Full-duplex Wireless Using MIMO Radios: Experiment-driven Model & System Capacity

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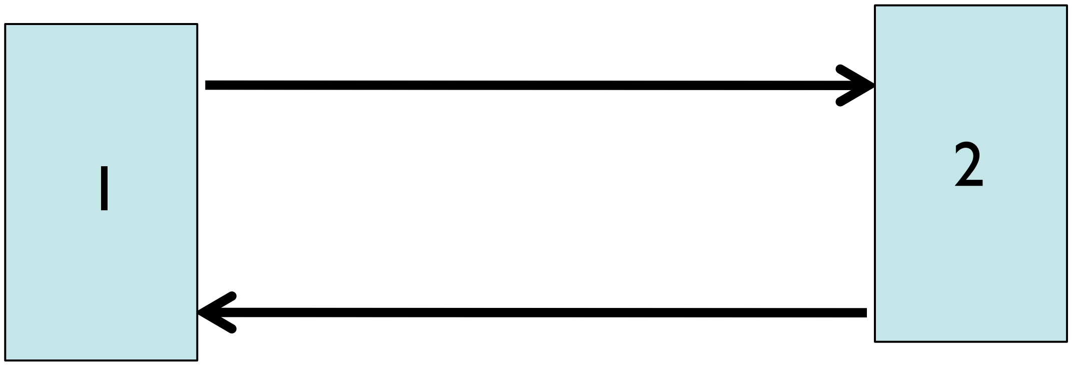
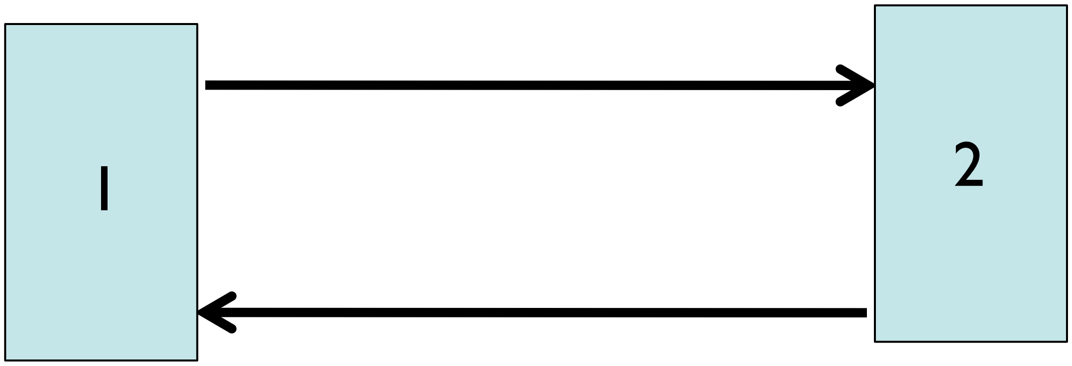
Full-duplex Wireless



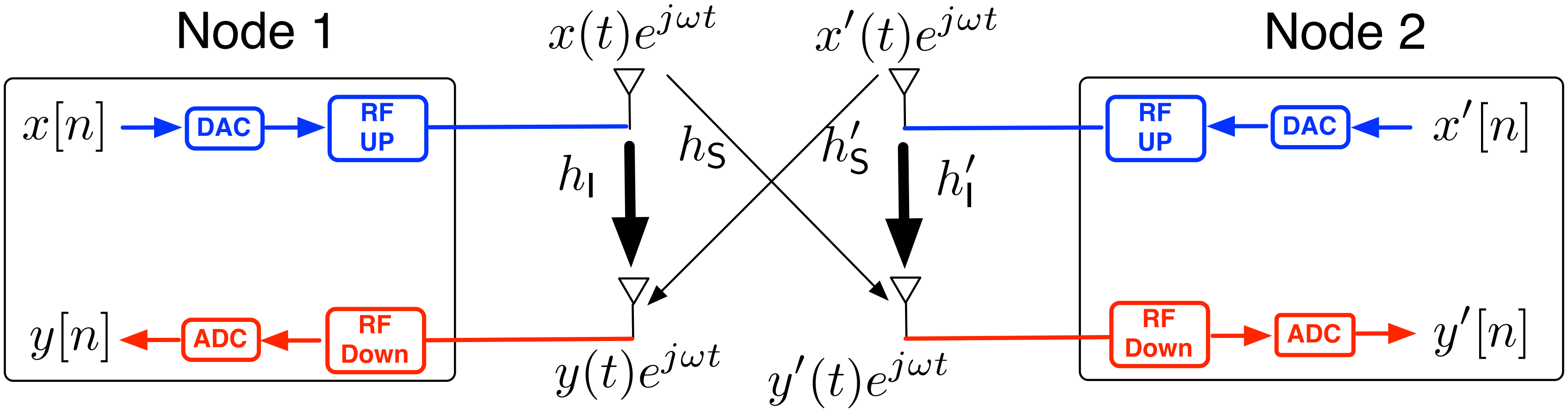
- Same time and same frequency band
- Assumed to be impossible
- Revisit this assumption

Full-duplex Wireless



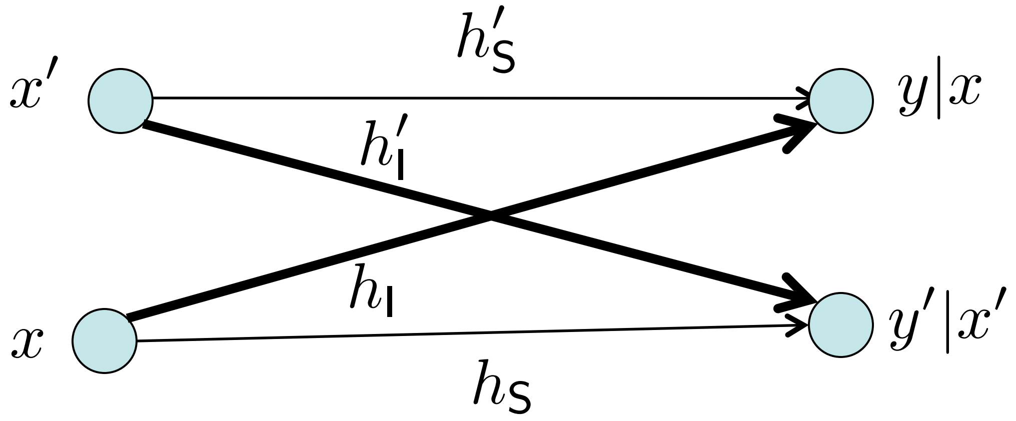
- Build a two-way system to establish feasibility
- Mixed signal techniques – analog and digital
- Measurable rate benefits

Main Challenge



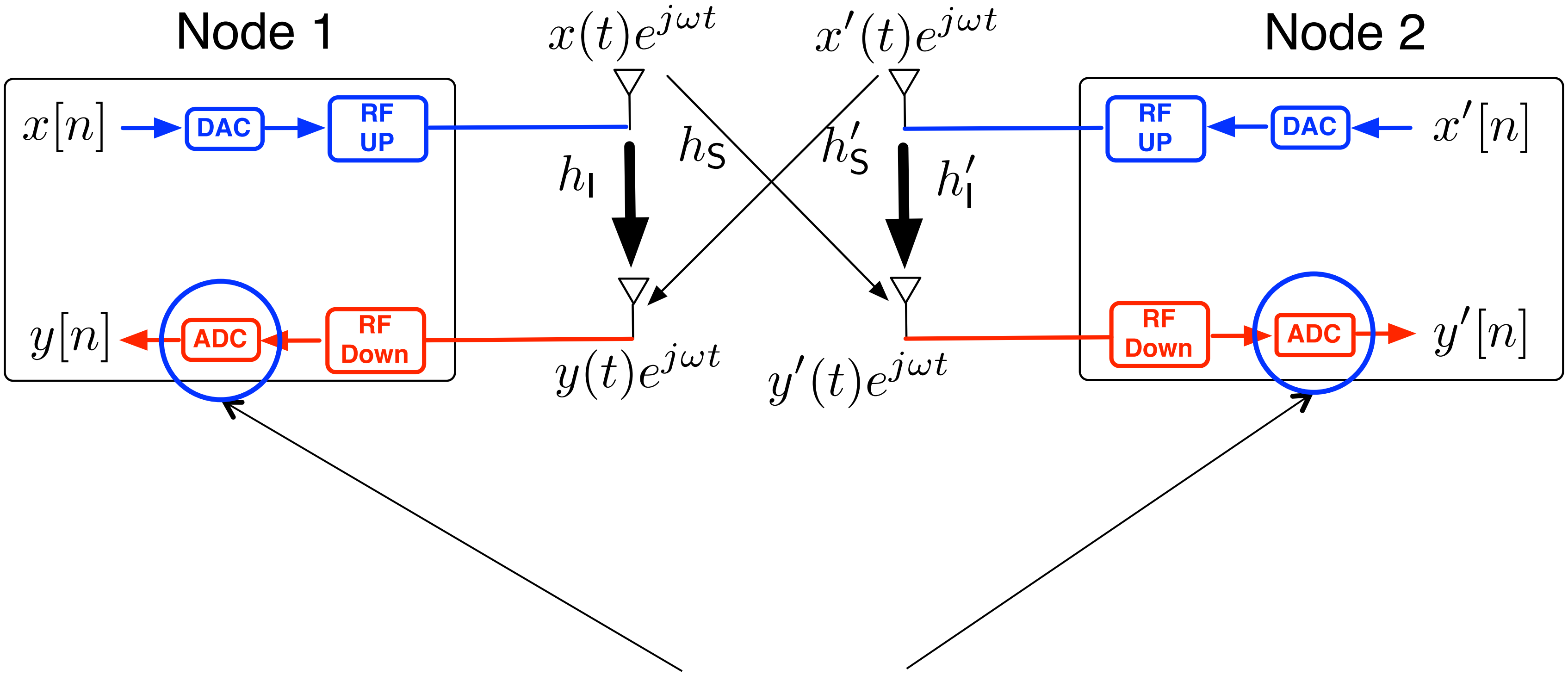
- Self-interference is huge since $h_I >> h_S$
- 15-110dB larger than signal of interest, depending on inter-node distance

That Should Be Nice



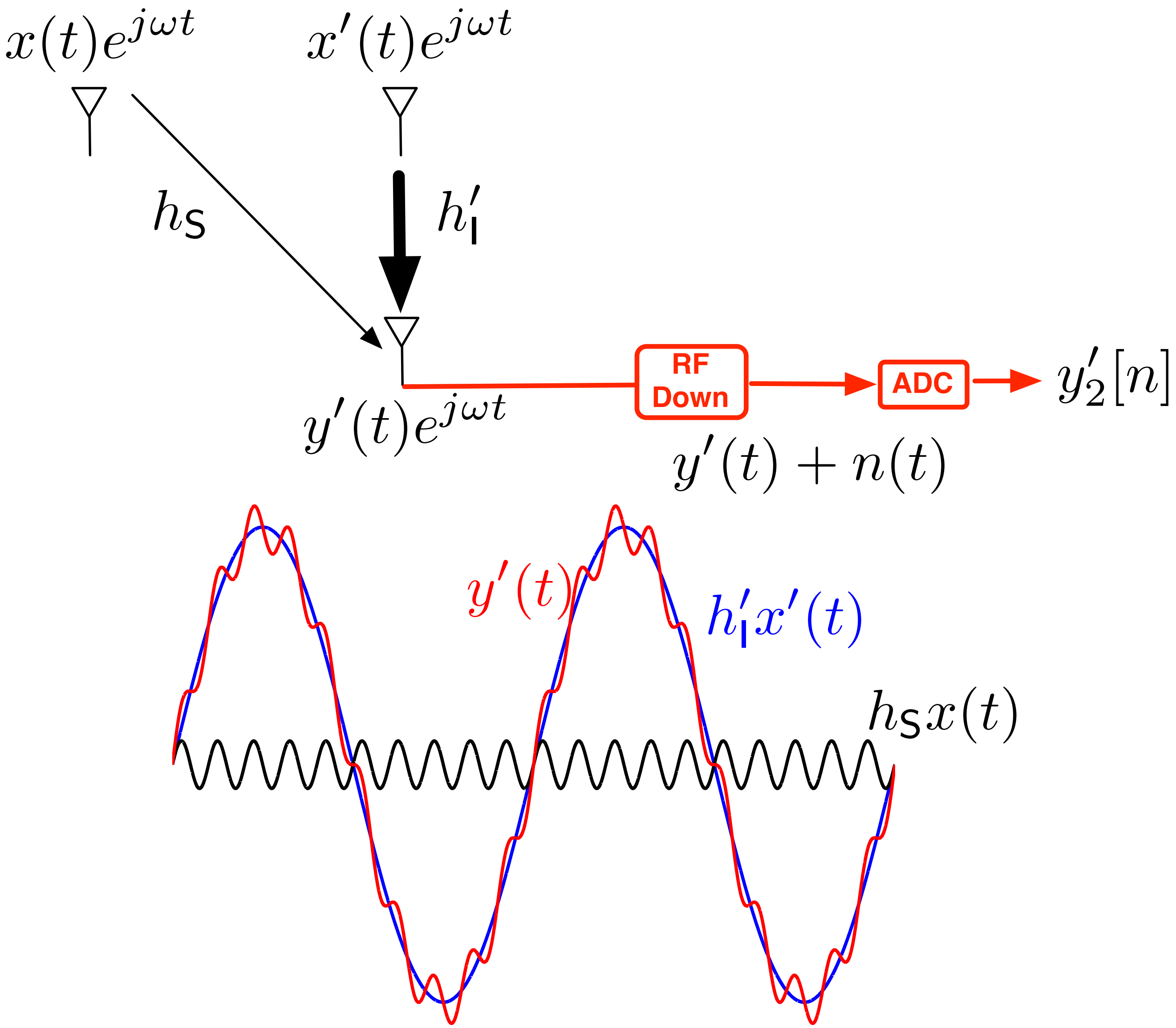
- Interference >> Signal
- Strong interference regime
- Interference is known, estimate channel, cancel, done !

Bottleneck in Implementation

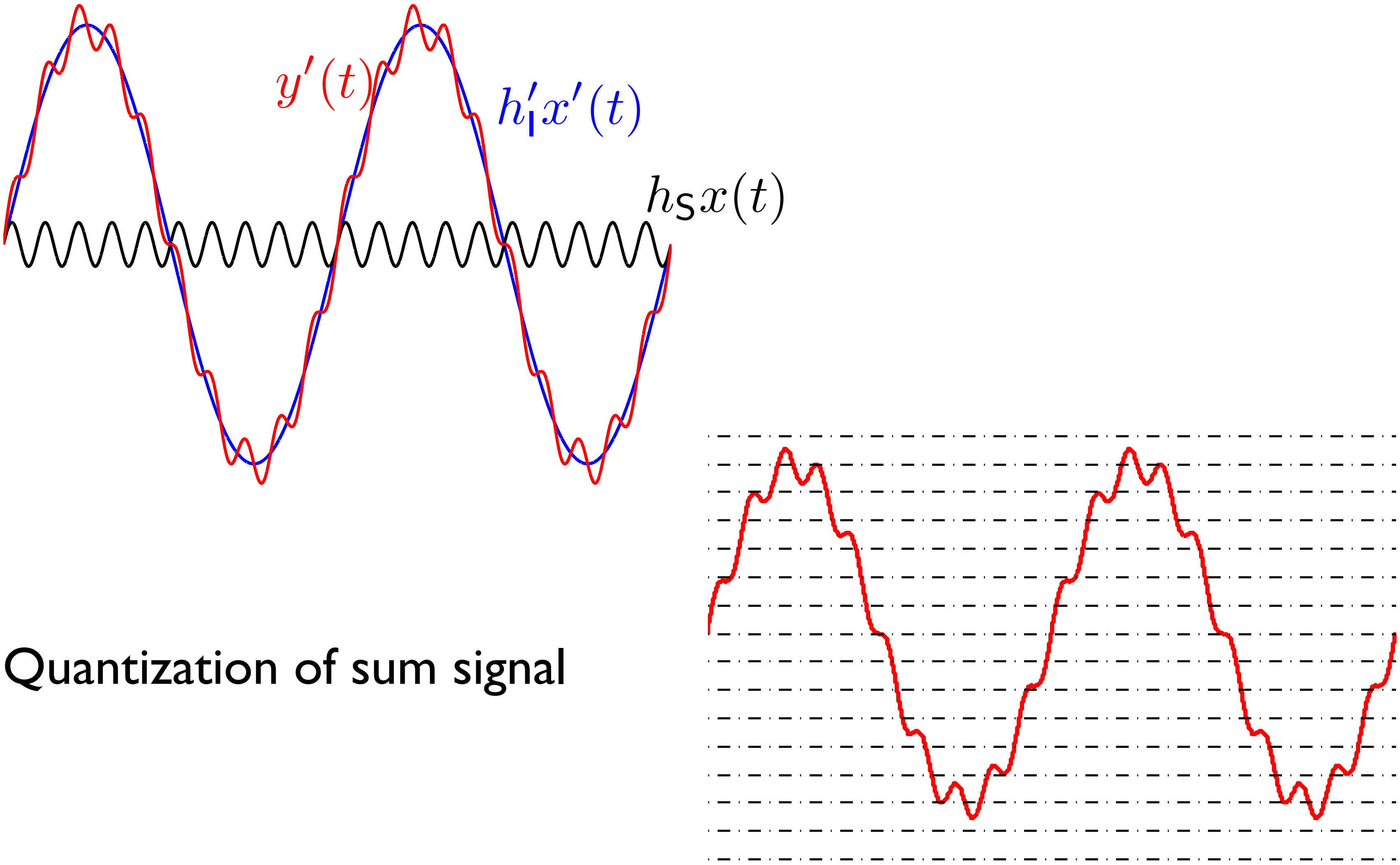


Analog-to-Digital Conversion
is the bottleneck

Analog to Digital Conversion



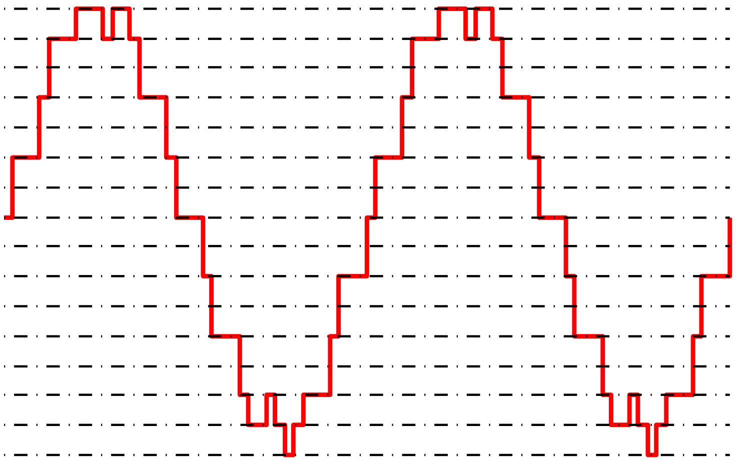
Analog to Digital Conversion



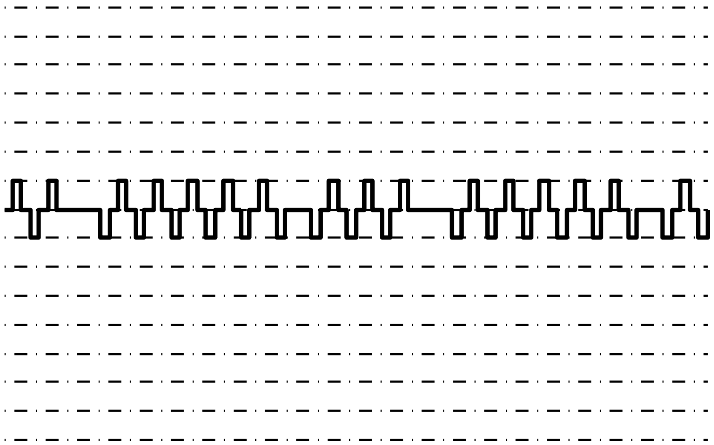
Quantization of sum signal

Signal of Interest Swamped

Quantized sum signal



Signal of interest



- Only a few bits for the signal of interest
- If INR(dB)-SNR(dB) > $20\log_{10}2^{(Q-1)}$ dB, then signal completely swamped by interference
- Q=12 bits, this limit ~70 dB.

Methods to Get More Bits

- Make ADC more capable
  - 16-bit is state-of-the-art for > 50 Msps
  - Best commercial 24-bit ADC < 500 Ksps

- No Moore's law for ADC
  - Limited by thermal noise
  - No consensus on limits of current technology
  - But consensus that progress is very slow

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- Make ADC more capable
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- No Moore's law for ADC
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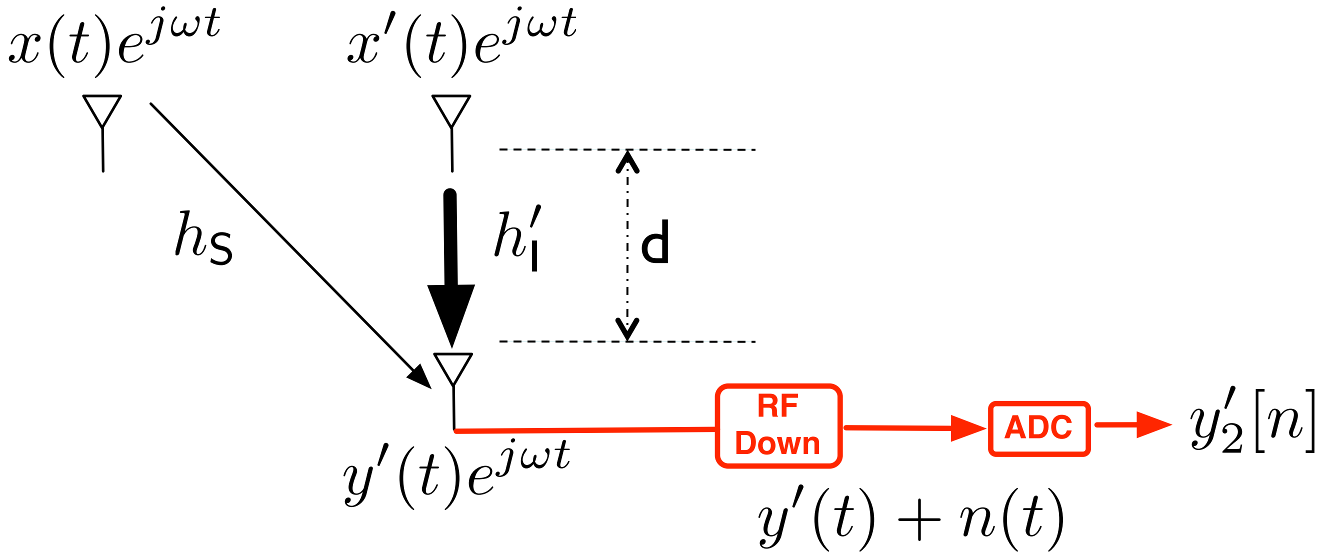
  - No consensus on limits of current technology
  - But consensus that progress is very slow
- Fundamentally limited by Heisenberg's uncertainty
  - Walden 1999
  - Krone and Fettweis, 2009

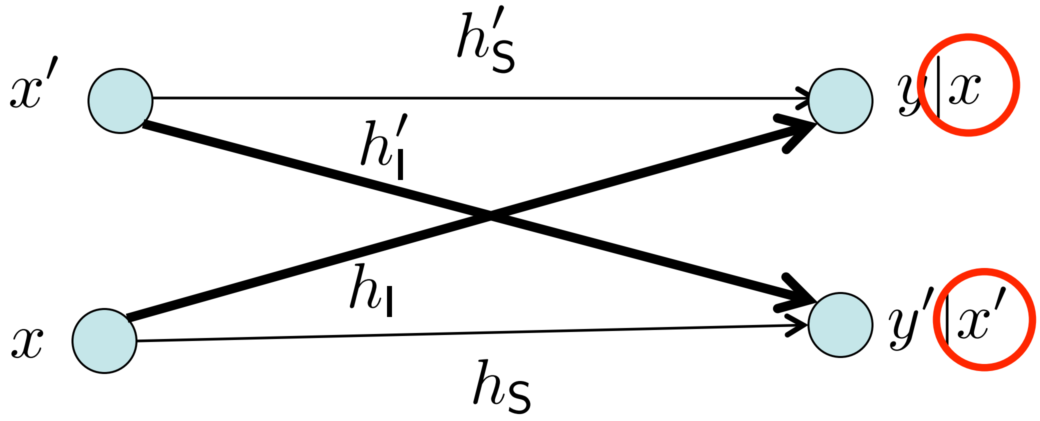
$$\Delta E \Delta t \geq \frac{h}{2\pi}$$

Alternate Mechanisms: Passive Rejection



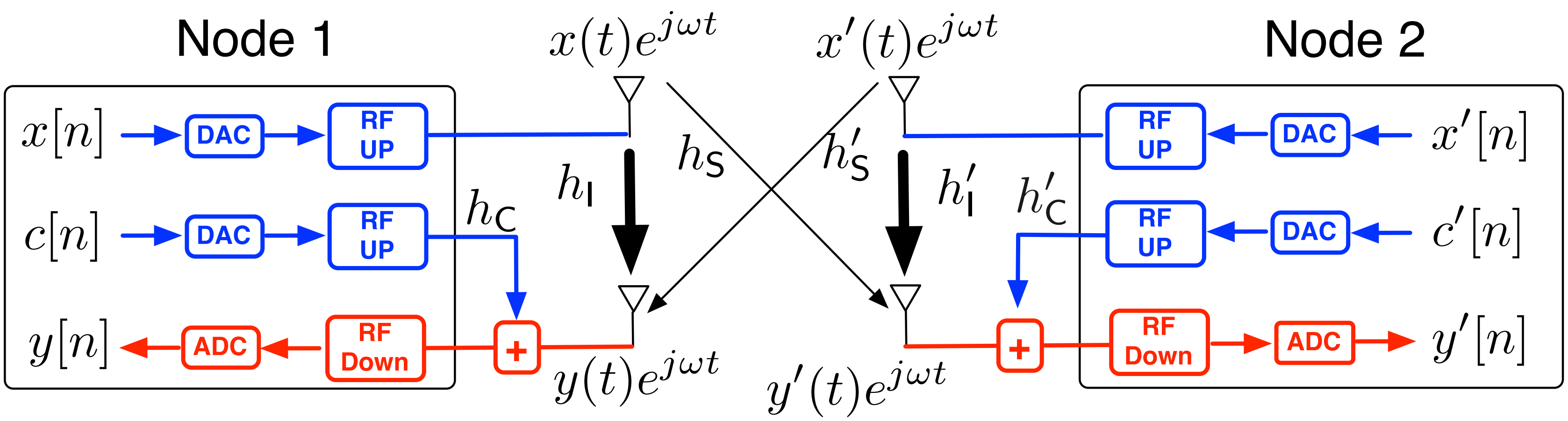
- Increase distance d between antennas
- Additional path loss
- Useful but limited by device dimensions
- Beamforming based suppression - Mobicom'10

Exploit Knowledge of Interference



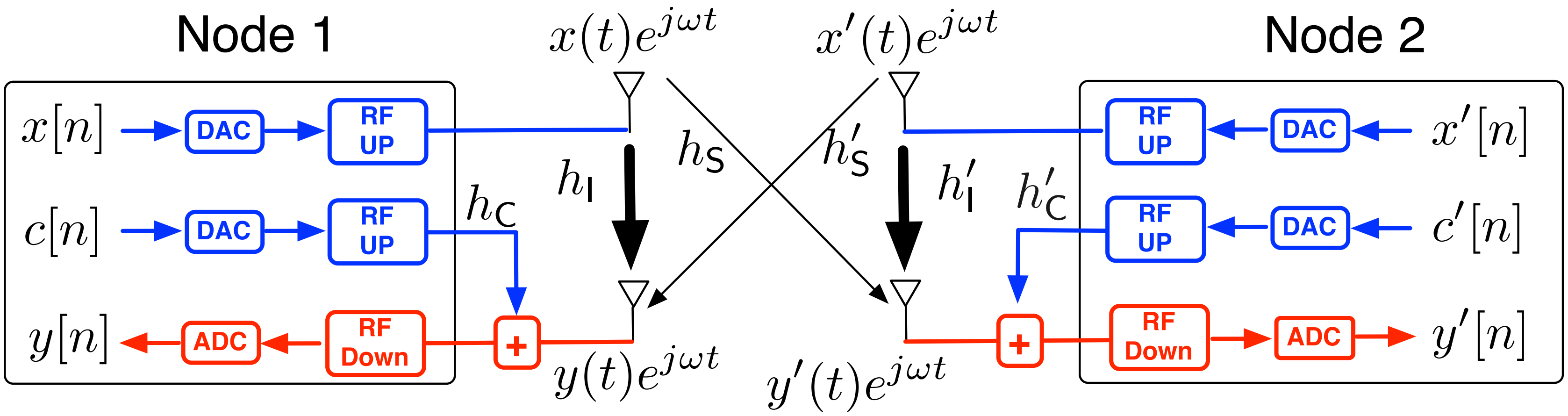
- Interfering signal is known
- Exploit it in analog ?

Alternate Mechanisms: Active Cancellation



- Have to suppress the signal before ADC
- Cancellation has to be performed in Analog
- Use another transmit RF chain to cancel in RF

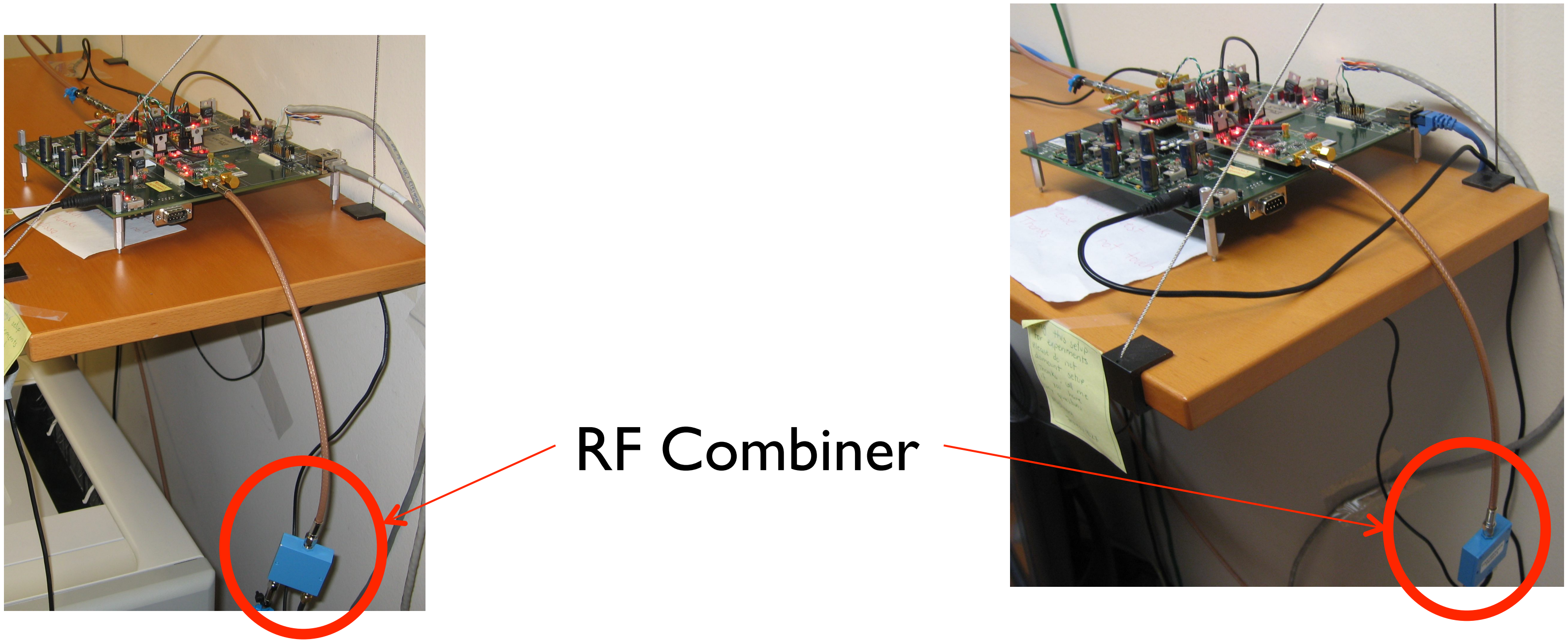
Alternate Mechanisms: Active Cancellation



- The cancellation signals

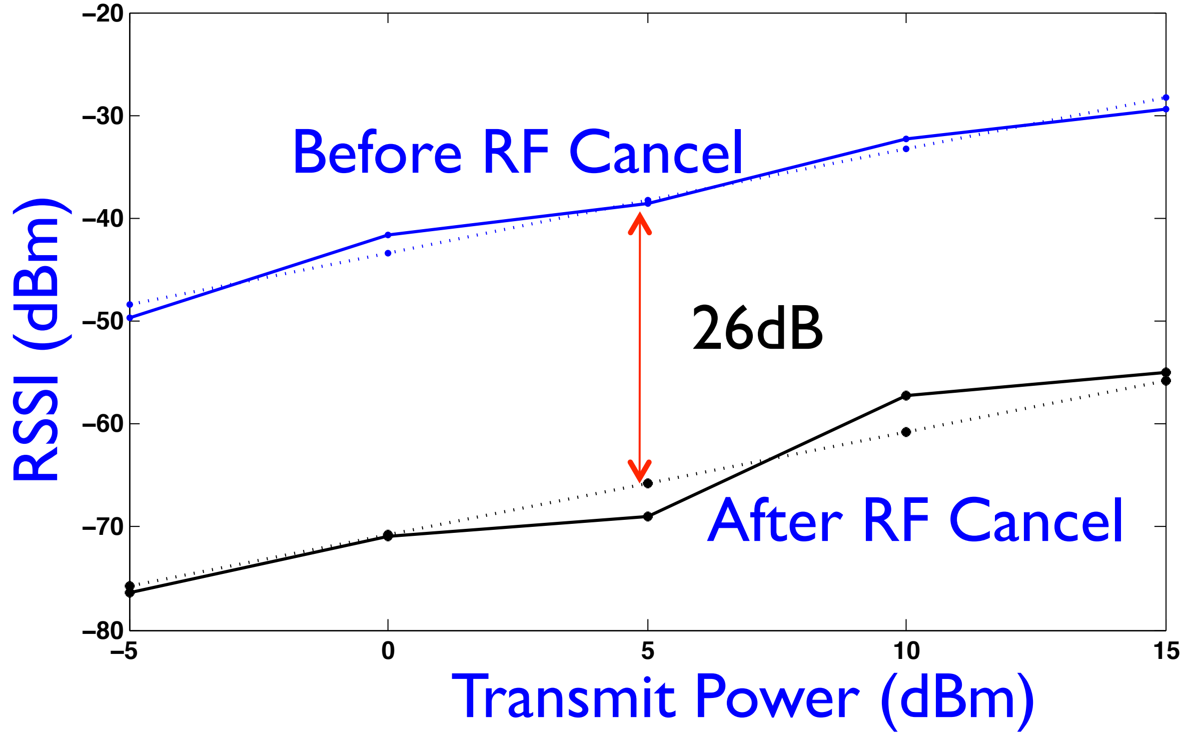
$$c[n] = -\frac{\widehat{h_I}}{\widehat{h_C}}x[n] \qquad c'[n] = -\frac{\widehat{h'_I}}{\widehat{h'_C}}x'[n]$$

Experimental Setup



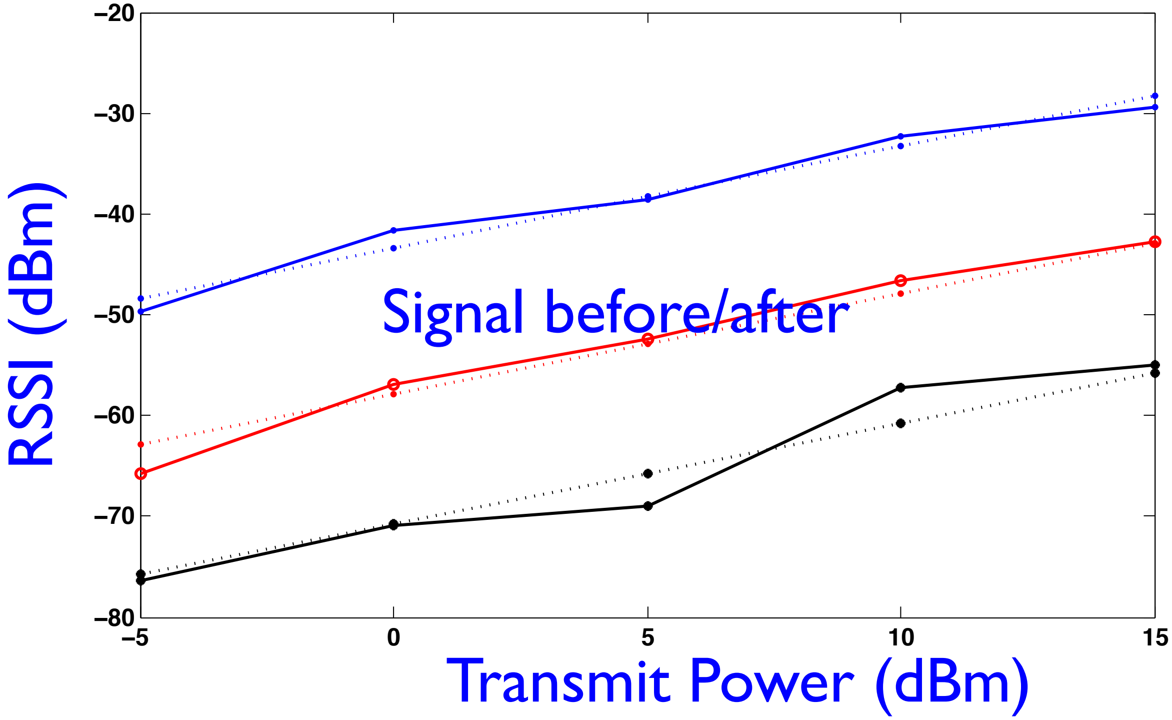
- 2 WARP nodes, each with 3 Radios (2 Tx + 1 Rx)
- WARPLab = WARP + Matlab, to generate/analyze signals
- Narrowband tests, 0.625 MHz
- d = 20cm and inter-node distance 6.5m.

Experimental Results: RF Canceller



- For example, if INR = SNR+70dB, then with 12-bit ADC, signal has ~5 bits
- Useful in Bluetooth/WiFi & maybe in femto/micro-cell

Experimental Results: Signal Linearity

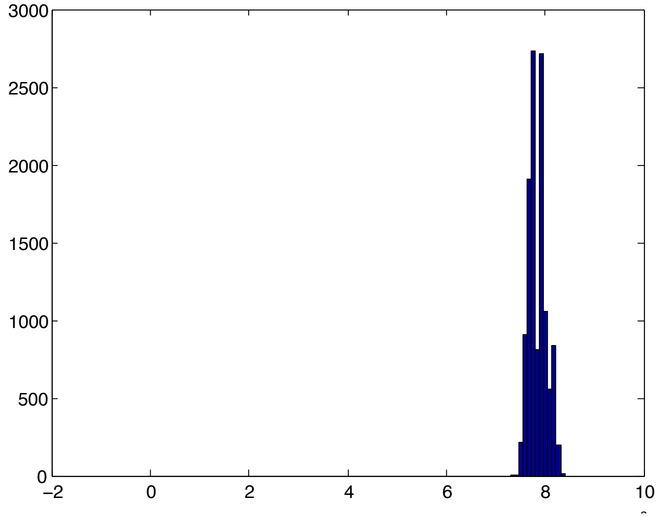


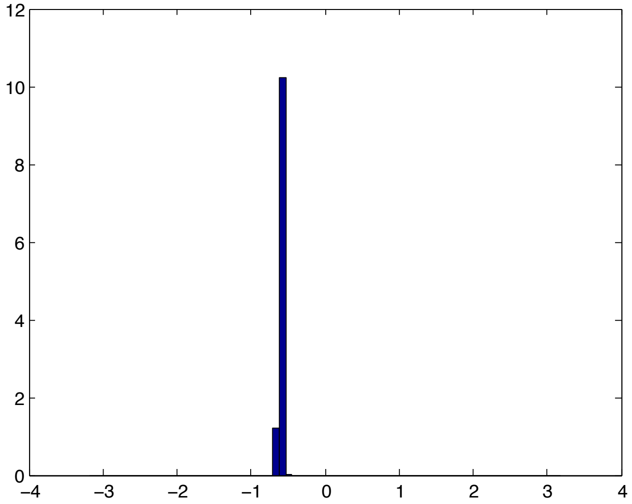
- Signal and interference stay linear in entire transmit range
- For these values of SIR, linear signal model is sufficient

$$y[n] = h_{\mathsf{S}} x'[n] + \tilde{h}_{\mathsf{I}} x[n] + \epsilon[n]$$

Measured Distributions: Self-interference Channel

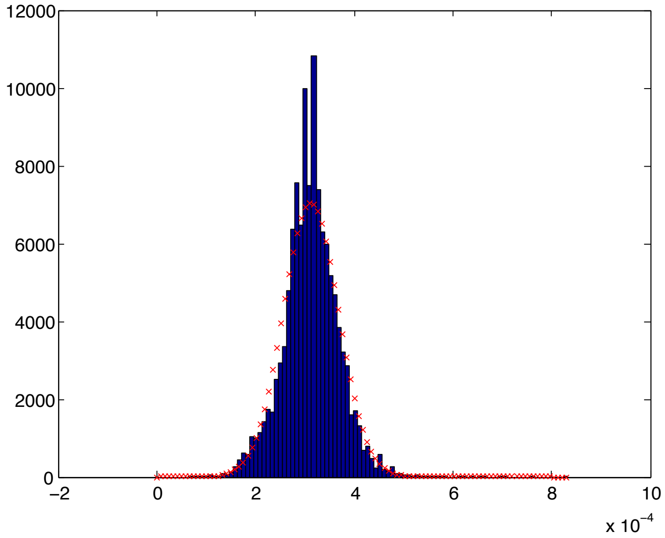
Before RF Cancel

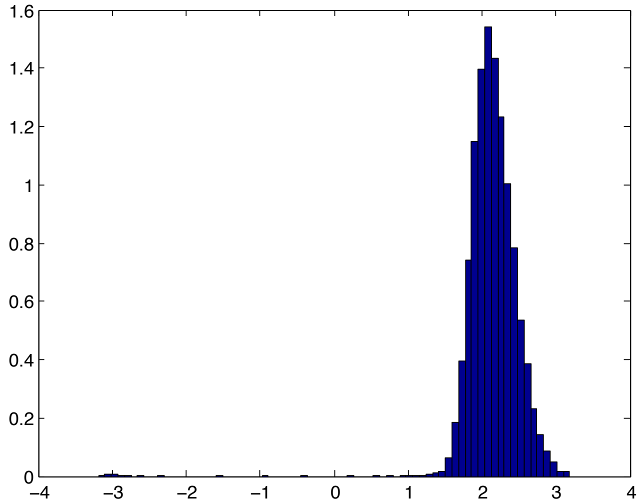




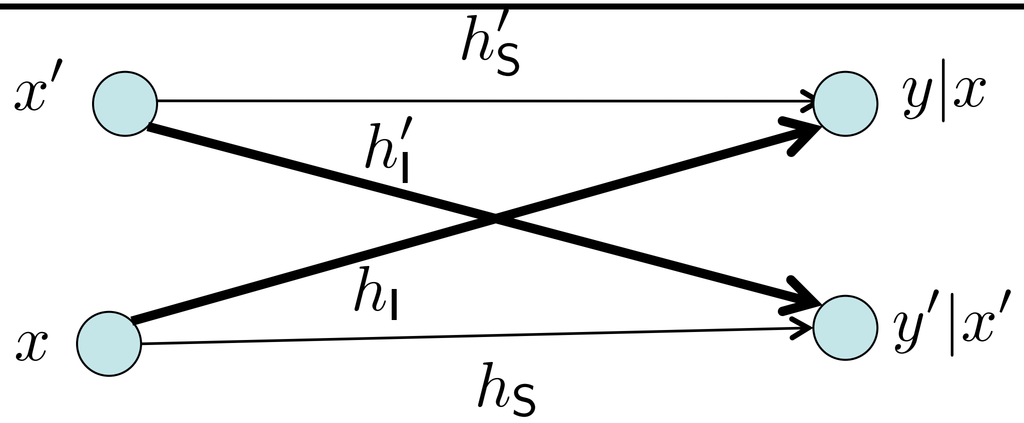
Magnitude **Phase**

After RF Cancel





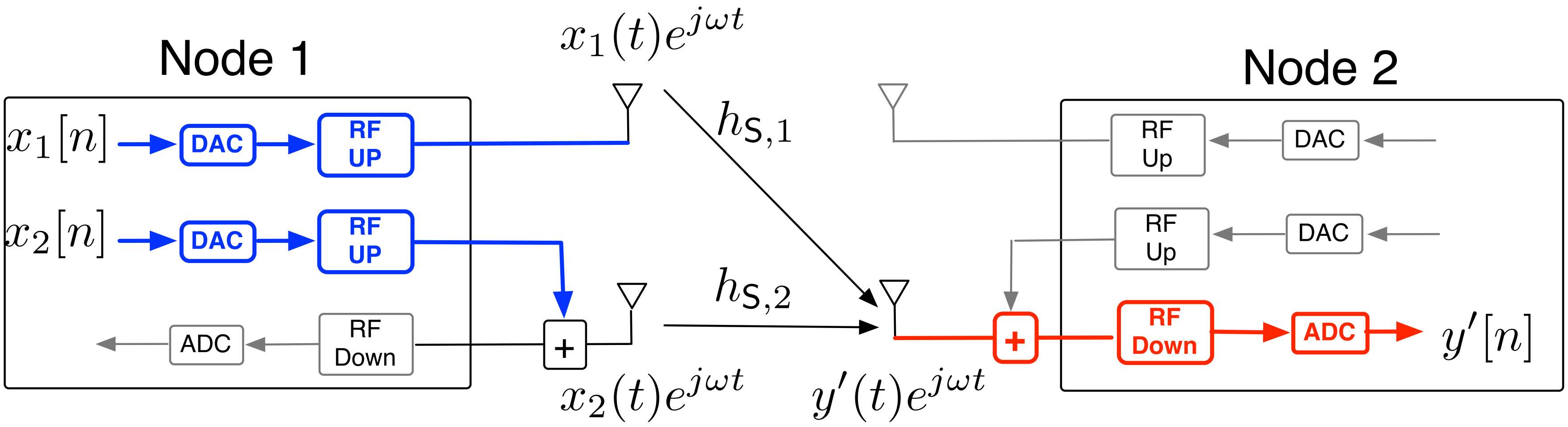
No-interference Sum-Capacity Upper Bound



$$
\begin{aligned}
C_{FD} &= \mathbb{E}_{h_{\mathsf{S}}} \log\left(1 + \frac{P|h_{\mathsf{S}}|^2}{\sigma^2}\right) + \mathbb{E}_{h'_{\mathsf{S}}} \log\left(1 + \frac{P|h'_{\mathsf{S}}|^2}{\sigma^2}\right) \\
&= \boxed{2\mathbb{E}_{h_{\mathsf{S}}} \log\left(1 + \frac{P|h_{\mathsf{S}}|^2}{\sigma^2}\right)}
\end{aligned}
$$

- Assume perfect cancellation
- Two interference-free SISO links

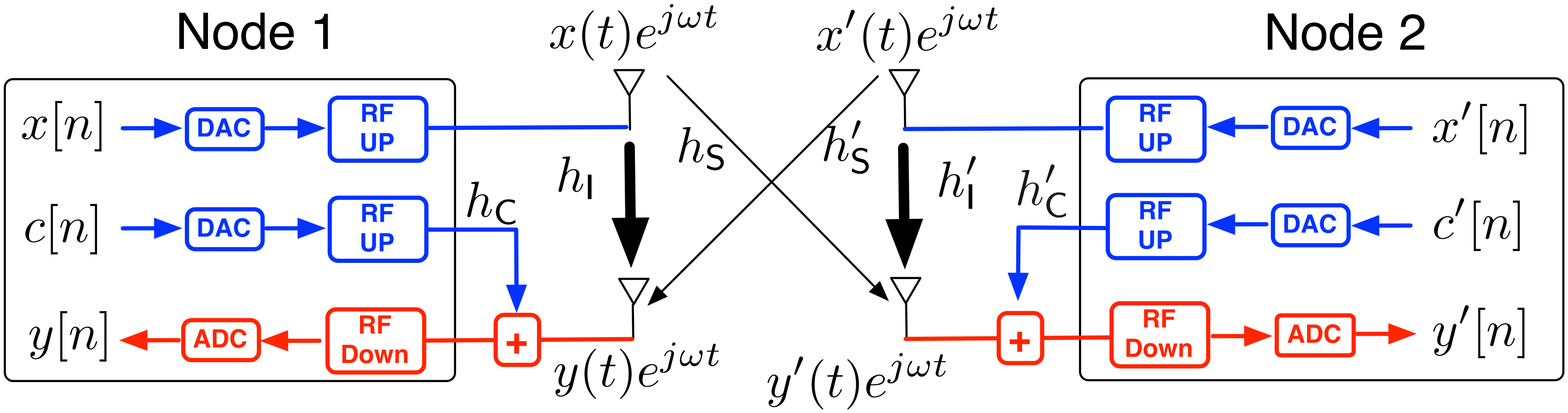
Half-duplex MISO Sum-capacity



$$C_{HD} = \mathbb{E}_{h_{S,1},h_{S,2}} \log\left(1 + \frac{P(|h_{S,1}|^2 + |h_{S,2}|^2)}{\sigma^2}\right)$$

- Each node has 2 up/1 down RF chain
- Thus 2x1 MISO in each direction for half-duplex

RF Cancellation



At RF $$y(t) = h_\mathsf{S} x'(t) + (h_\mathsf{I} - \hat{h}_\mathsf{I})x(t) + \epsilon(t)$$

At Baseband $$y[n] = h_\mathsf{S} x'[n] + \underbrace{\tilde{h}_\mathsf{I} x[n]}_{\text{residual interference}} + \epsilon[n]$$

Cancellation at Baseband

At Baseband

$$y[n] = h_{\mathsf{S}} x'[n] + \underset{\text{Unknown}}{\tilde{h}_{\mathsf{I}}} \underset{\text{Known, treat as training}}{x[n]} + \epsilon[n]$$

Additional baseband suppression

$$\begin{aligned} y[n] &= h_{\mathsf{S}} x'[n] + (\tilde{h}_{\mathsf{I}} - \widehat{\tilde{h}}_{\mathsf{I}}) x[n] + \epsilon[n] \\ &= h_{\mathsf{S}} x'[n] + \underbrace{\tilde{\tilde{h}}_{\mathsf{I}} x[n]}_{\text{treat as noise}} + \epsilon[n] \end{aligned}$$

Gaussian Code Bound

After RF + baseband suppression

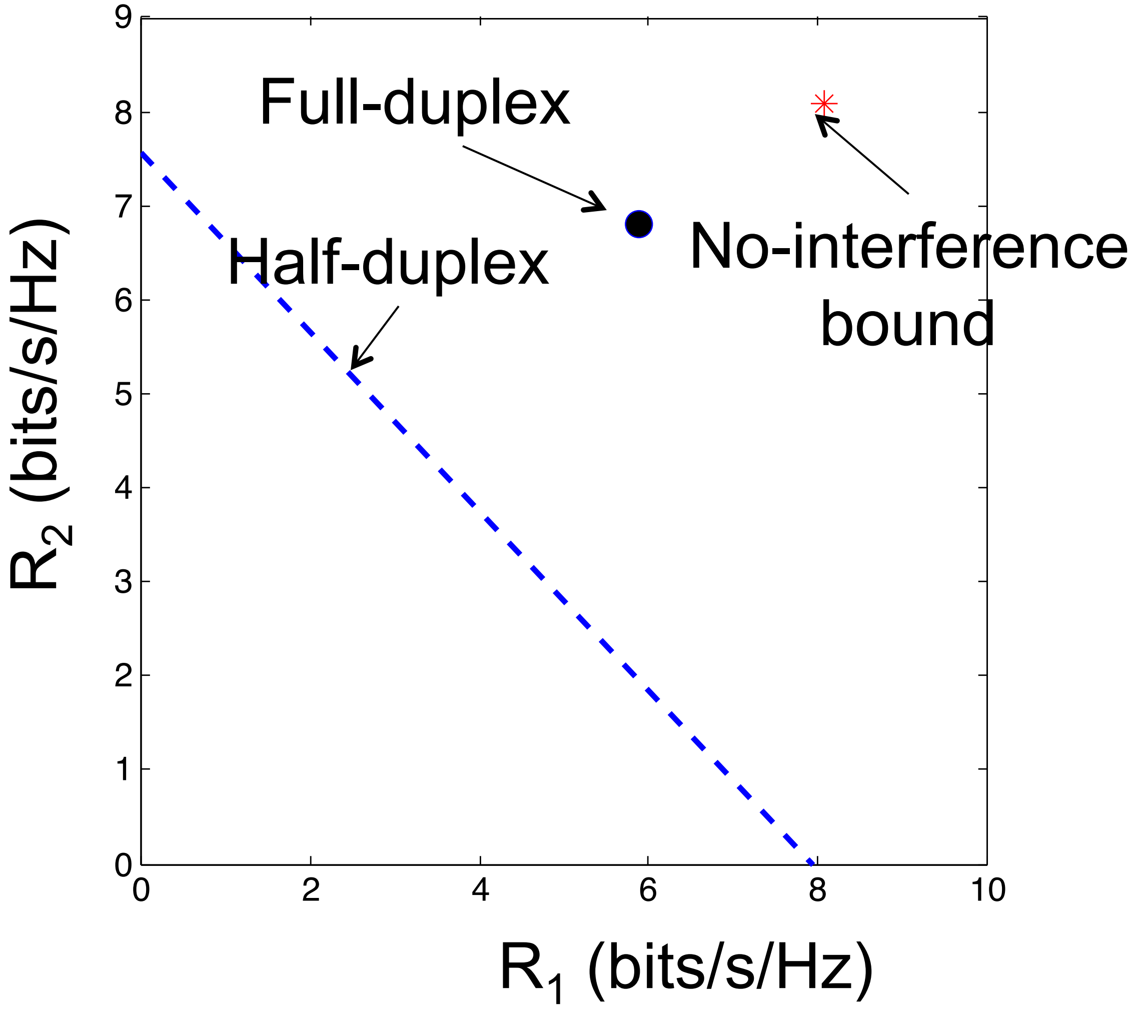
$$\begin{aligned} y[n] &= h_{\mathsf{S}} x'[n] + (\tilde{h}_{\mathsf{I}} - \widehat{\tilde{h}}_{\mathsf{I}}) x[n] + \epsilon[n] \\ &= h_{\mathsf{S}} x'[n] + \underset{\text{treat as noise}}{\underline{\tilde{\tilde{h}}_{\mathsf{I}} x[n]}} + \epsilon[n] \end{aligned}$$

$$\mathsf{SINR} = \frac{|h_{\mathsf{S}}|^2 P}{\left|\tilde{\tilde{h}}\right|^2 P + \sigma^2}$$

$$\boxed{R_{\mathsf{sum}} = 2\mathbb{E}\log\left(1 + \mathsf{SINR}\right)}$$

Measured Capacity

d = 20 cm
D = 6.5 m
LOS channel



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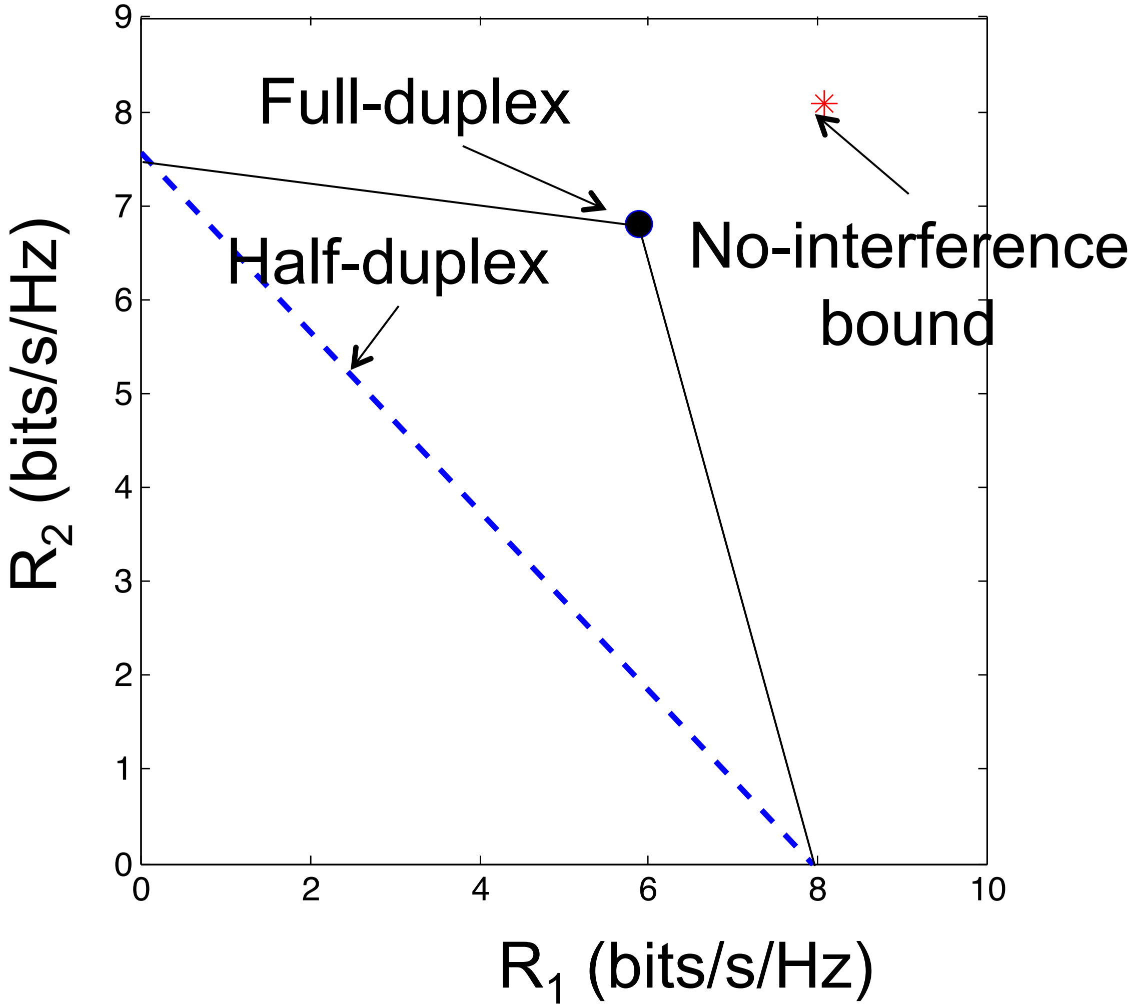

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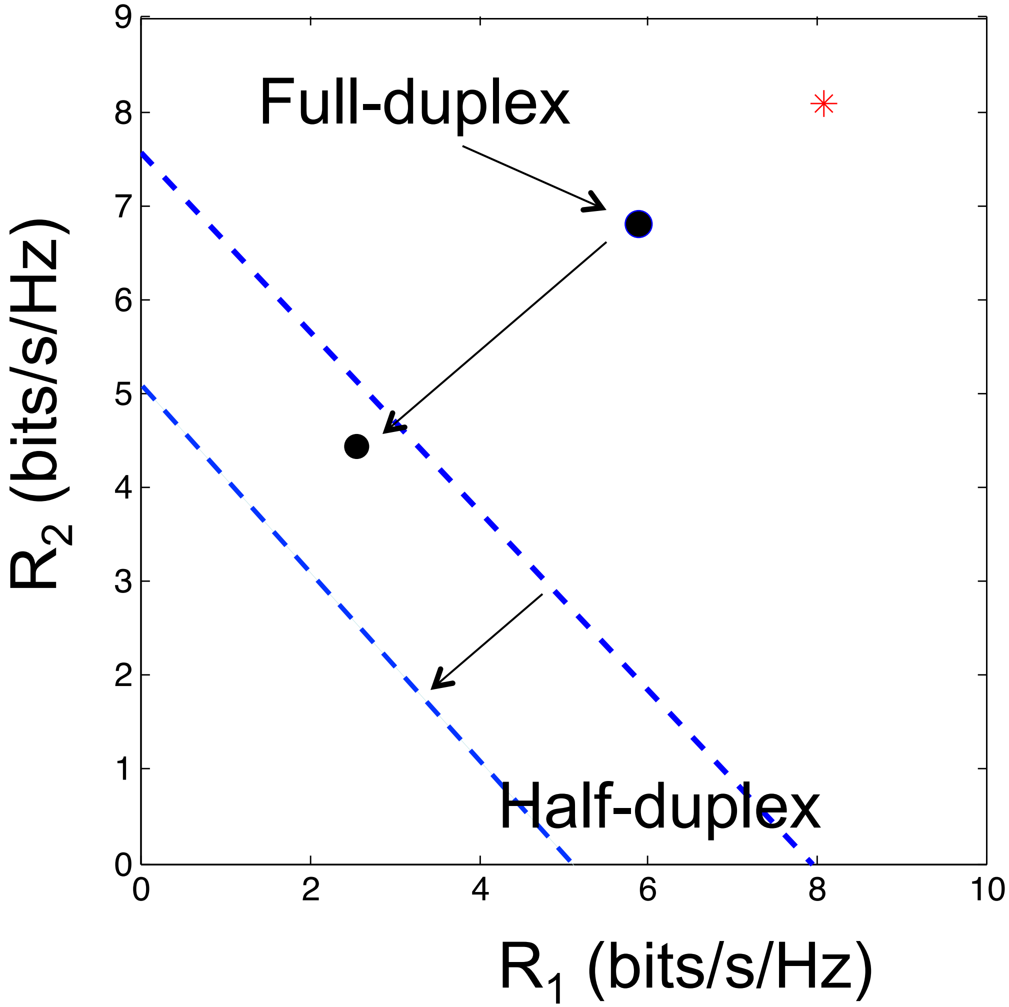
As D increases,
the gain reduces



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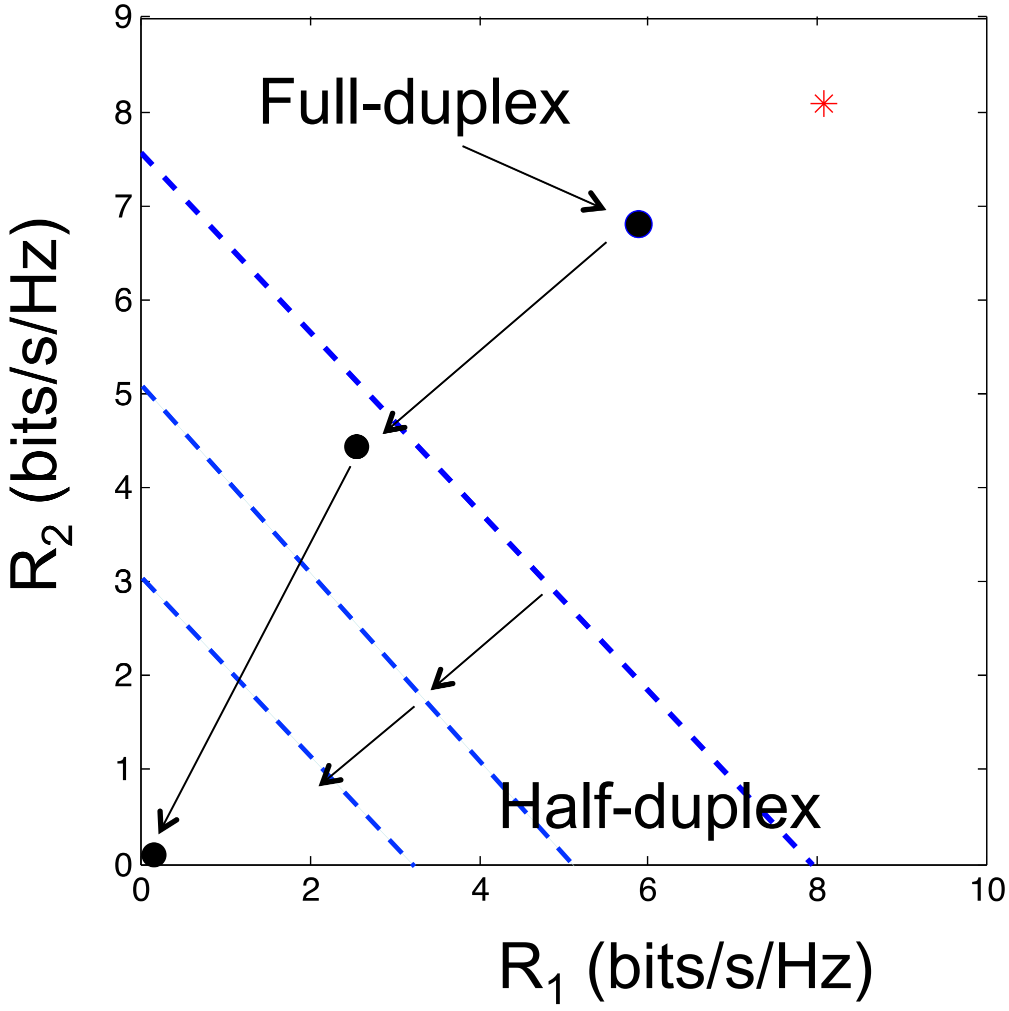

Impact Beyond Full-Duplex

- Issue in multiuser systems with large near-far ratio
- In interference networks, many signals add up
- Need to understand the regime where A/D becomes a dominant effect

Conclusions

- Promising start
  - Half-duplex constraint not fundamental
  - Useful regime for full-duplex

- Ongoing work
  - More extensive experimental characterization
  - Local feedback based suppression (exploit long coherence)
  - Antenna and radio re-design for improved suppression
  - Asynchronous architectures

- Two-way Full-duplex channel
  - Implicit fast feedback possible

Questions ?

- WARP Project - http://warp.rice.edu