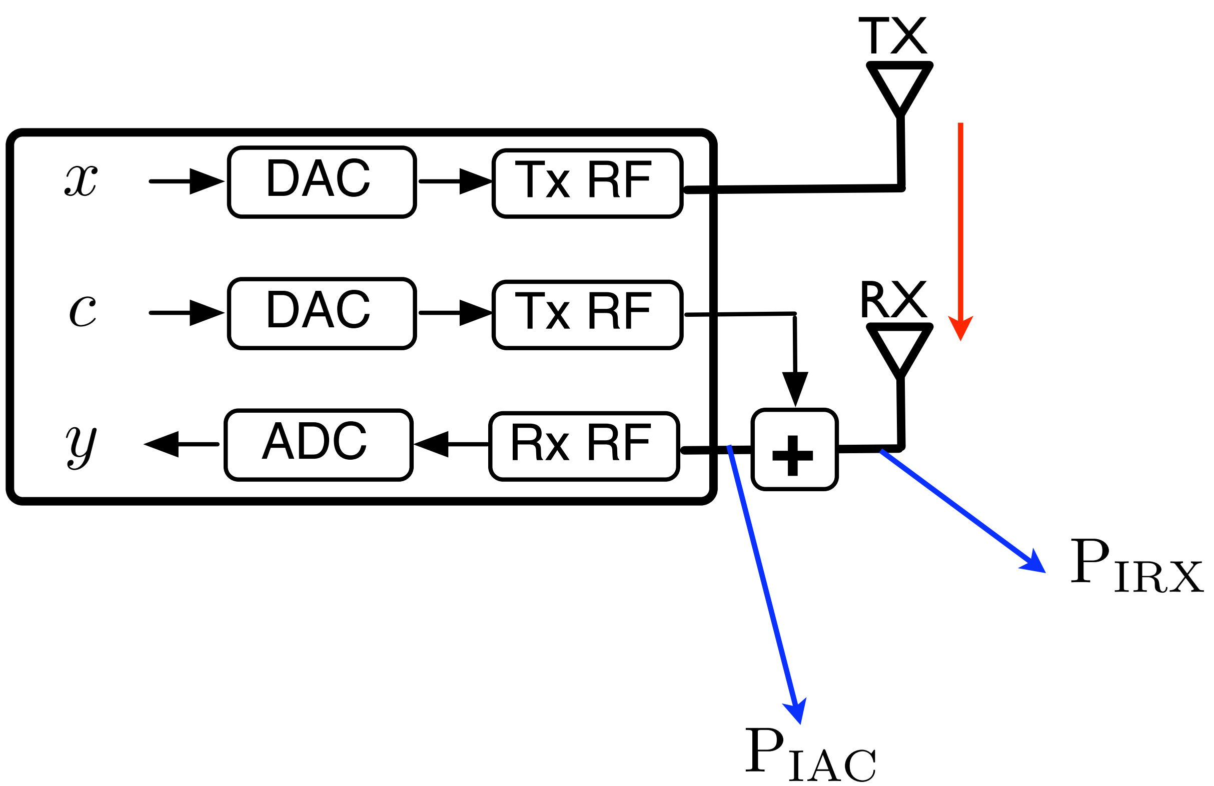


Characterization of Average Cancellation

- Digital cancellation
- Analog cancellation

$$\alpha_{\mathrm{AC}} = \mathrm{P}_{\mathrm{IRX}} - \mathrm{P}_{\mathrm{IAC}}$$

- Analog and digital cancellation



Characterization of Average Cancellation

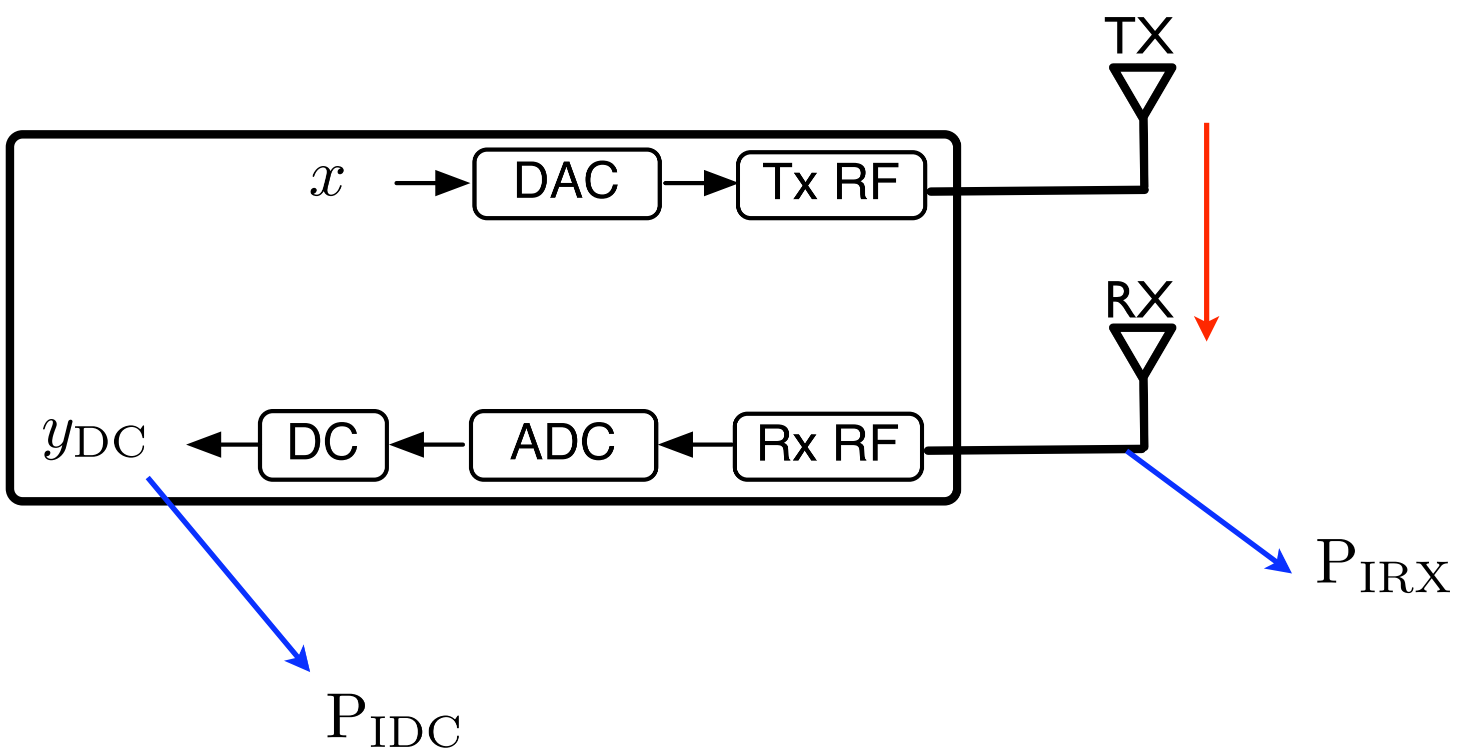
- Digital cancellation

$$\alpha_{\mathrm{DC}} = \mathrm{P}_{\mathrm{IRX}} - \mathrm{P}_{\mathrm{IDC}}$$

- Analog cancellation

$$\alpha_{\mathrm{AC}} = \mathrm{P}_{\mathrm{IRX}} - \mathrm{P}_{\mathrm{IAC}}$$

- Analog and digital cancellation



Characterization of Average Cancellation

- Digital cancellation

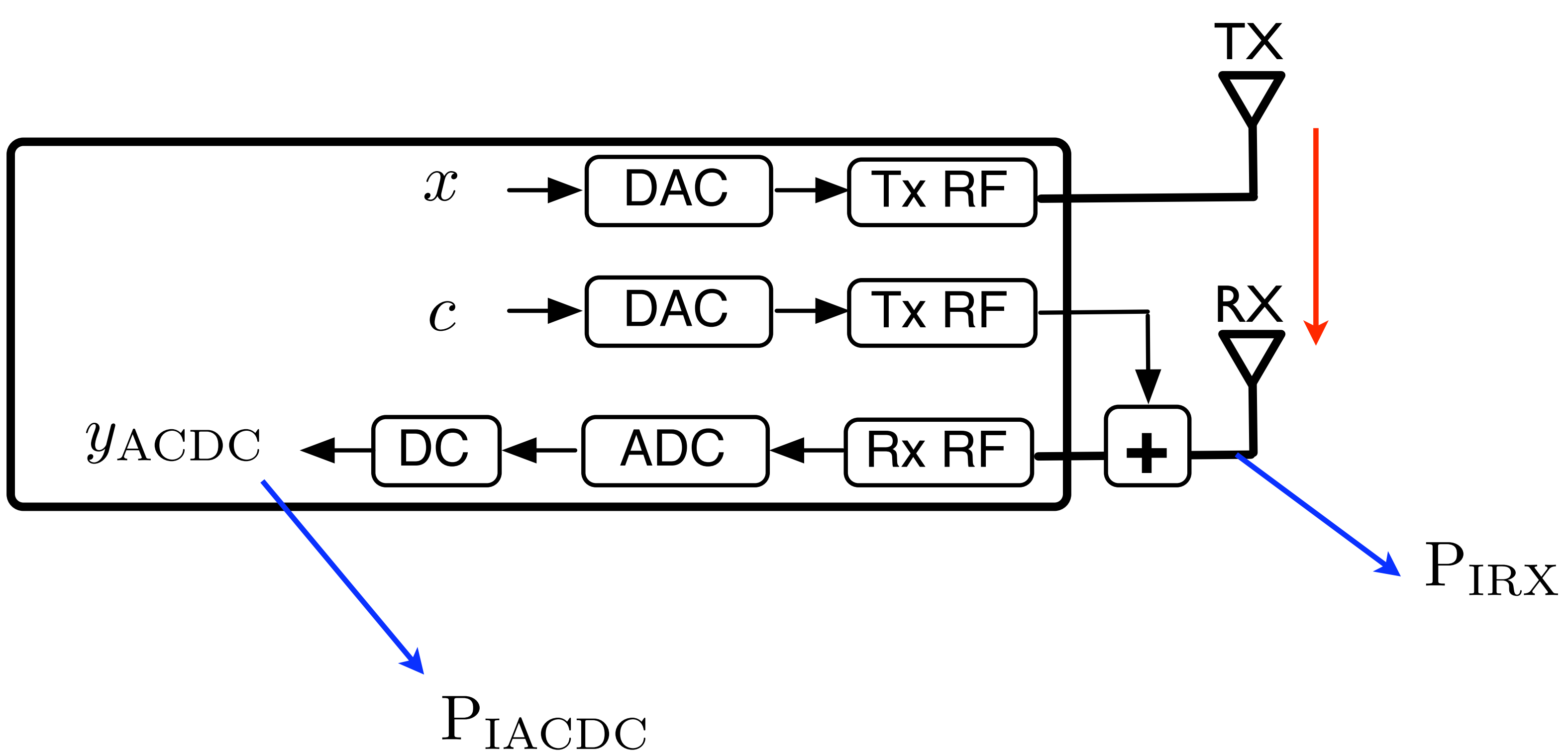
  $$\alpha_{\mathrm{DC}} = \mathrm{P}_{\mathrm{IRX}} - \mathrm{P}_{\mathrm{IDC}}$$

- Analog cancellation

  $$\alpha_{\mathrm{AC}} = \mathrm{P}_{\mathrm{IRX}} - \mathrm{P}_{\mathrm{IAC}}$$

- Analog and digital cancellation

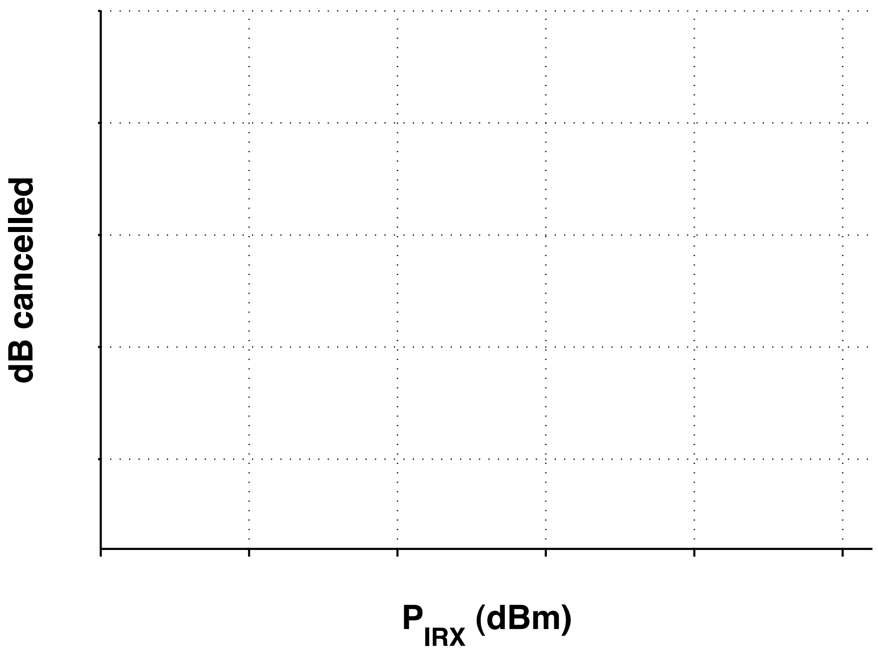
  $$\alpha_{\mathrm{ACDC}} = \mathrm{P}_{\mathrm{IRX}} - \mathrm{P}_{\mathrm{IACDC}}$$



Characterization of Average Cancellation

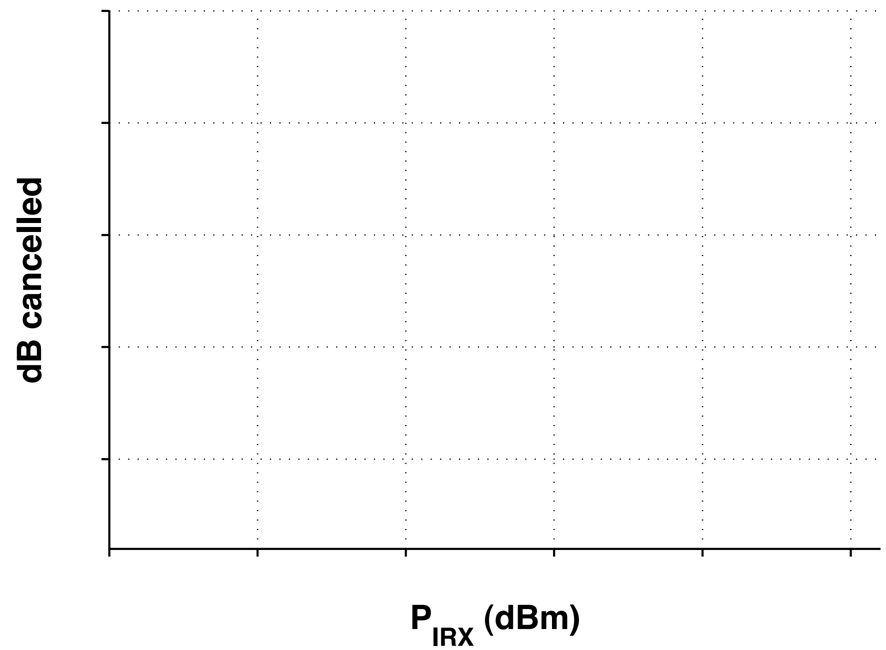
- Digital cancellation

$$\alpha_{\mathrm{DC}} = \mathrm{P_{IRX}} - \mathrm{P_{IDC}}$$



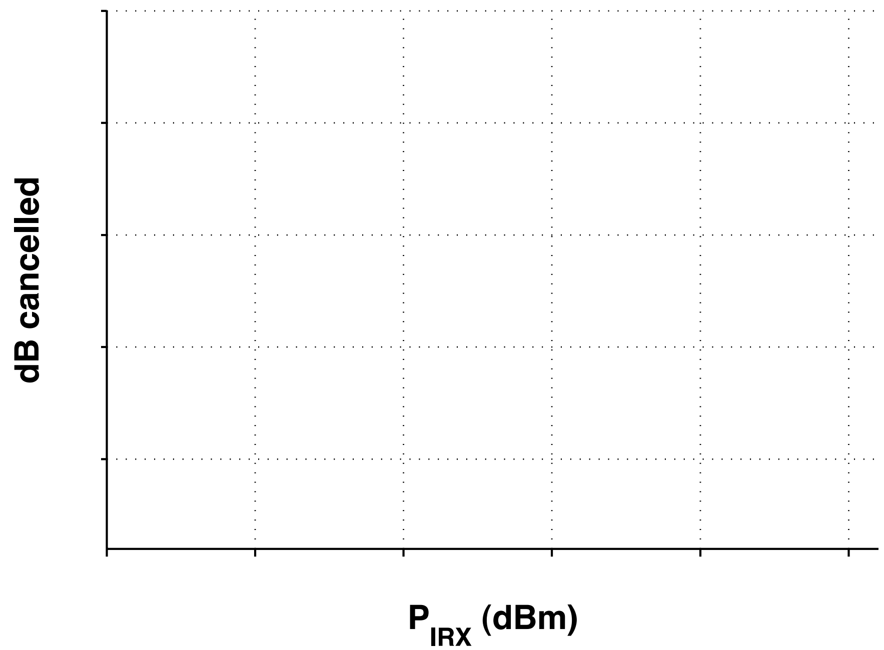
- Analog cancellation

$$\alpha_{\mathrm{AC}} = \mathrm{P_{IRX}} - \mathrm{P_{IAC}}$$



- Analog and digital cancellation

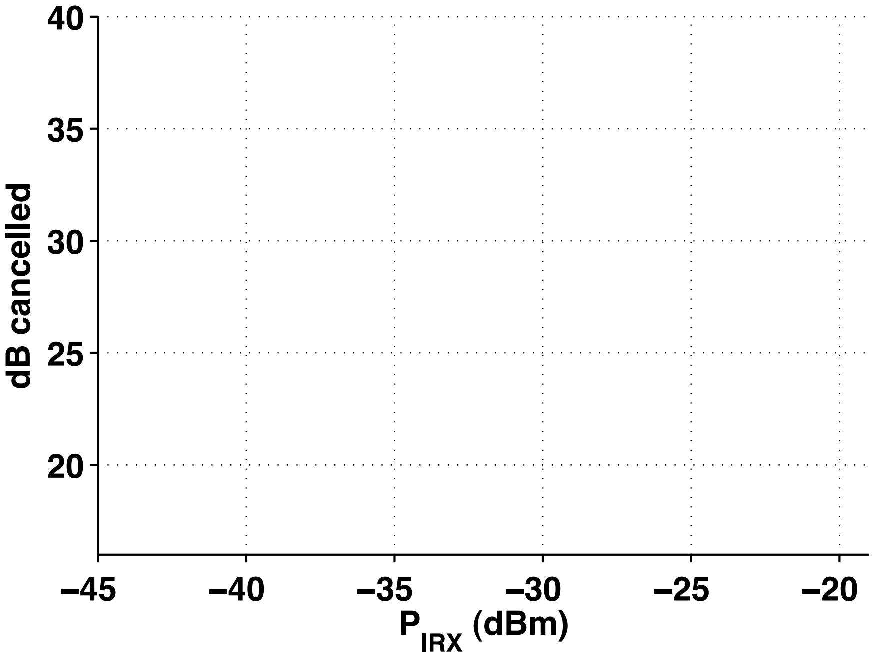
$$\alpha_{\mathrm{ACDC}} = \mathrm{P_{IRX}} - \mathrm{P_{IACDC}}$$



Characterization of Average Cancellation

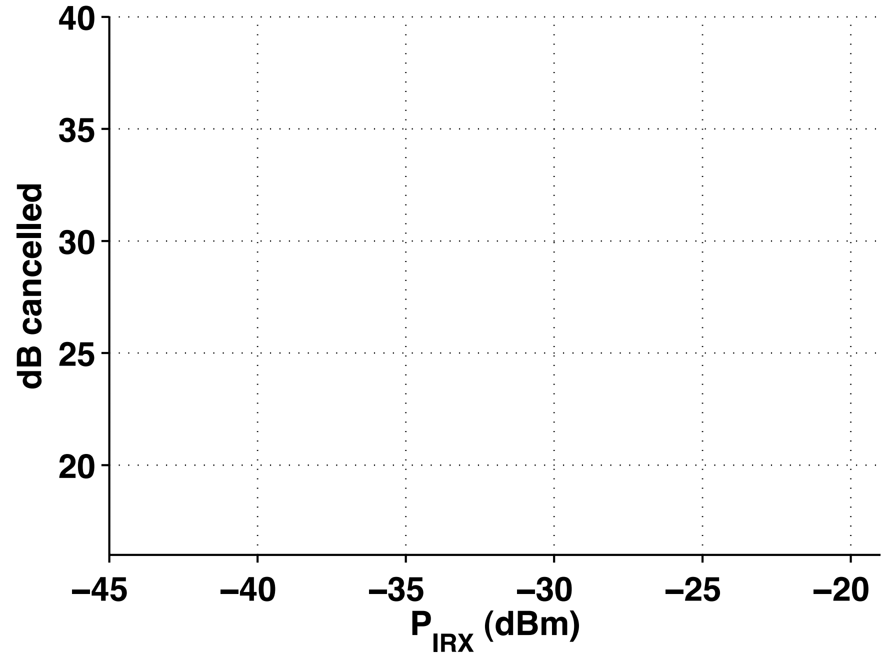
- Digital cancellation

$$\alpha_{\mathrm{DC}} = \mathrm{P}_{\mathrm{IRX}} - \mathrm{P}_{\mathrm{IDC}}$$



- Analog cancellation

$$\alpha_{\mathrm{AC}} = \mathrm{P}_{\mathrm{IRX}} - \mathrm{P}_{\mathrm{IAC}}$$



- Analog and digital cancellation

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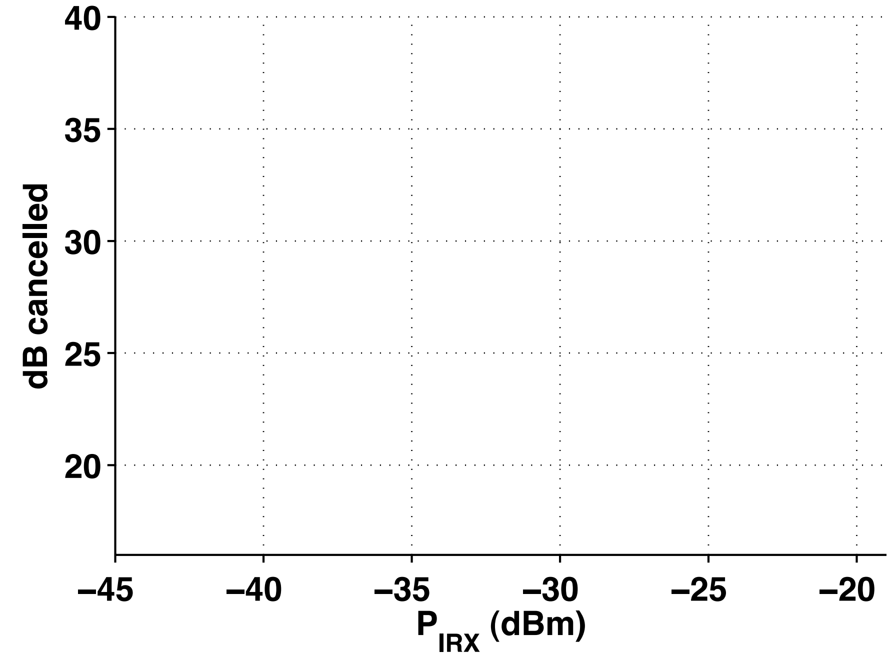

Characterization of Average Cancellation

- Digital cancellation

$$\alpha_{\mathrm{DC}} = \mathrm{P}_{\mathrm{IRX}} - \mathrm{P}_{\mathrm{IDC}}$$

- Analog cancellation

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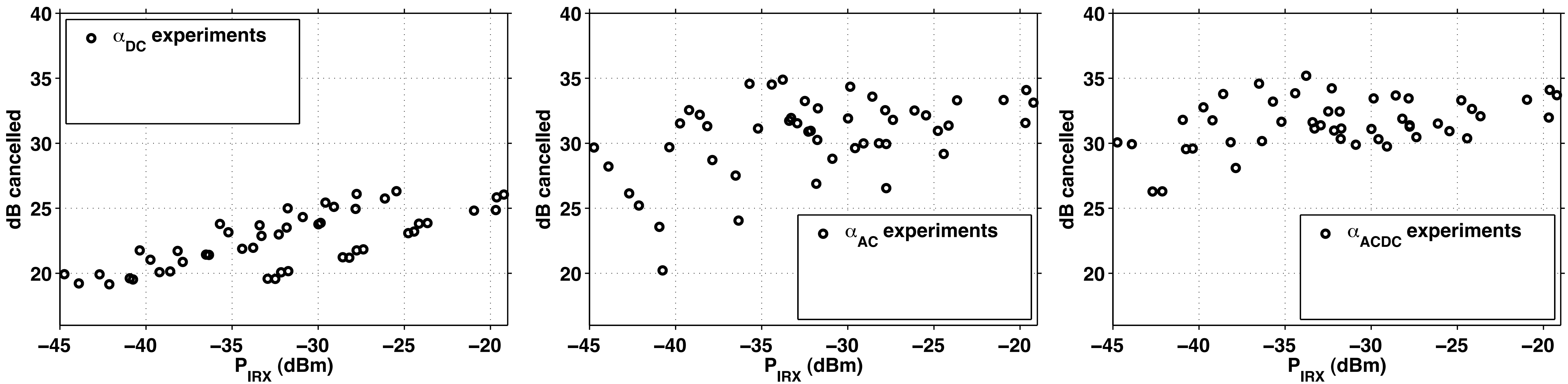
- Analog and digital cancellation

$$\alpha_{\mathrm{ACDC}} = \mathrm{P}_{\mathrm{IRX}} - \mathrm{P}_{\mathrm{IACDC}}$$



Characterization of Average Cancellation

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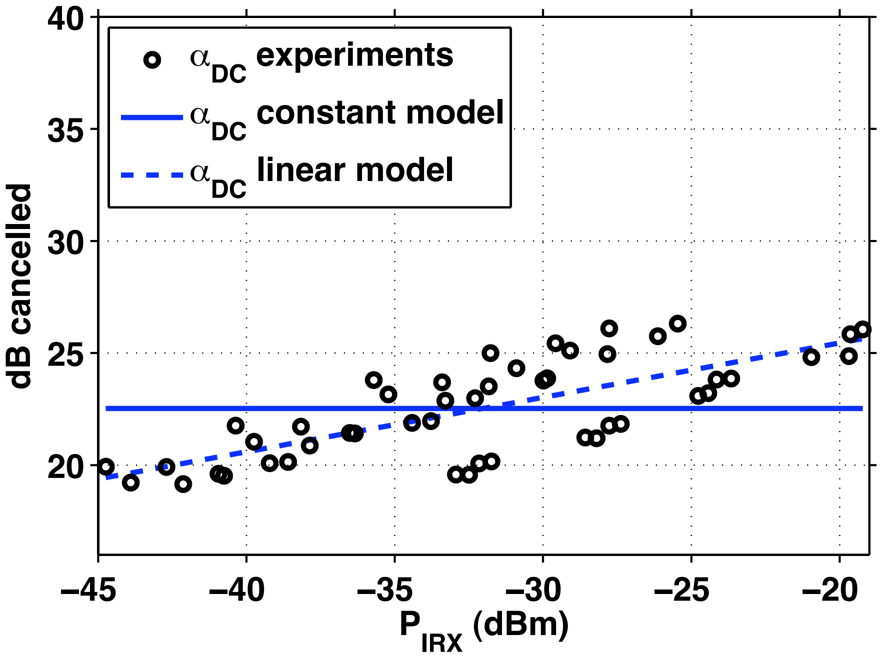
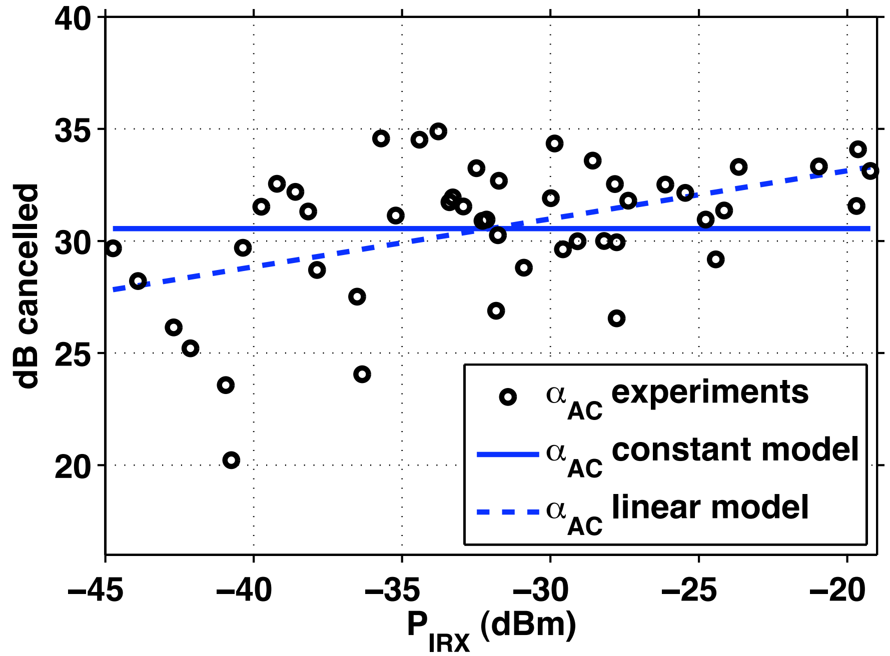


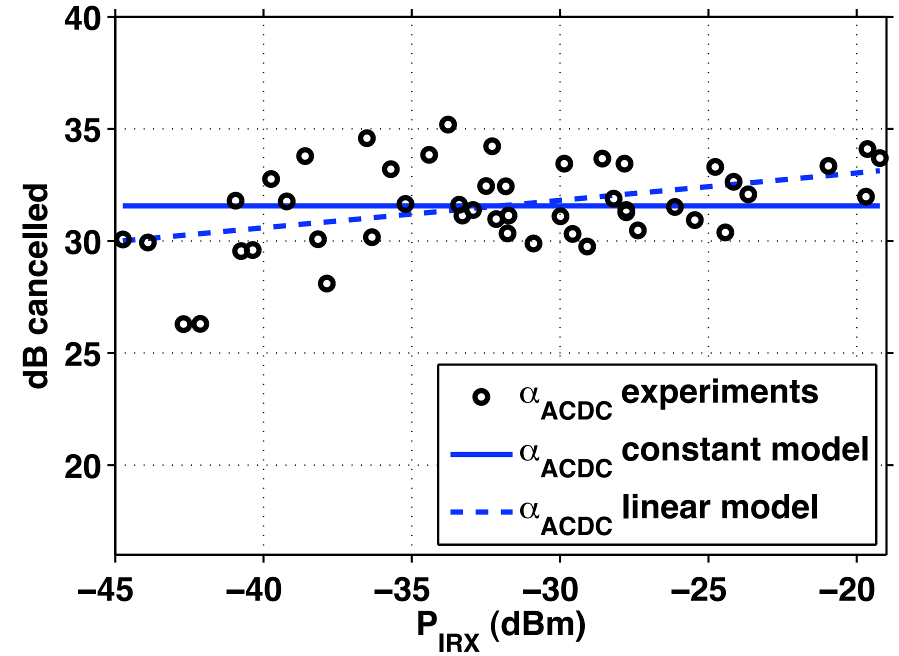
- Analog cancellation

$$\alpha_{\mathrm{AC}} = \mathrm{P}_{\mathrm{IRX}} - \mathrm{P}_{\mathrm{IAC}}$$



- Analog and digital cancellation

$$\alpha_{\mathrm{ACDC}} = \mathrm{P}_{\mathrm{IRX}} - \mathrm{P}_{\mathrm{IACDC}}$$

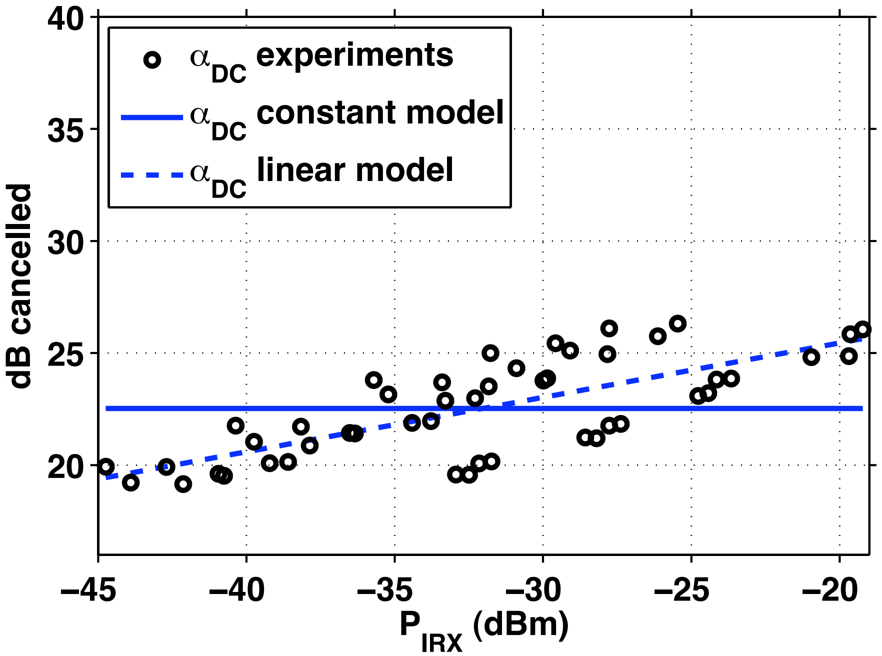


- We want a simple model for the average cancellation
  - Option 1: Fit the data to a constant model
  - Option 2: Fit the data to a linear model

Characterization of Average Cancellation

- Digital cancellation

$$\alpha_{\mathrm{DC}} = \mathrm{P}_{\mathrm{IRX}} - \mathrm{P}_{\mathrm{IDC}}$$



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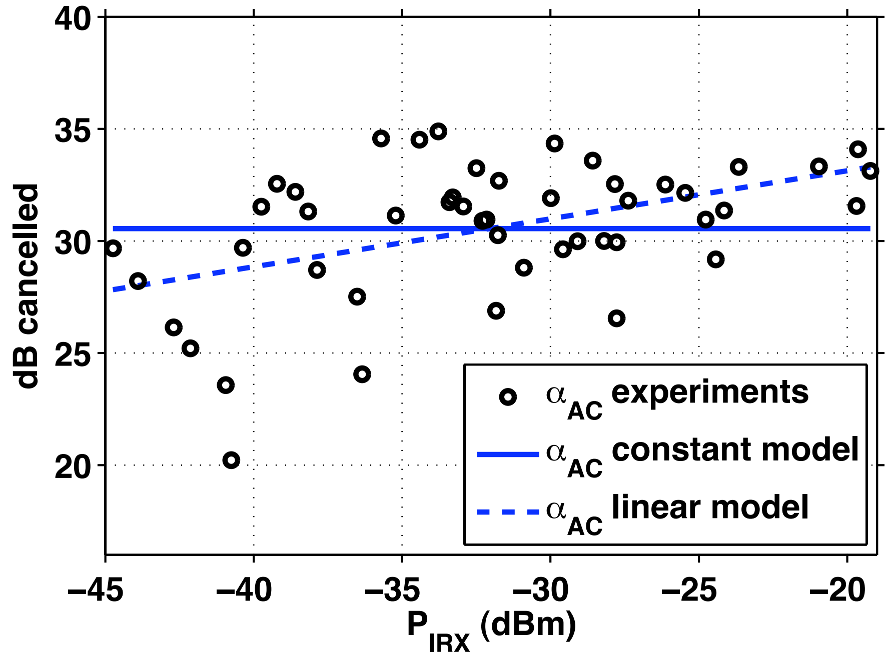

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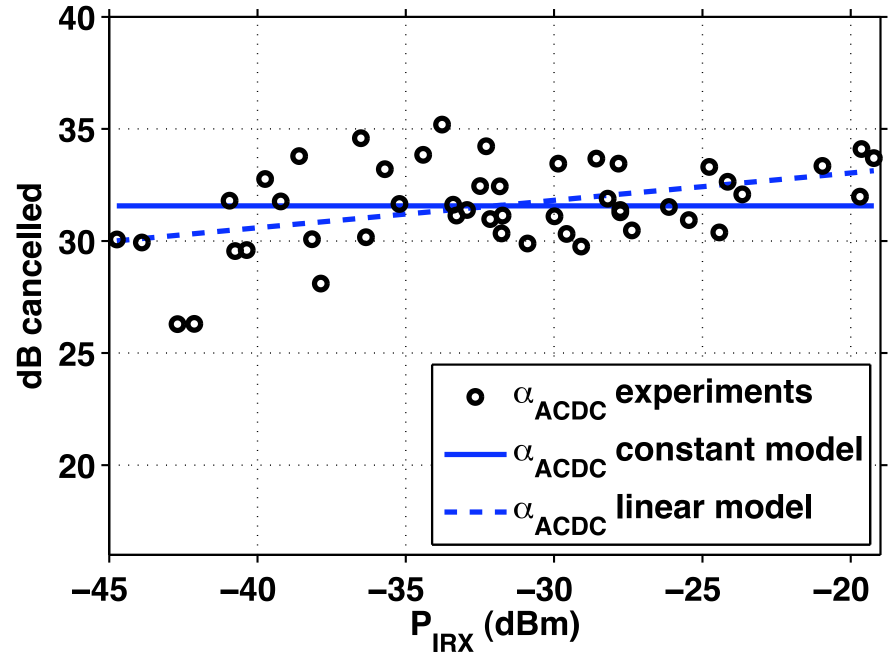
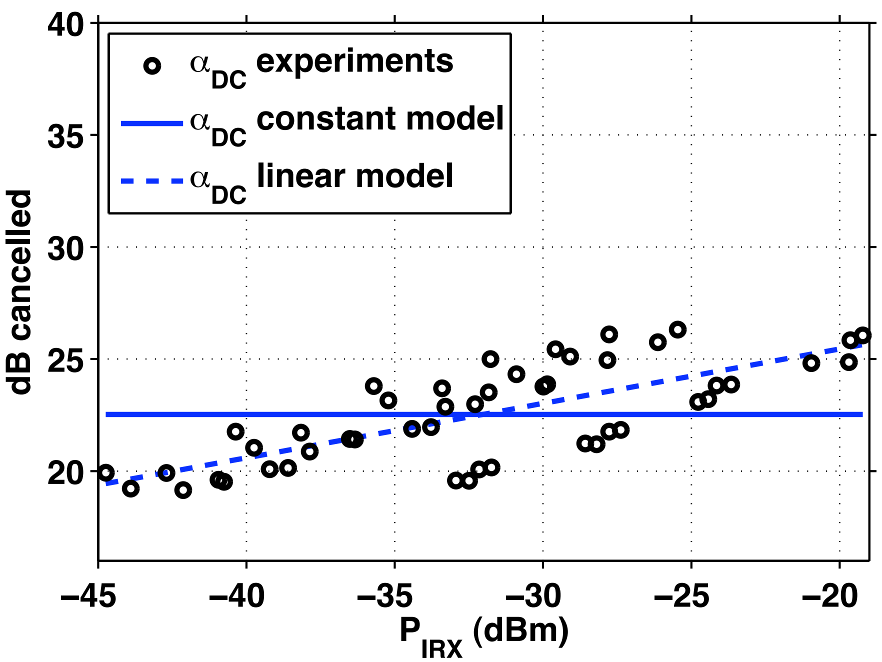


- Result 1:
  - As received interference power $\mathrm{P}_{\mathrm{IRX}}$ increases amount of cancellation increases
- Reason:
  - Cancellation is based on channel measurement
  - Higher $\mathrm{P}_{\mathrm{IRX}}$ means higher SNR for channel estimation
  - Better estimation and hence increased cancellation

Characterization of Average Cancellation

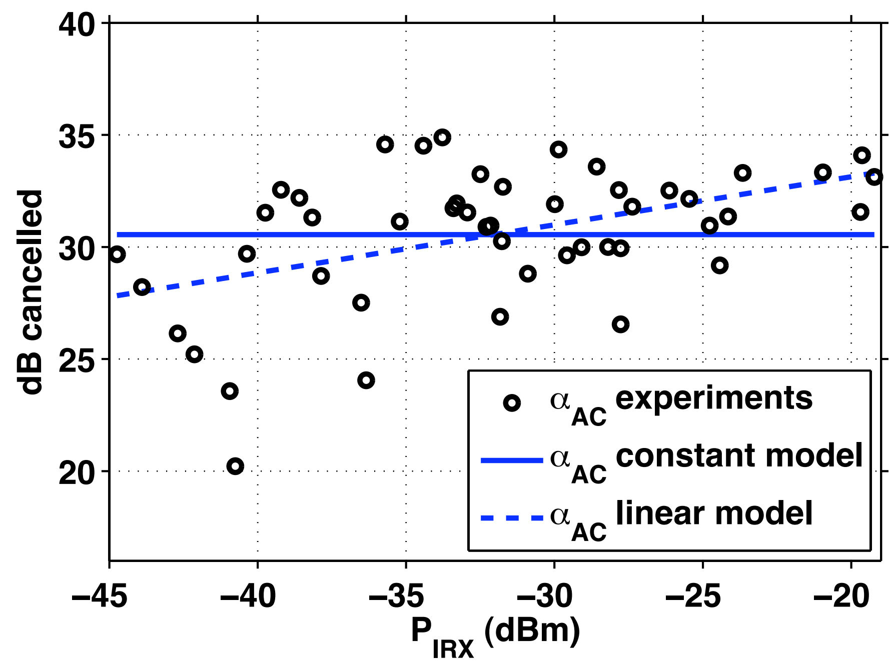
- Digital cancellation

$$\alpha_{DC} = P_{IRX} - P_{IDC}$$



- Analog cancellation

$$\alpha_{AC} = P_{IRX} - P_{IAC}$$



- Analog and digital cancellation

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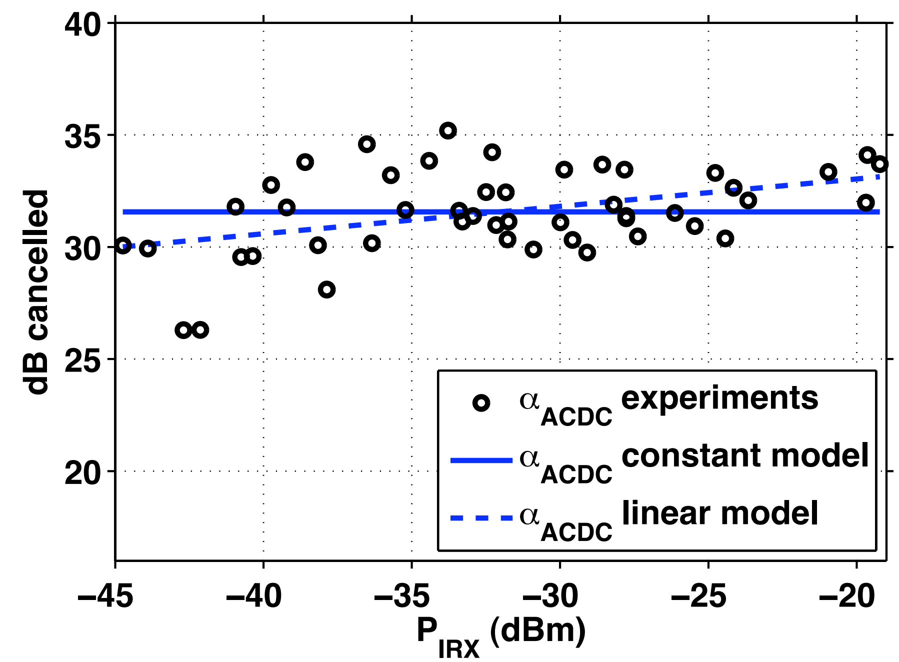


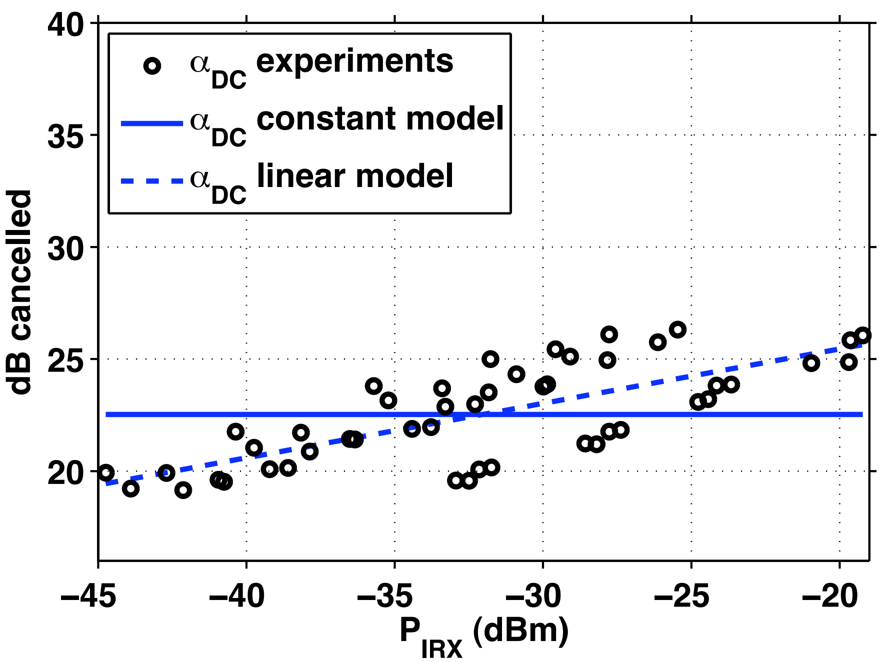
- Result 2:

  (a) Concatenation of cancellation mechanisms does not result in a sum of their individual cancellations

Characterization of Average Cancellation

- Digital cancellation

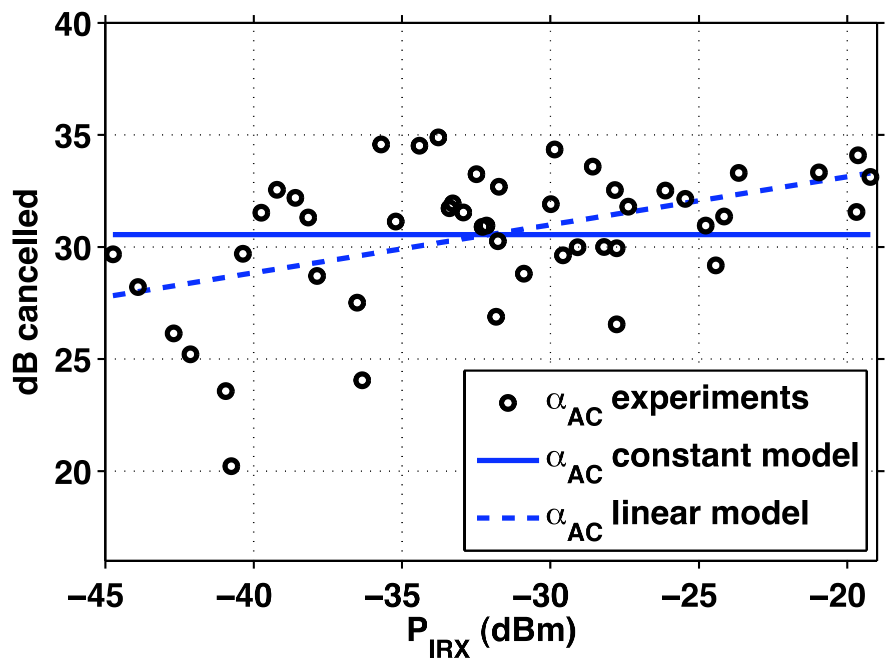
$$\alpha_{\mathrm{DC}} = \mathrm{P}_{\mathrm{IRX}} - \mathrm{P}_{\mathrm{IDC}}$$



Max cancellation : 27 dB

- Analog cancellation

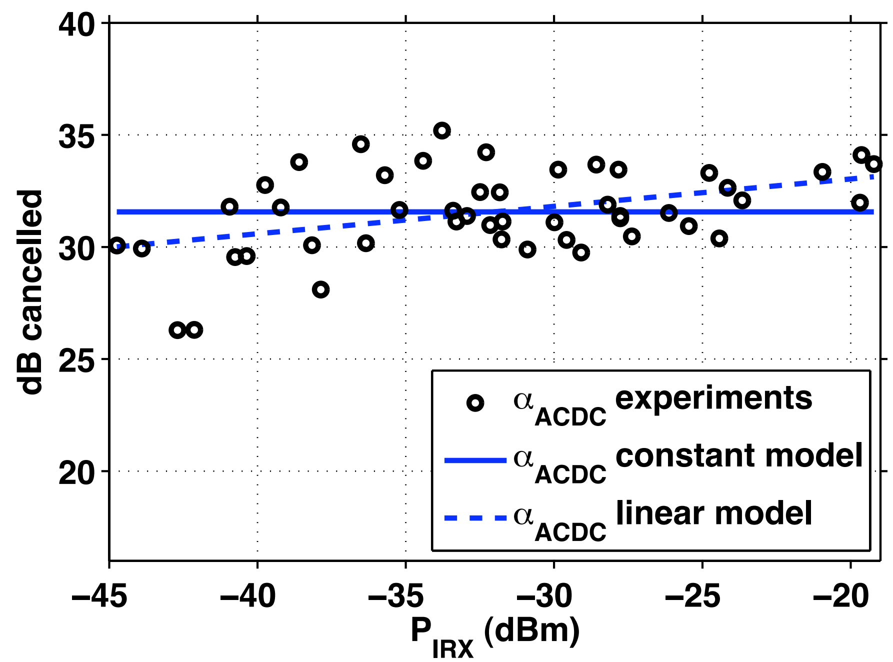
$$\alpha_{\mathrm{AC}} = \mathrm{P}_{\mathrm{IRX}} - \mathrm{P}_{\mathrm{IAC}}$$



Max cancellation : 35 dB

- Analog and digital cancellation

$$\alpha_{\mathrm{ACDC}} = \mathrm{P}_{\mathrm{IRX}} - \mathrm{P}_{\mathrm{IACDC}}$$



Max cancellation : 36 dB

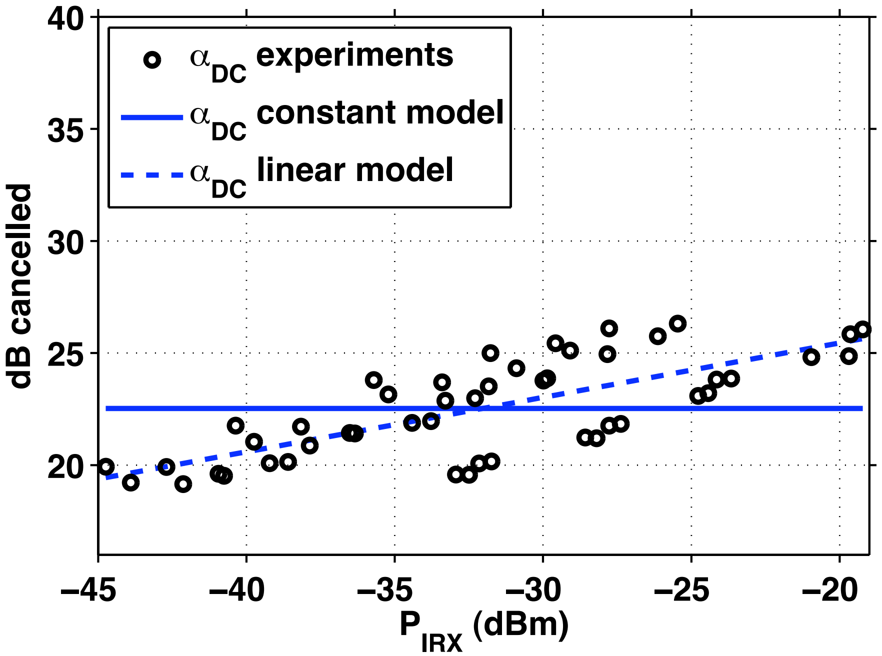
- Result 2:

  (a) Concatenation of cancellation mechanisms does not result in a sum of their individual cancellations

Characterization of Average Cancellation

- Digital cancellation

$$\alpha_{\mathrm{DC}} = \mathrm{P}_{\mathrm{IRX}} - \mathrm{P}_{\mathrm{IDC}}$$



Max cancellation : 27 dB

- Analog cancellation

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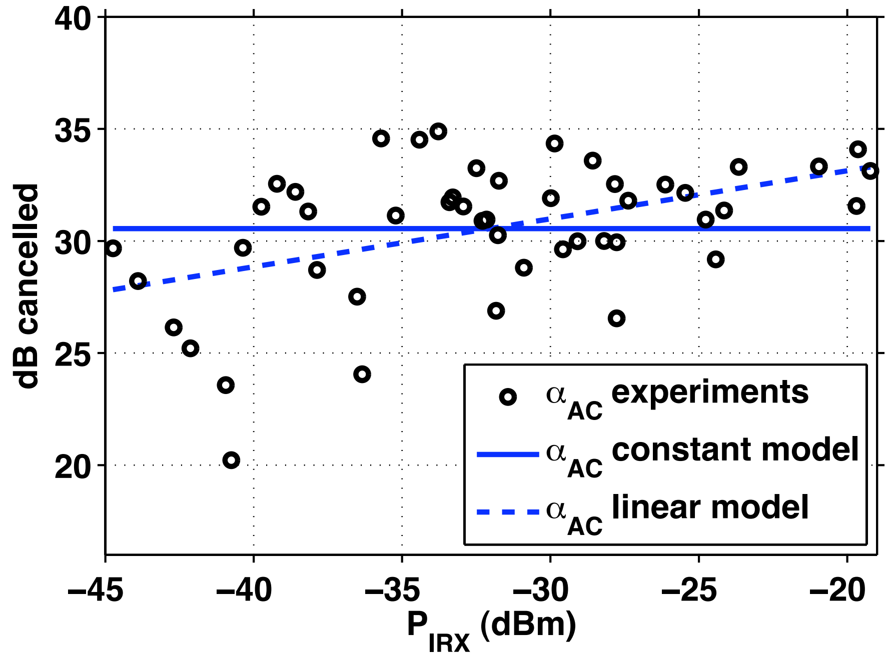
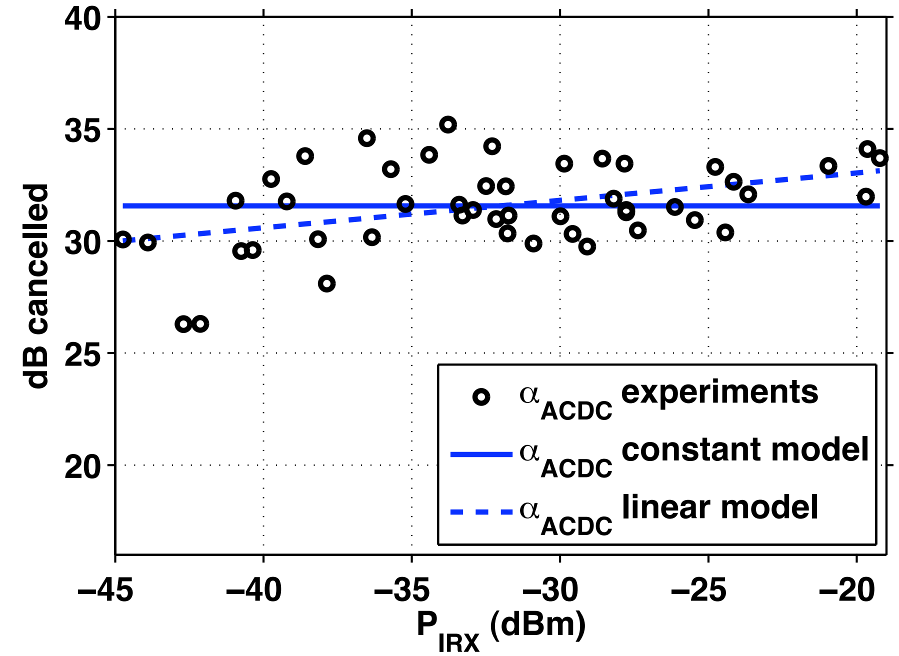


Max cancellation : 35 dB

- Analog and digital cancellation

$$\alpha_{\mathrm{ACDC}} = \mathrm{P}_{\mathrm{IRX}} - \mathrm{P}_{\mathrm{IACDC}}$$



Max cancellation : 36 dB

- Result 2:

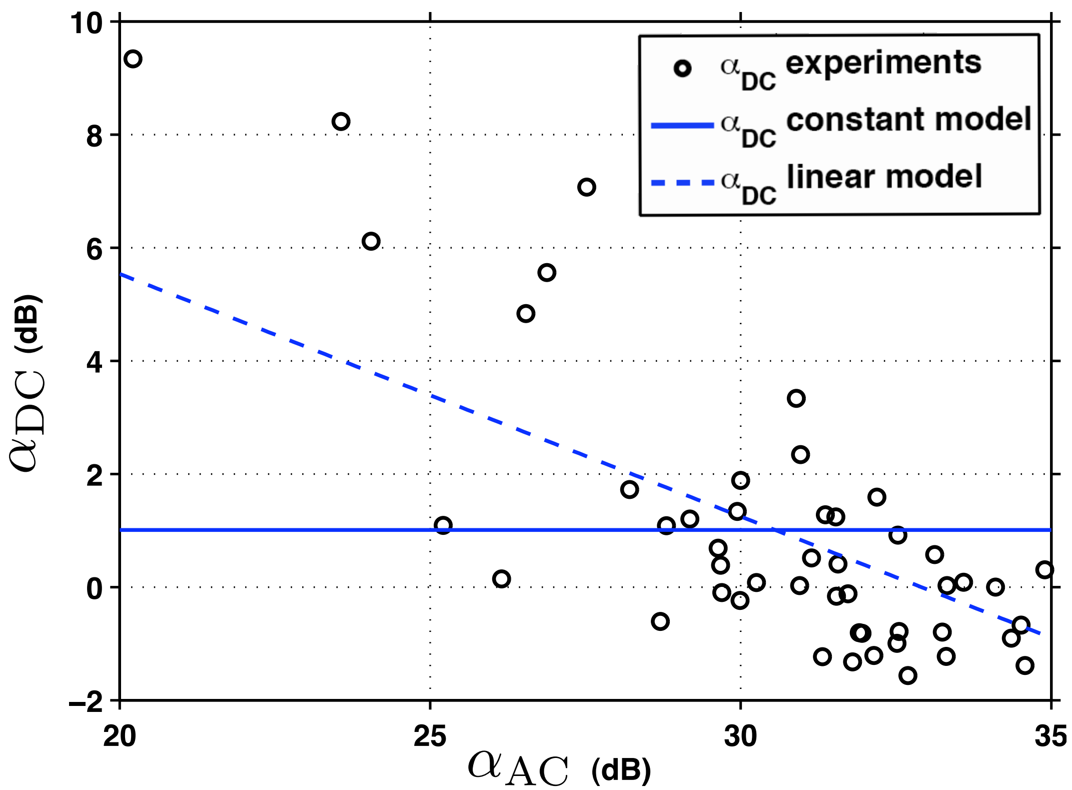
  (a) Concatenation of cancellation mechanisms does not result in a sum of their individual cancellations

  (b) As the performance of analog cancellation gets better, the effectiveness of digital cancellation after analog cancellation reduces (observed on average and per frame)

Characterization of Average Cancellation

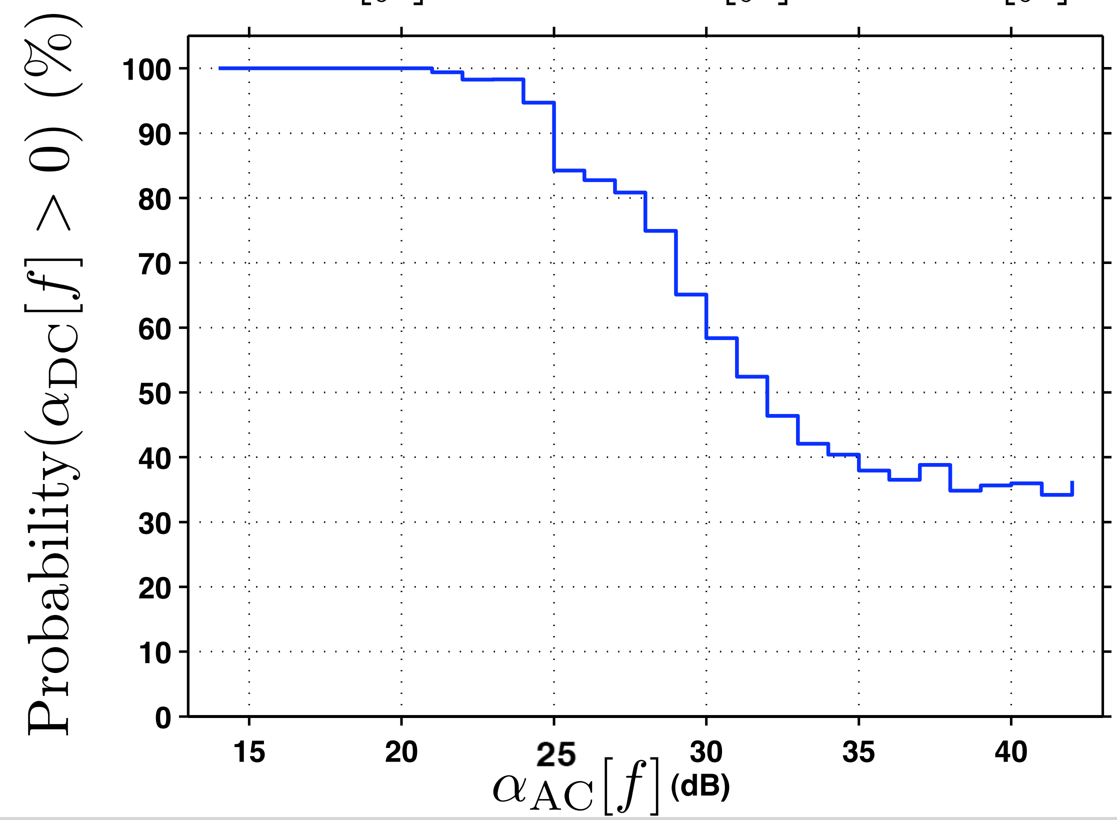
- Average performance

$$\alpha_{DC} = \alpha_{ACDC} - \alpha_{AC}$$



- Per frame performance

$$\alpha_{DC}[f] = \alpha_{ACDC}[f] - \alpha_{AC}[f]$$



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Characterization of Average Cancellation

- Average performance

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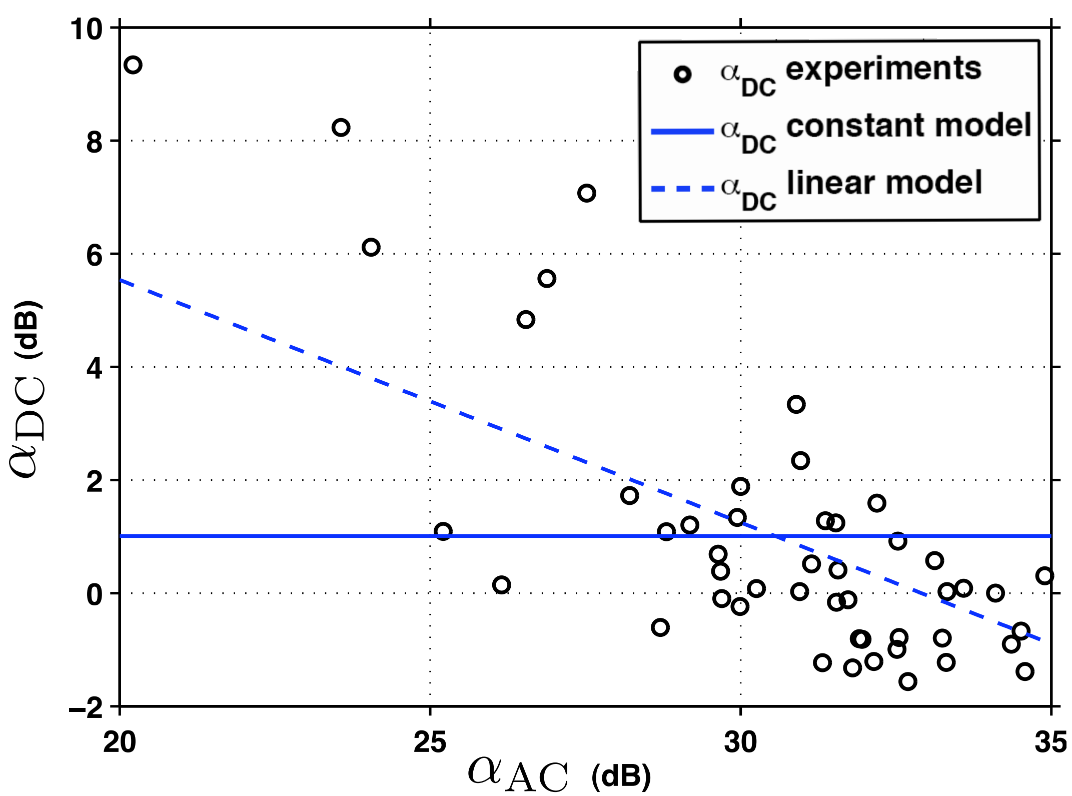
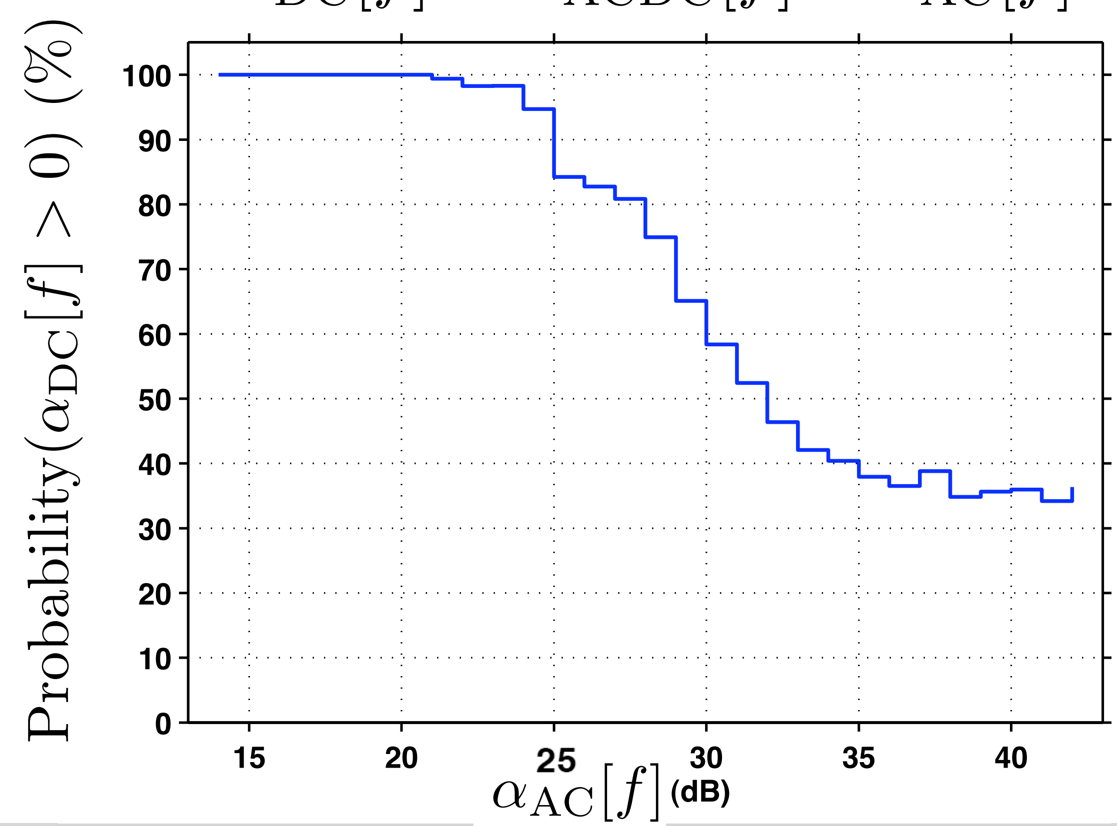


- Per frame performance

$$\alpha_{\mathrm{DC}}[f] = \alpha_{\mathrm{ACDC}}[f] - \alpha_{\mathrm{AC}}[f]$$



- Reasons for Result 2:
  - As residual interference becomes smaller the effectiveness of cancelling the residual reduces
  - If analog cancellation could achieve ∞ dB of cancellation then digital cancellation would be unnecessary
    - Furthermore applying digital cancellation would increase the noise

Summary of Results

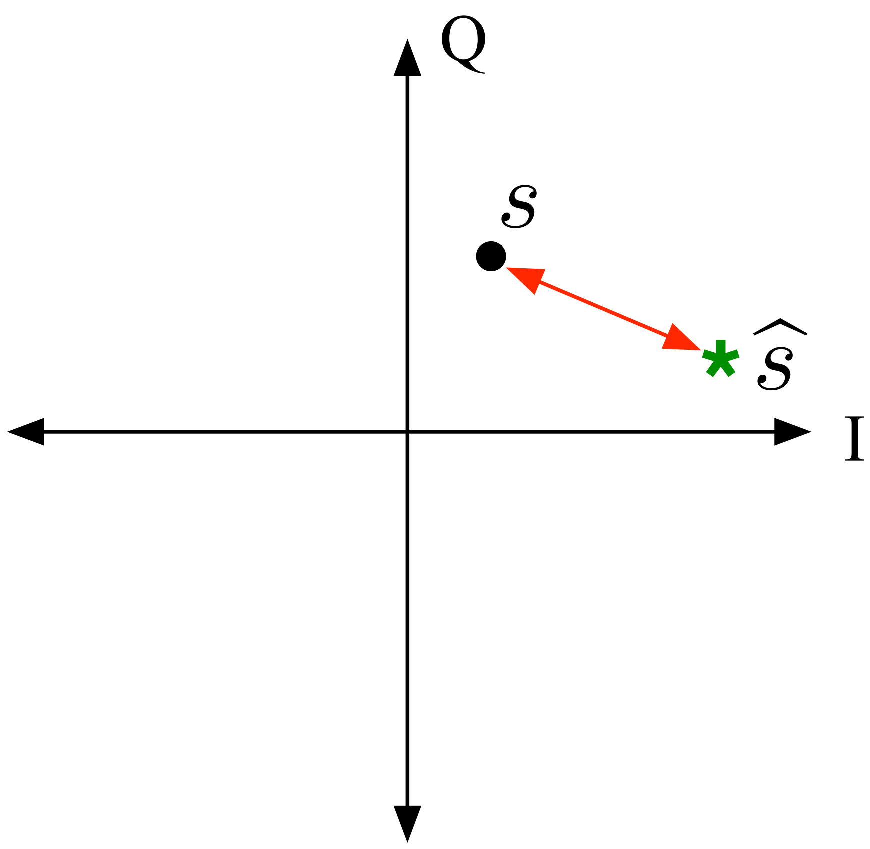
- Characterization of self-interference cancellation mechanisms
  - Amount of cancellation
  - Impact on full-duplex achievable rate performance

- Comparison with half-duplex systems
  - Demonstrated that full-duplex can achieve higher rates than half-duplex

- Duarte et al. *Full-Duplex Wireless Communications using Off-The-Shelf Radios: Feasibility and First Results*. Asilomar 2010.
- Duarte et al. *Experiment-Driven Characterization of Full-duplex Wireless Systems*. Submitted to IEEE Trans. Wireless 2011.

Computation of Achievable Sum Rate

- Achievable Sum Rate (ASR) b/s/Hz computed based on post processing SINR



- Compute SINR per frame

$$\mathrm{SINR}[f] = \frac{E\left[|s^2|\right]}{E\left[|s - \widehat{s}|^2\right]}$$

- Compute achievable rate

$$\mathrm{AR} = E\left[\log(1 + \mathrm{SINR}[f])\right]$$

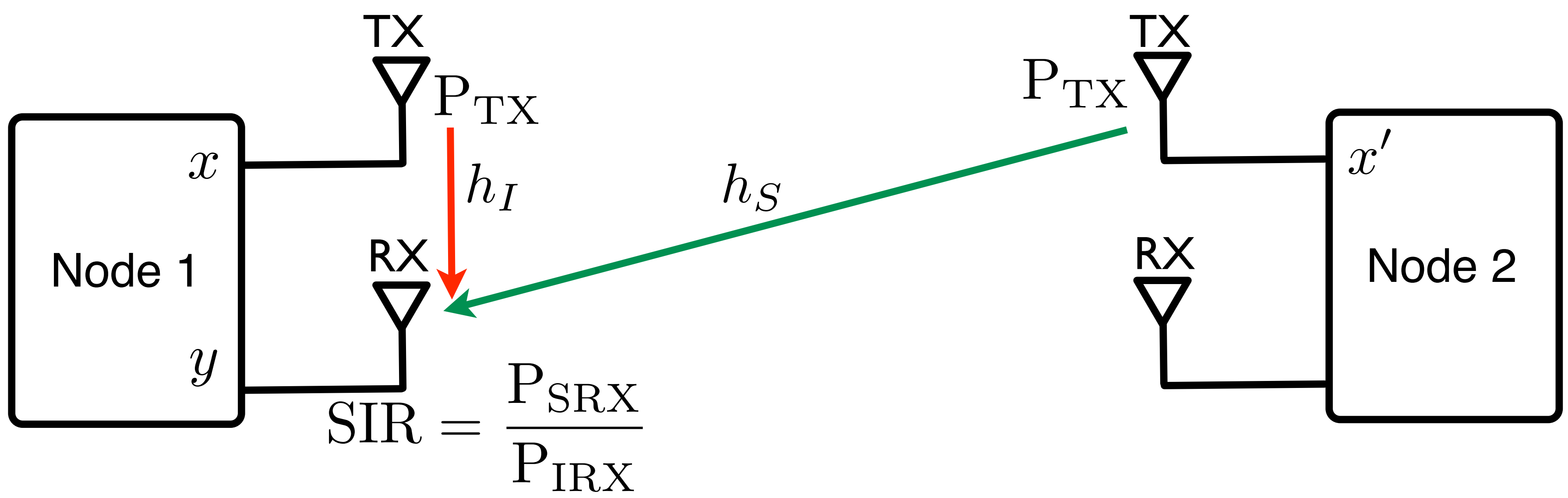
- Sum rate full-duplex

$$\mathrm{ASR} = \mathrm{AR}_{12} + \mathrm{AR}_{21}$$

- Sum rate half-duplex

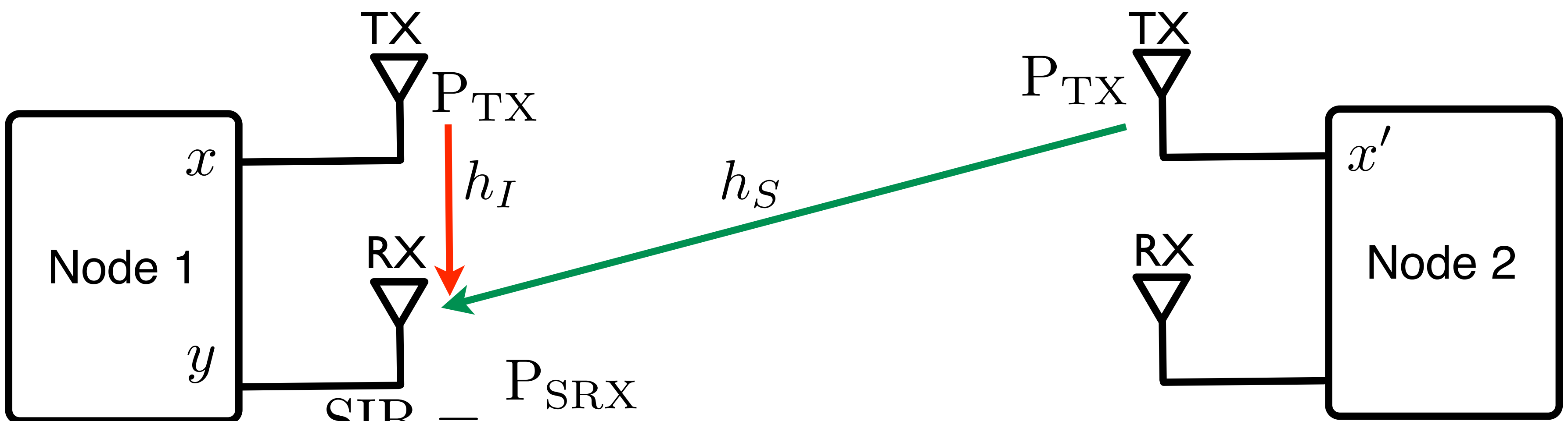
$$\mathrm{ASR} = \frac{1}{2}\mathrm{AR}_{12} + \frac{1}{2}\mathrm{AR}_{21}$$

Achievable Sum Rate Analysis



- Result 3:
  - For a fixed SIR at Rx antenna, increasing the transmit power increases the total achievable rate.
- Reasons for Result 3 ...

Achievable Sum Rate Analysis



$$\mathrm{SIR} = \frac{P_{SRX}}{P_{IRX}}$$

- Without active cancellation

$$y = h_S x' + h_I x + z$$

- With active cancellation

$$y = h_S x' + \left(h_I - \widehat{h}_I\right) x + z$$

- With active cancellation rewrite as

$$y = h_S x' + h_R \sqrt{\frac{\Omega}{\alpha}} x + z \longrightarrow \mathrm{SINR} = \frac{1}{\frac{1}{\alpha \mathrm{SIR}} + \frac{1}{\mathrm{SNR}}}$$

h_R : normalized residual channel

Ω : due to antenna separation

α : due to active cancellation

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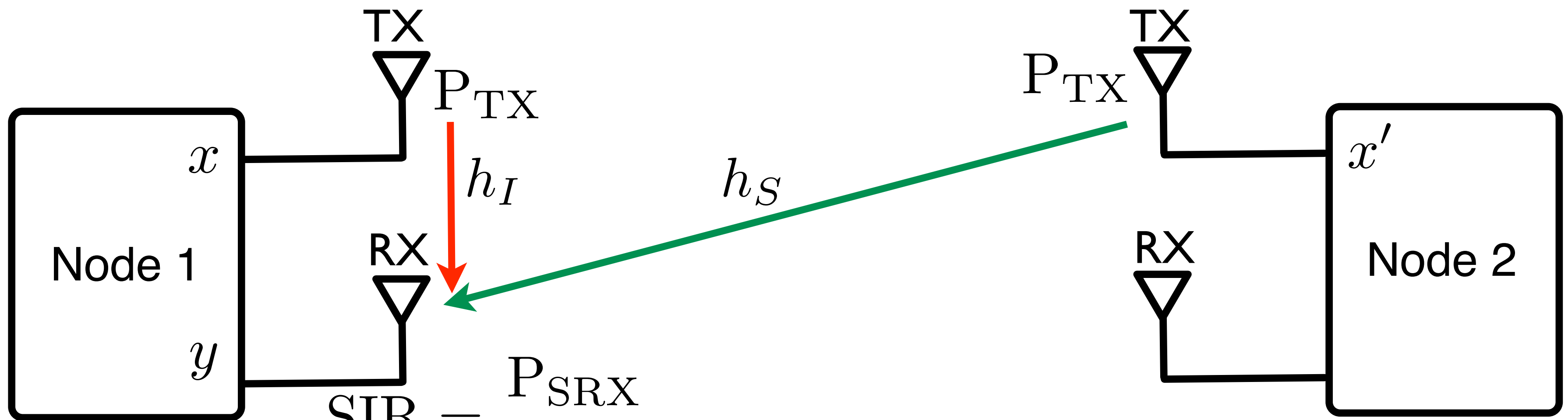
Achievable Sum Rate Analysis

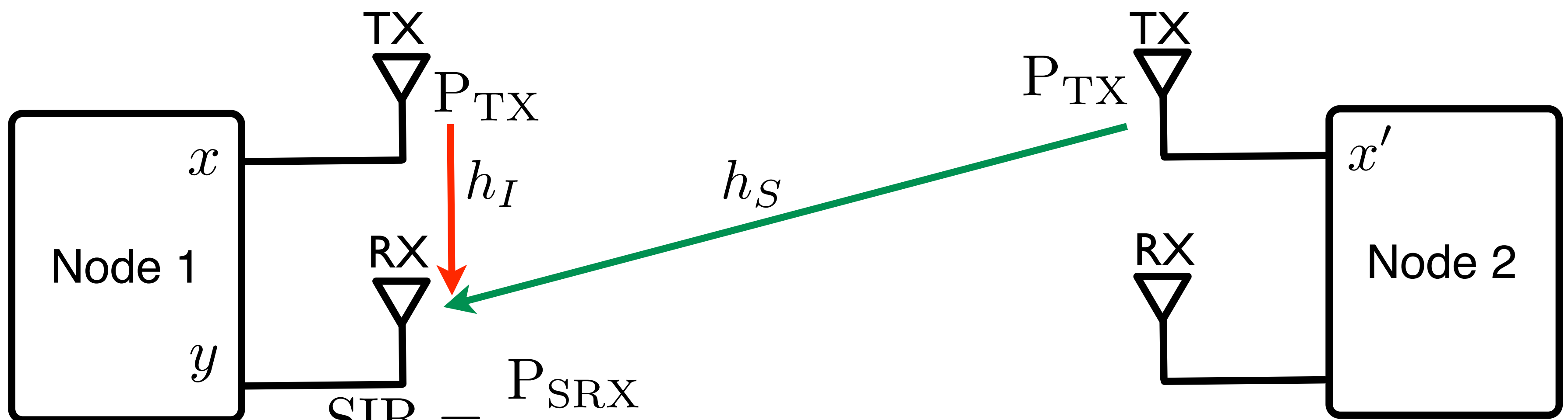


$$\mathrm{SIR} = \frac{\mathrm{P_{SRX}}}{\mathrm{P_{IRX}}}$$

- Achievable sum rate

$$\mathrm{ASR} = \log\left(1 + \mathrm{SINR}_1\right) + \log\left(1 + \mathrm{SINR}_2\right) \qquad \mathrm{SINR}_i = \frac{1}{\frac{1}{\alpha_i \mathrm{SIR}_i} + \frac{1}{\mathrm{SNR}_i}}$$

Achievable Sum Rate Analysis



$$\mathrm{SIR} = \frac{P_{SRX}}{P_{IRX}}$$

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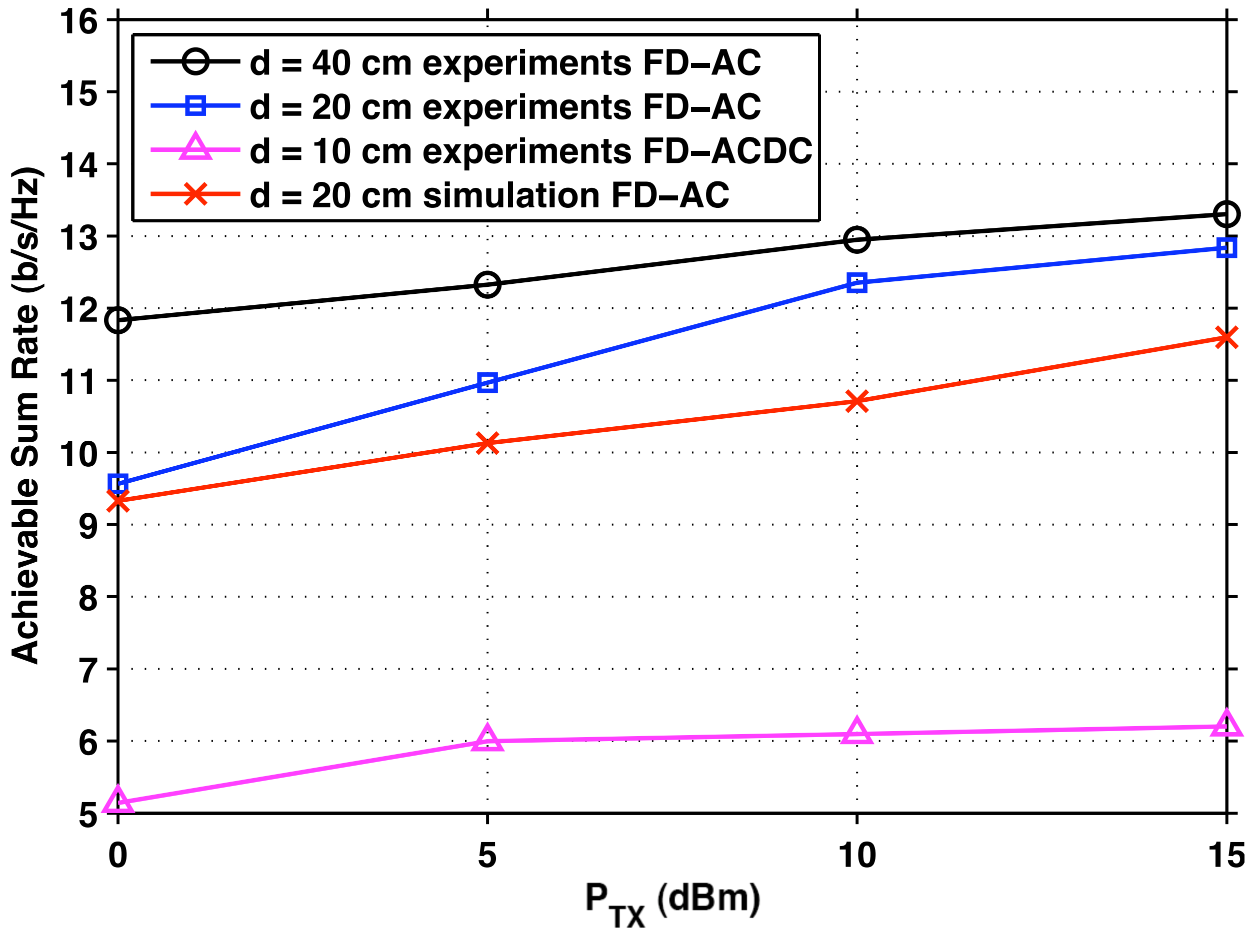
- Result 3:
  - For a fixed SIR at Rx antenna, increasing the transmit power increases the total achievable rate.

- Reasons for Result 3:
  - If P_{TX} at both nodes increases by same amount then
    - SIR doesn't change
    - α increases (from Result 1)
    - SNR increases

→ SINR increases → Achievable rate increases

Achievable Sum Rate Analysis

- Result 3 demonstrated in experiments and simulation

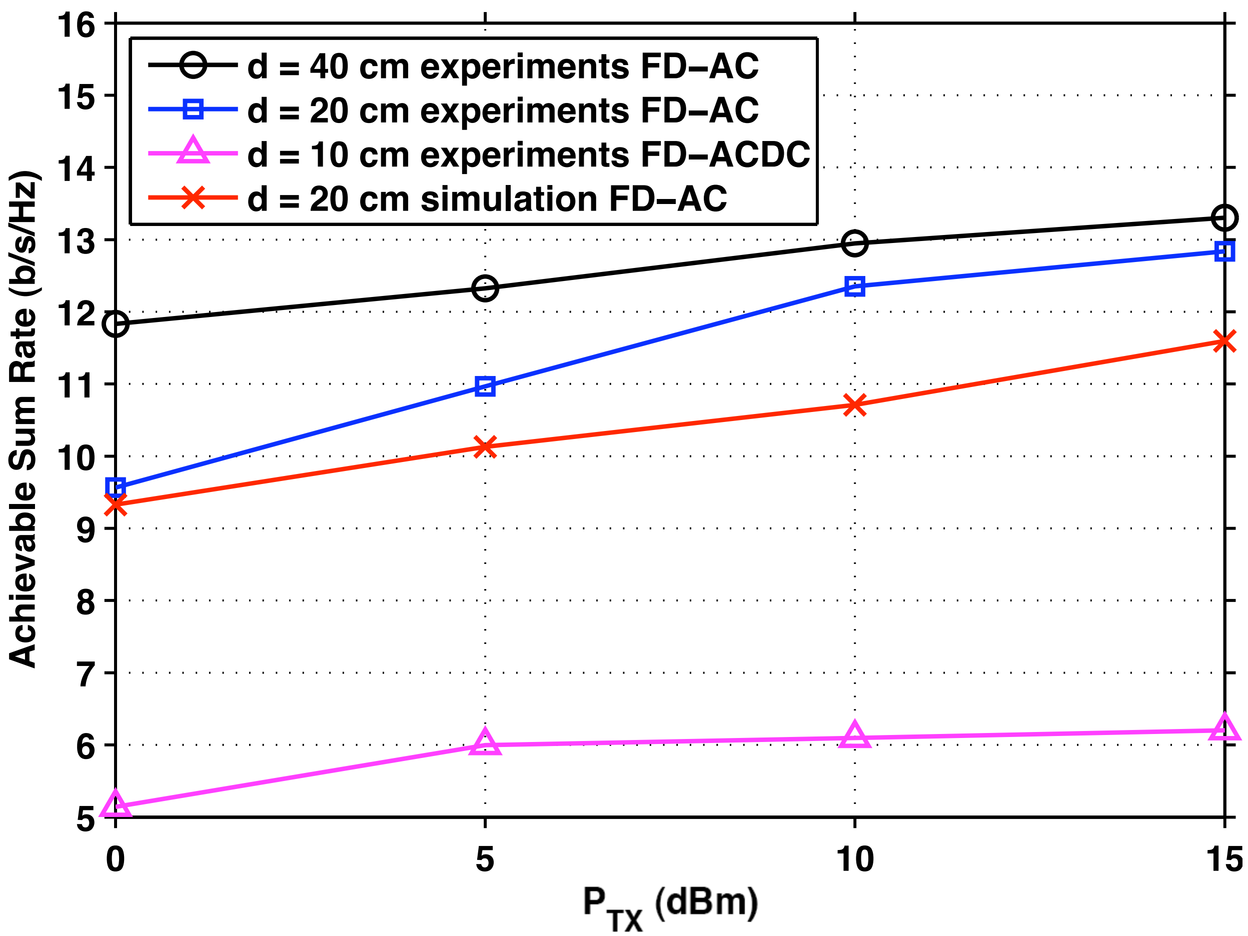


- FD-AC: Full-duplex with antenna separation and Analog Cancellation

- FD-ACDC: Full-duplex with antenna separation and combined Analog and Digital Cancellation

Achievable Sum Rate Analysis

- Result 3 demonstrated in experiments and simulation



- FD-AC: Full-duplex with antenna separation and Analog Cancellation

- FD-ACDC: Full-duplex with antenna separation and combined Analog and Digital Cancellation

- Simulation results obtained using model

$$y = h_S x' + h_R \sqrt{\frac{\Omega}{\alpha}} x + z \qquad \text{SINR} = \frac{1}{\frac{1}{\alpha \text{SIR}} + \frac{1}{\text{SNR}}}$$

- Setting

$\text{SNR} = \infty$ $\text{SIR} =$ Measured in experiments $\alpha =$ Linear fit

- Linear fit model seems reasonably accurate

Achievable Sum Rate Analysis

- Result 4:
  - Best performance is achieved when applying digital cancellation selectively based on measured suppression values
- Reasons for Result 4:

- For each frame decide if digital cancellation after analog cancellation should be applied or not as follows
  - Use training at the beginning of the frame to estimate $\alpha_{\mathrm{AC}}[f]$ and $\alpha_{\mathrm{ACDC}}[f]$
  - Apply digital cancellation after analog cancellation during frame f only if

$$\alpha_{\mathrm{ACDC}}[f] - \alpha_{\mathrm{AC}}[f] > 0$$

Achievable Sum Rate Analysis

- Result 4:
  - Best performance is achieved when applying digital cancellation selectively based on measured suppression values

- Reasons for Result 4:
  - Follows from Result 2:

  (a) Concatenation of cancellation mechanisms does not result in a sum of their individual cancellations

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Achievable Sum Rate Analysis

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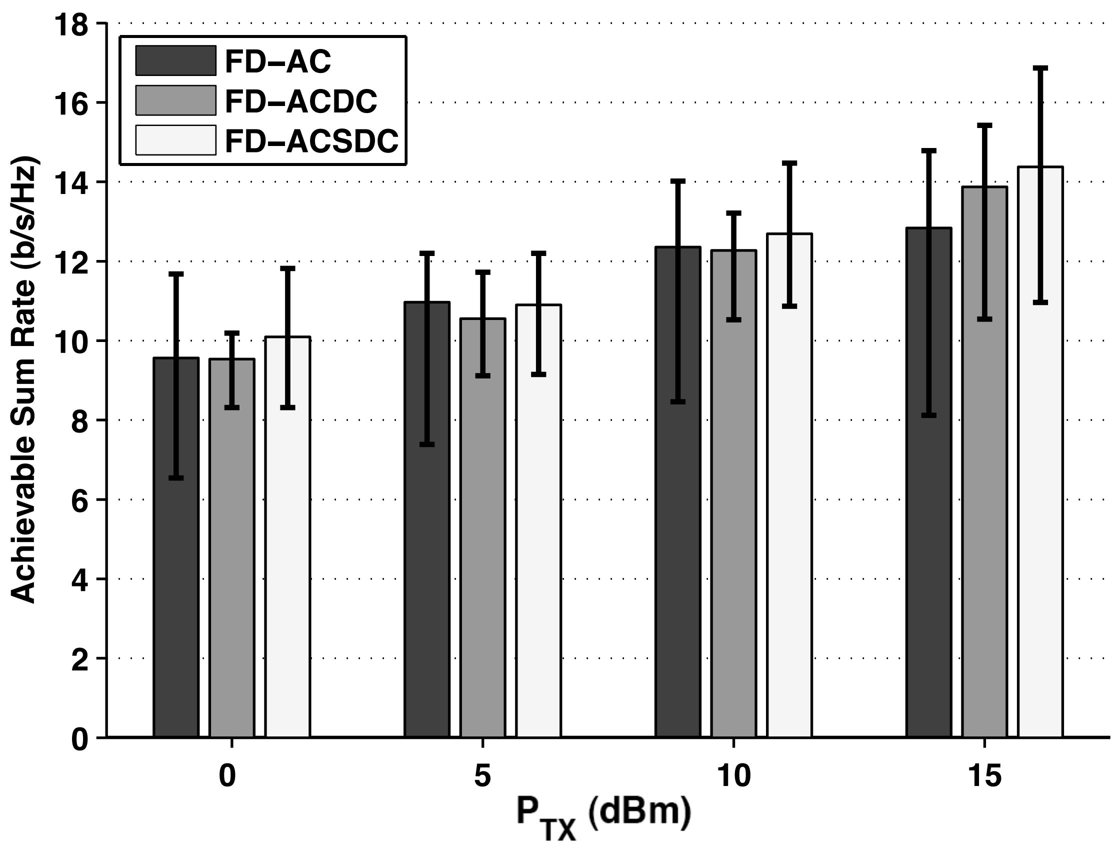
- Experiment results



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- FD-ACDC: Full-duplex with antenna separation and combined Analog and Digital Cancellation
- FD-ACSDC: Full-duplex with antenna separation and combined Analog and Selective Digital Cancellation

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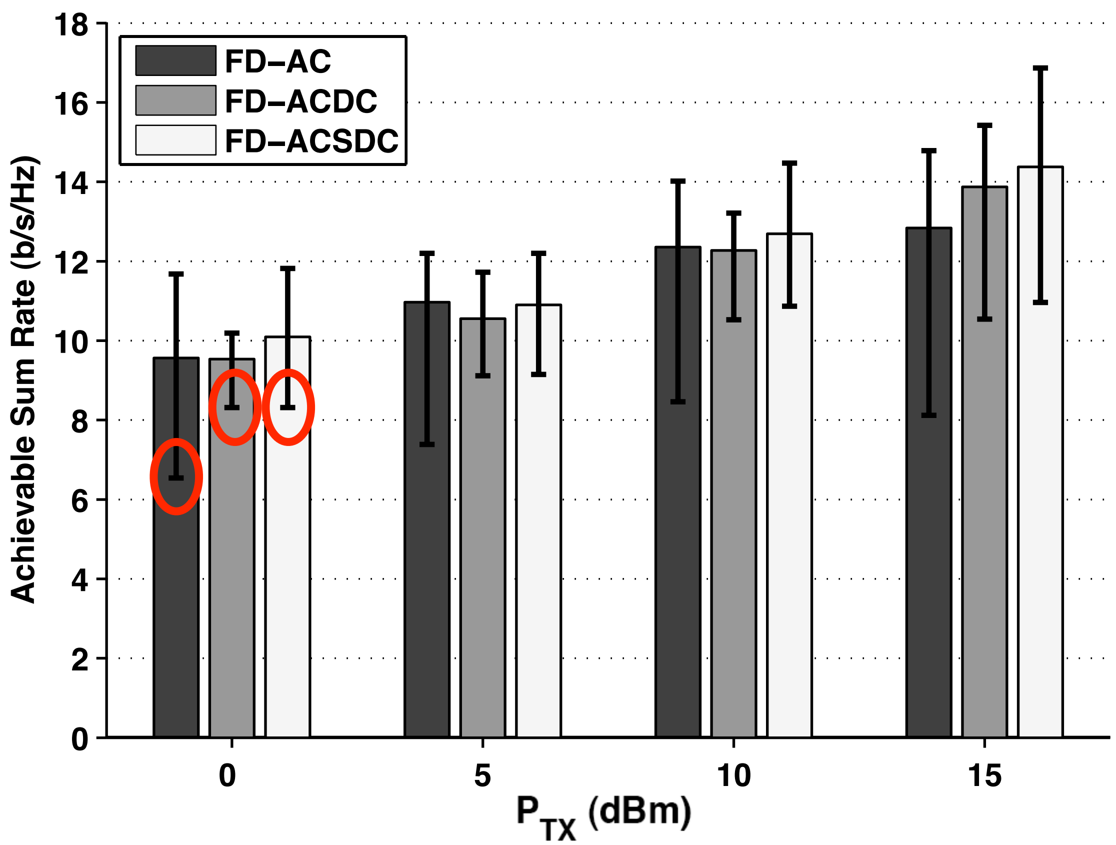

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- Benefits of selective digital cancellation
  - Uses digital cancellation as a safety net in frames where analog cancellation delivers poor performance
  - Avoids adding noise to the system when analog cancellation delivers good performance
  - Results in largest average achievable sum rate

Achievable Sum Rate Analysis

- Result 4:
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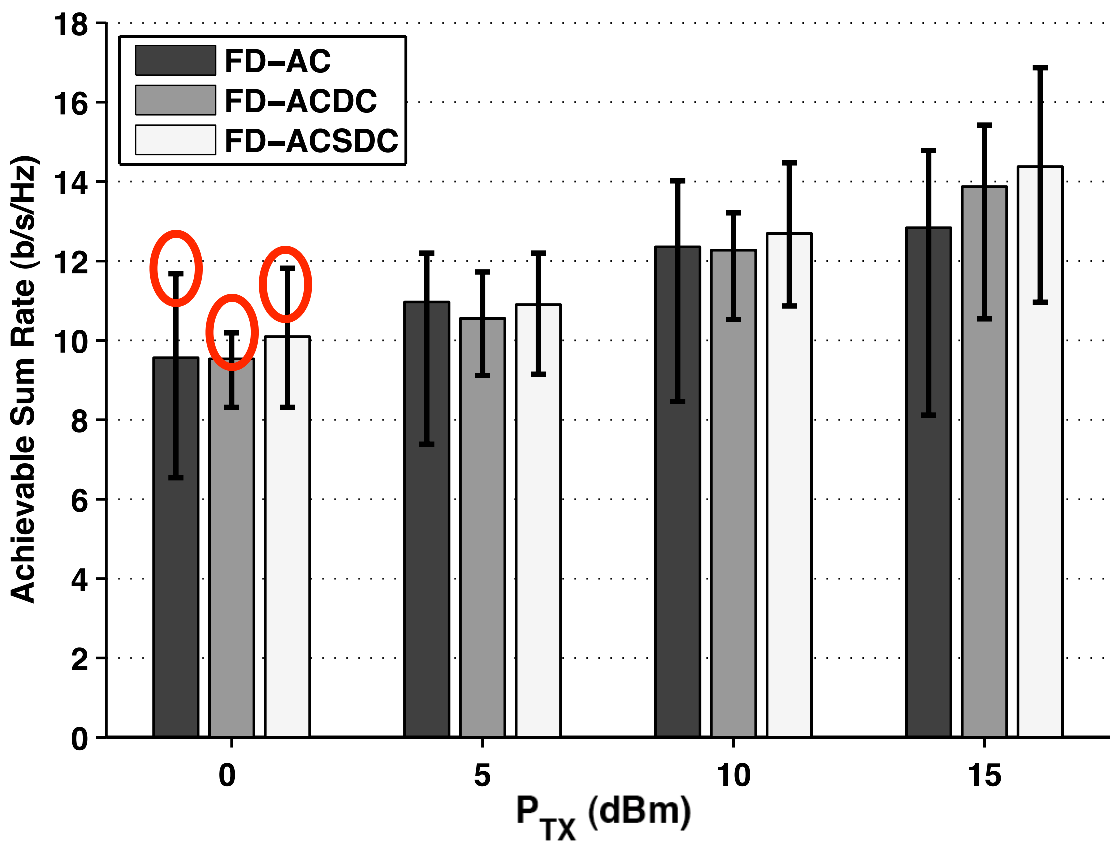
- Experiment results



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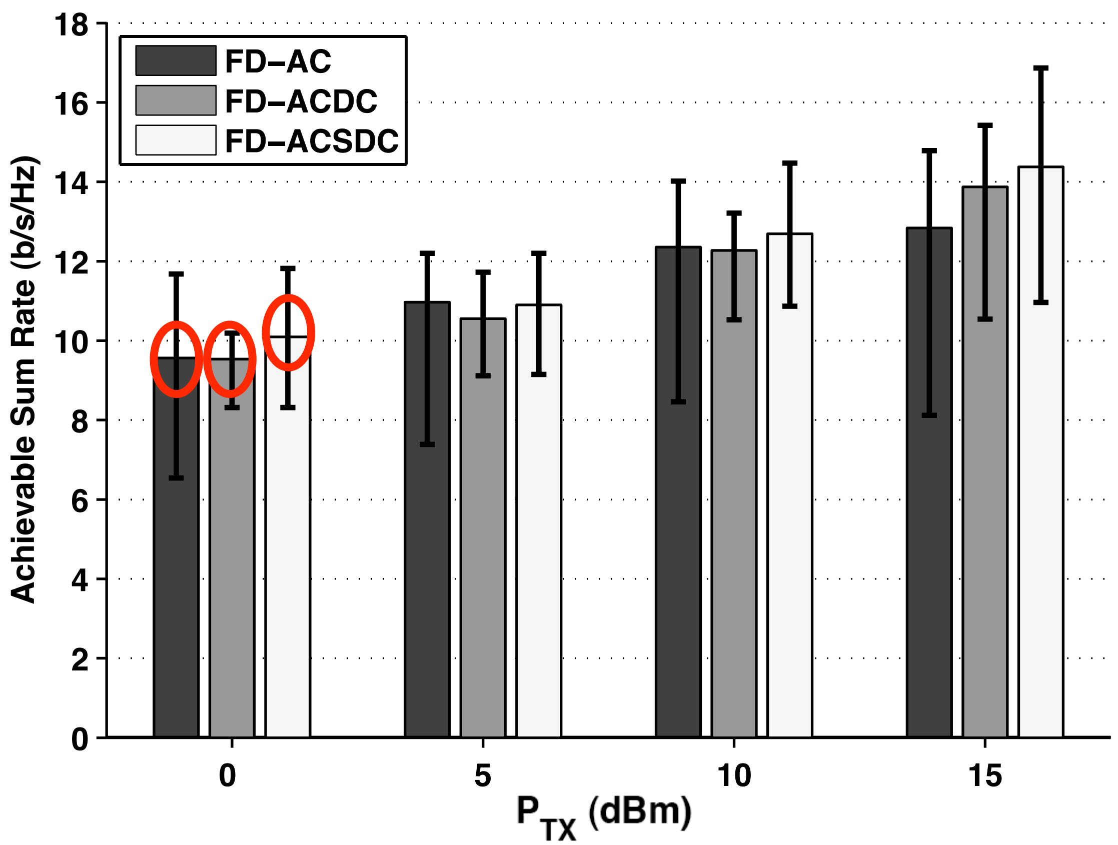

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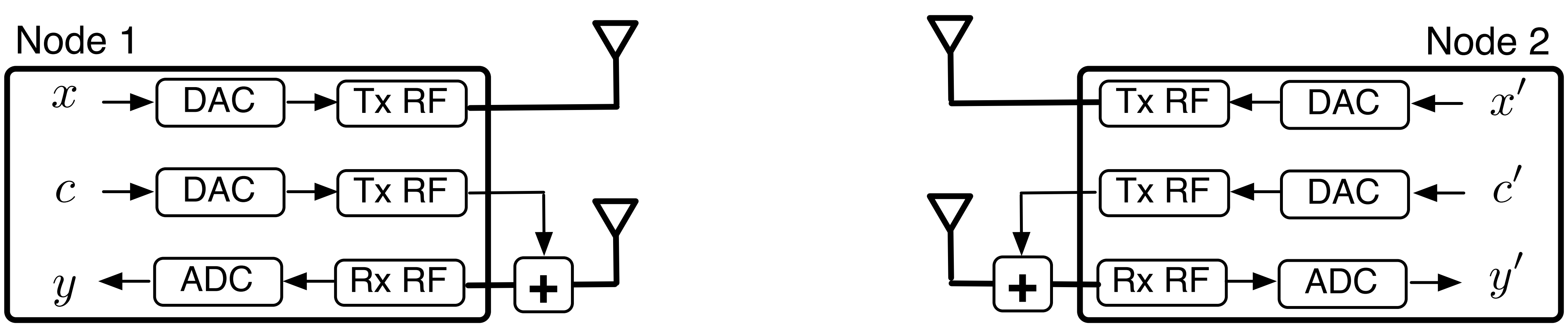
Full-Duplex vs. Half-Duplex

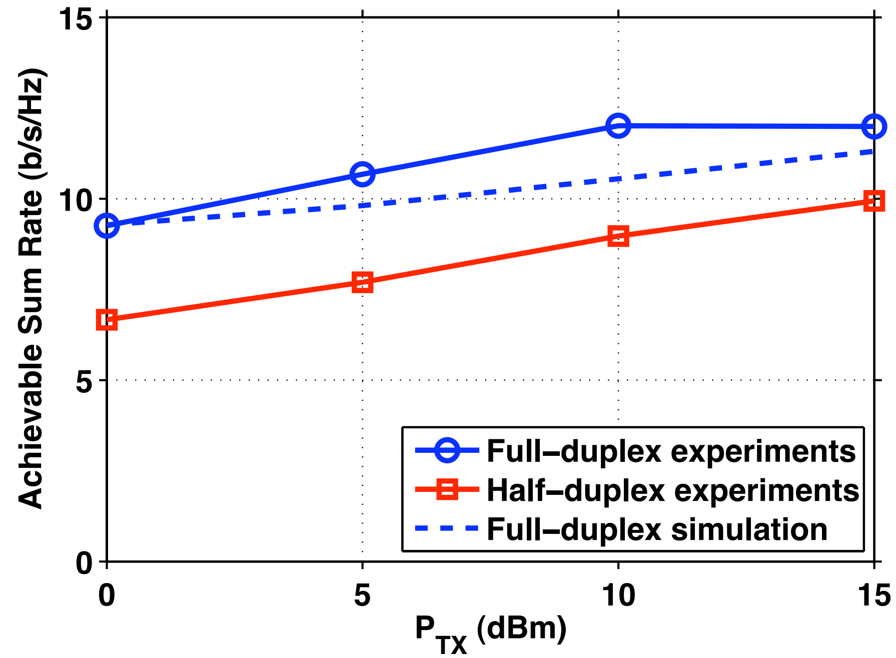
Compare half-duplex and full-duplex systems that use same resources

	Full-duplex with analog cancellation	Half-duplex 2x1 Alamouti
Antennas per node	2	2
Tx RF radios per node	2	2
Rx RF radios per node	1	1
Tx power per antenna	P_{TX}	P_{TX}



Full-Duplex vs. Half-Duplex

- d = 10 cm
- d = 20 cm
- d = 40 cm



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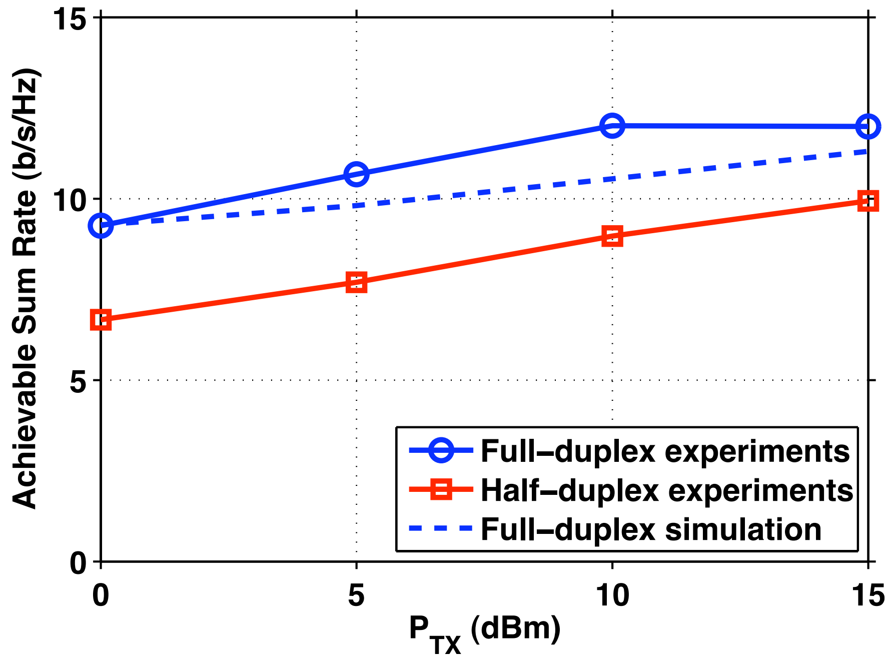
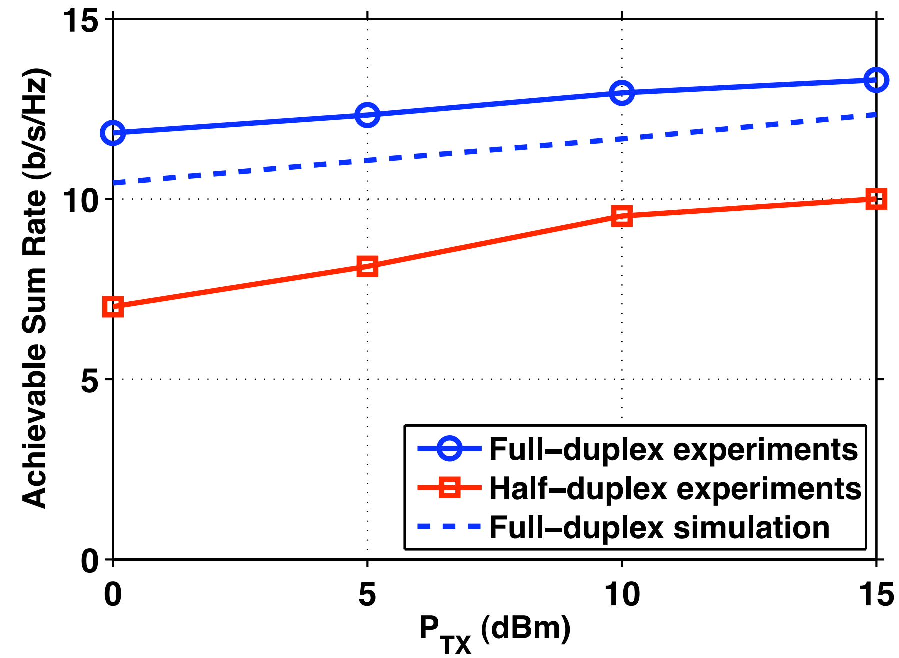


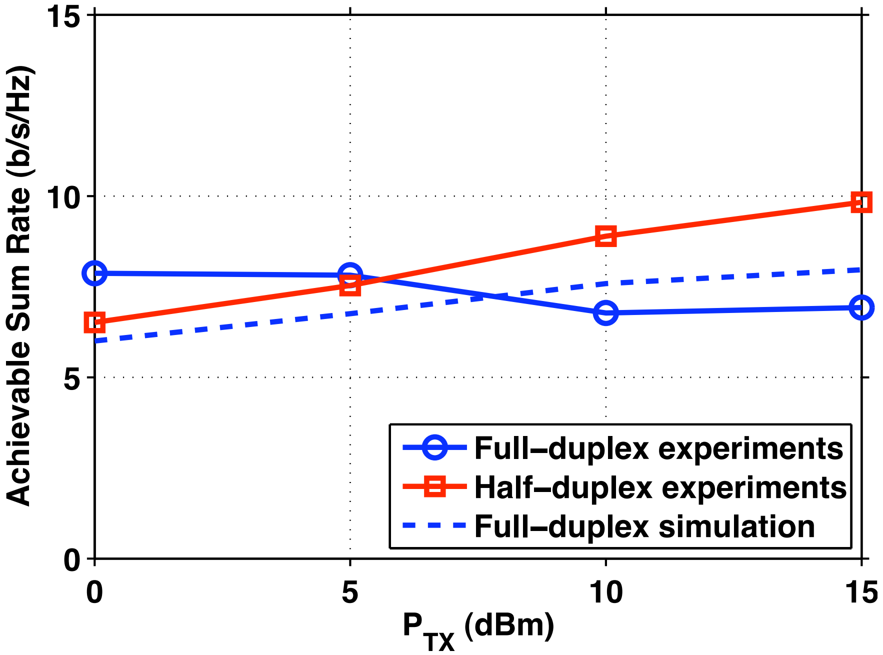
- d = 40 cm



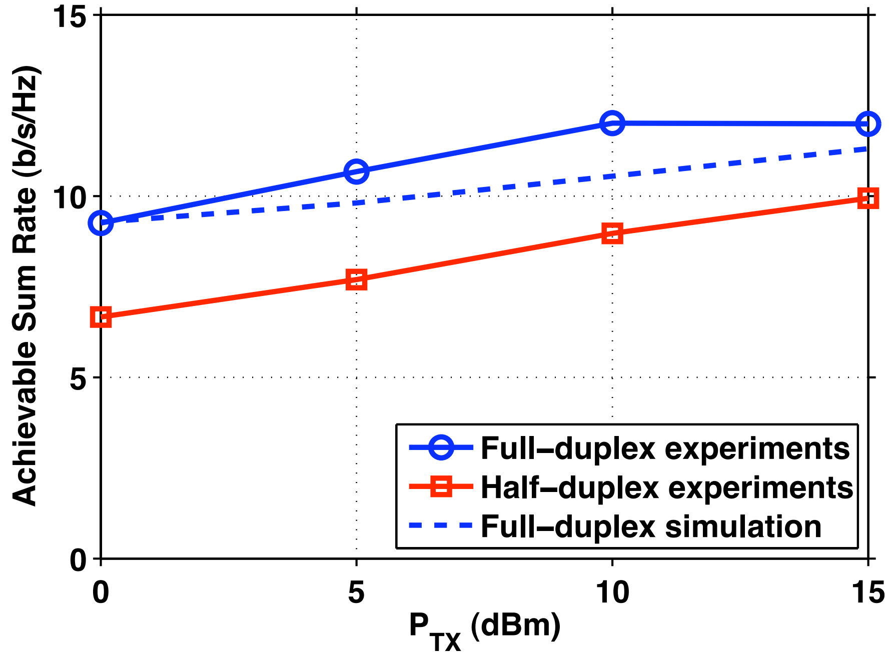
- Full-duplex can achieve higher rates than half-duplex
- The linear fit model is reasonable accurate

Full-Duplex vs. Half-Duplex

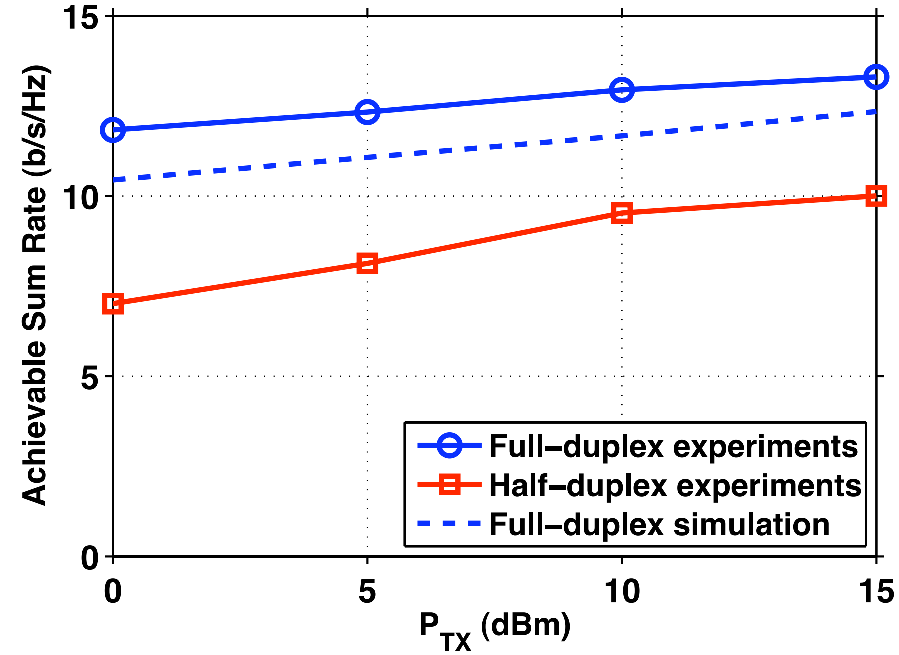
- d = 10 cm



- d = 20 cm



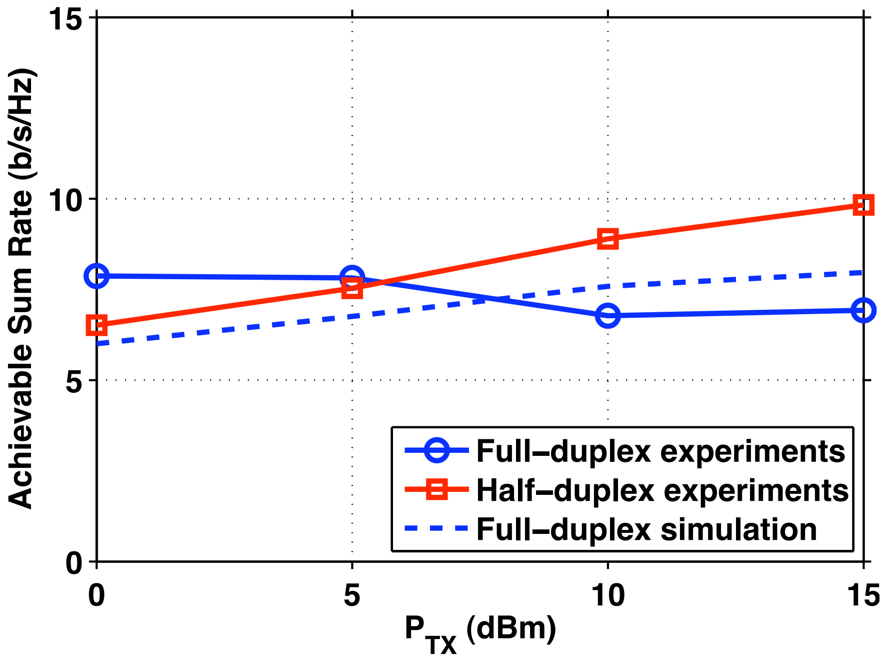
- d = 40 cm



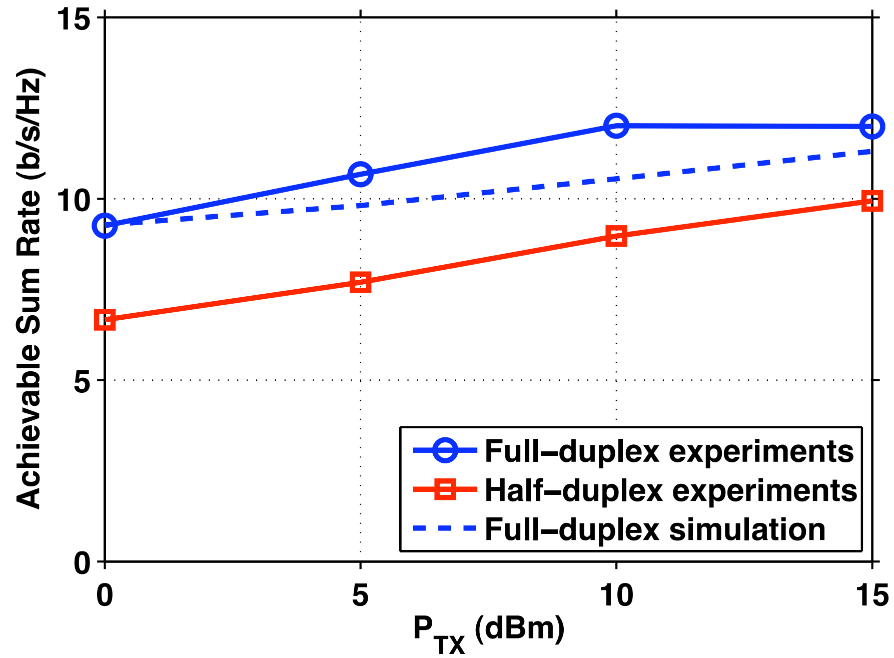
- Full-duplex can achieve higher rates than half-duplex
- The linear fit model is reasonable accurate
- Close antennas imply in some scenarios half-duplex wins-out

Full-Duplex vs. Half-Duplex

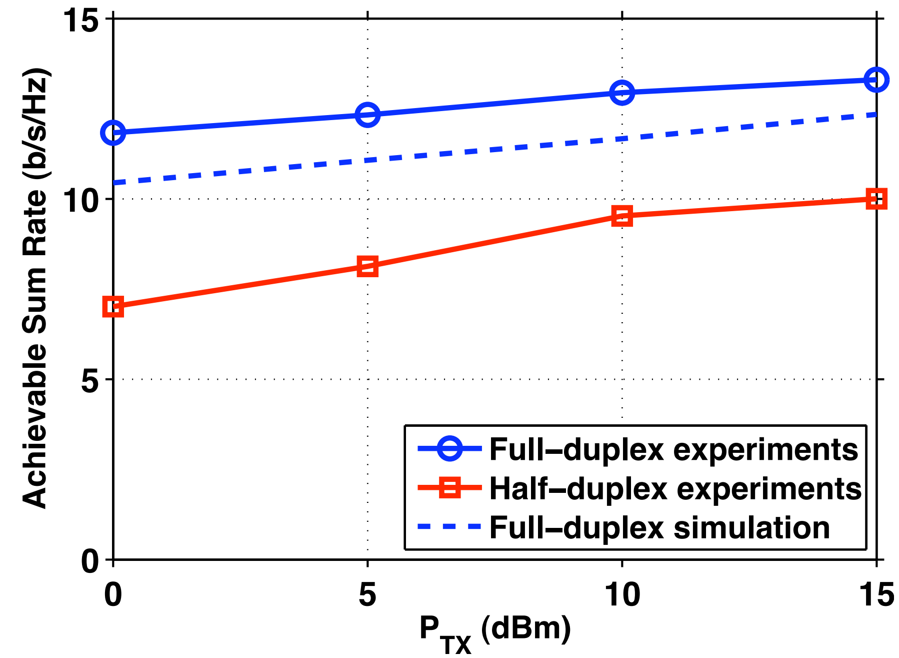
- d = 10 cm



- d = 20 cm



- d = 40 cm



- Full-duplex can achieve higher rates than half-duplex
- The linear fit model is reasonable accurate
- Close antennas imply in some scenarios half-duplex win-out

- Full-duplex without analog cancellation and only digital cancellation always performs worse than half-duplex due to quantization noise
  - Duarte et al. *Full-Duplex Wireless Communications using Off-The-Shelf Radios: Feasibility and First Results*. Asilomar 2010.

Conclusions

- Full-duplex can achieve higher rates than half-duplex.
- Amount of active cancellation increases as the received self-interference power increases.
- At a constant SIR@Rx antenna more interference is actually good. It allows better cancellation and thus improved rates.
- Digital cancellation is more effective when applied selectively after analog cancellation.

Conclusions

- Full-duplex can achieve higher rates than half-duplex.
- Amount of active cancellation increases as the received self-interference power increases.
- At a constant SIR@Rx antenna more interference is actually good. It allows better cancellation and thus improved rates.
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Recent and ongoing work at Rice

- Asynchronous full-duplex.
    - Receive-while-sending.
    - (not send-while-receiving)
- Antenna design and MAC protocols.
- MIMO and OFDM analysis.

Everett et. al. *Empowering Full-Duplex Wireless Communication by Exploiting Directional Diversity.* Asilomar 2011.

Sahai et al. *Pushing the Limits of Full-Duplex: Design and Real-Time Implementation.* Tech. Report 2011. Rice University.