Achieving Single Channel Full-Duplex Wireless Communication

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Can a wireless node transmit AND receive at the same time on a single band?

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Status quo: NO

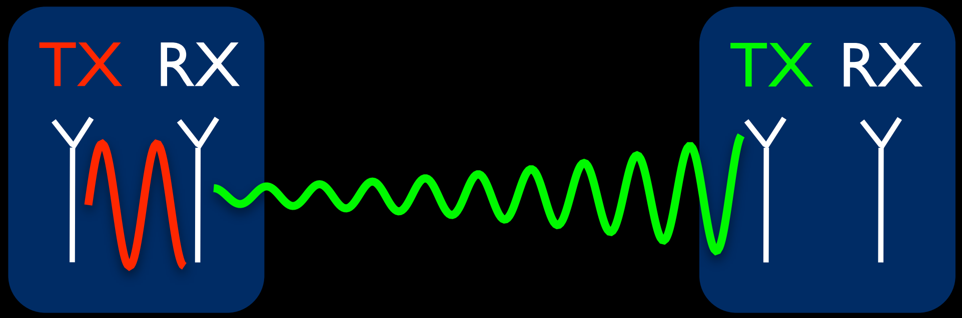
Current wireless radios

- In-band half-duplex
- Full-duplex through other dimensions
  - E.g. different frequencies
  - Bandwidth is a precious resource

Why not full-duplex on the same band?

Why not full-duplex on the same band?

- Very strong self-interference
  - ~70dB stronger for 802.15.4
  - Analog to Digital converter (ADC) saturates



Existing Techniques

- Digital cancellation: Subtracting known interference digital samples from received digital samples.

  ZigZag[1], Analog Network Coding[2] etc.

- Hardware cancellation: RF noise cancellation circuits with transmit signal as noise reference

  Radunovic et al.[3]

[1] Gollakota et al. "ZigZag Decoding: Combating Hidden Terminals in Wireless Networks", ACM SIGCOMM 2008
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Existing Techniques

- Digital cancellation: Subtracting known interference digital samples from received digital samples.

  ZigZag[1], Analog Network Coding[2] etc. ~15dB

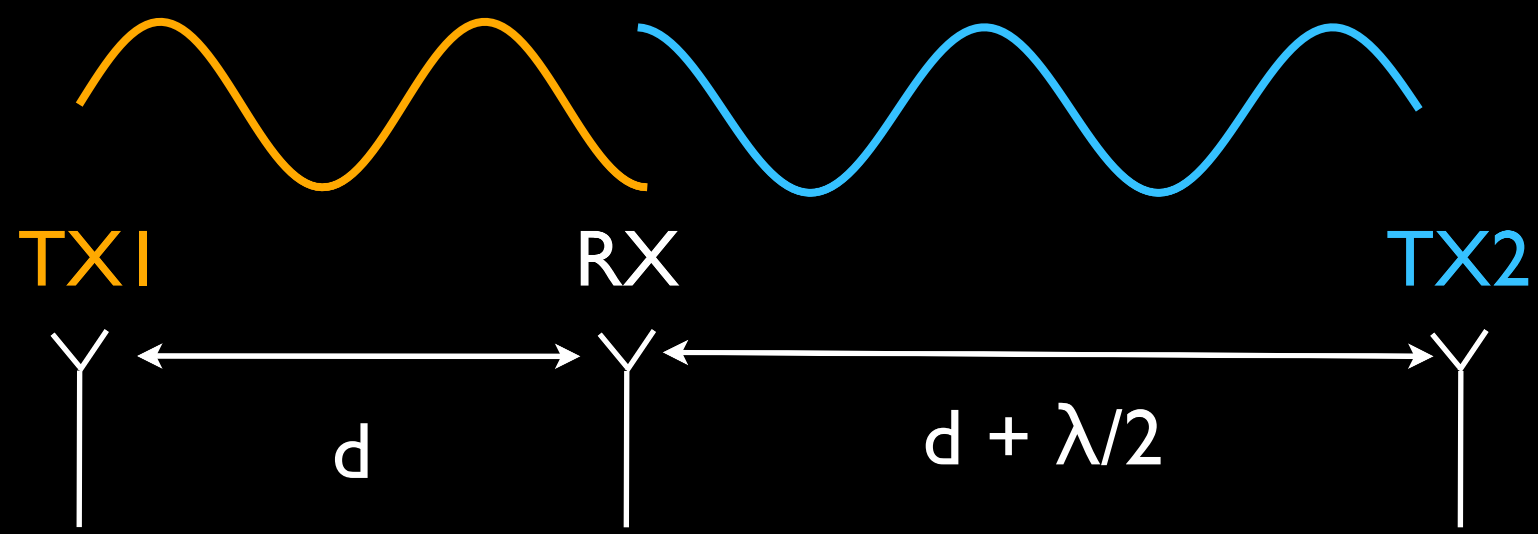
  Ineffective if ADC is saturated

- Hardware cancellation: RF noise cancellation circuits with transmit signal as noise reference

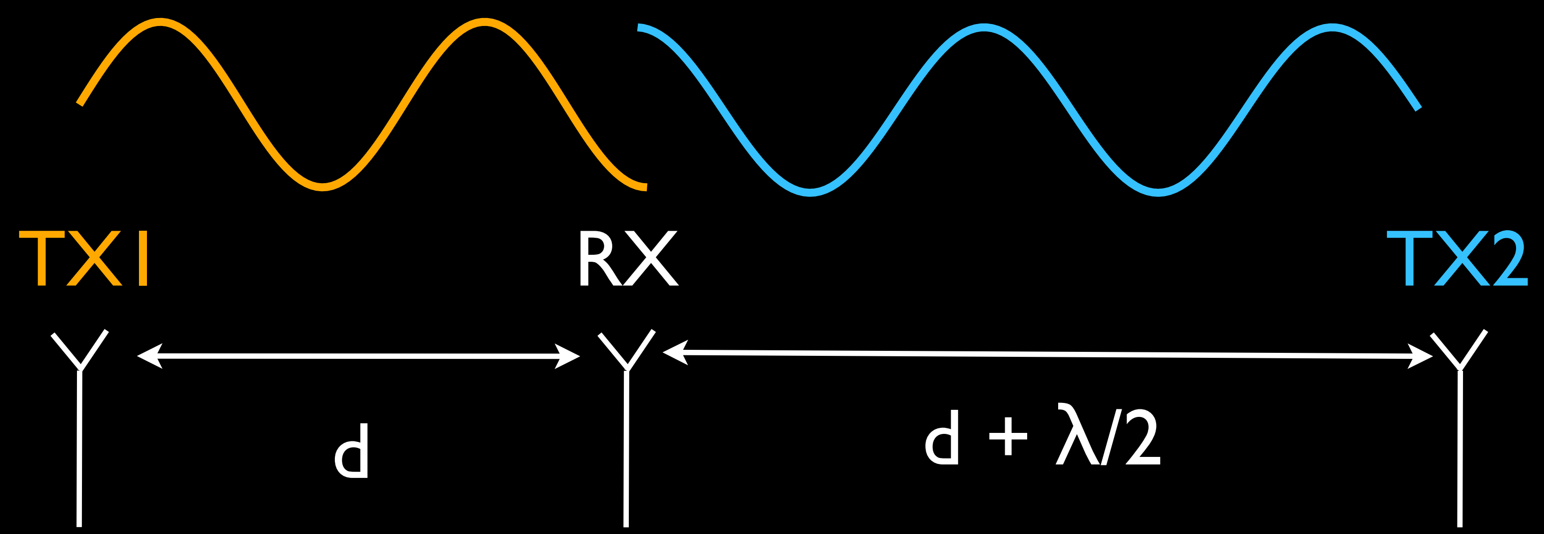
  Radunovic et al.[3] ~25dB

These are not enough 25dB +15dB < 70dB

Our innovation: Antenna Cancellation



Our innovation: Antenna Cancellation



~30dB self-interference cancellation

Enables full-duplex when combined with Digital (15dB) and Hardware (25dB) cancellation.

Can a wireless node transmit AND receive at the same time on a single band?

Can a wireless node transmit AND receive at the same time on a single band?

YES, IT CAN!

Full-duplex prototype achieves 92% of the throughput of an "ideal" full-duplex system

Talk Outline

- Design of Full-Duplex Wireless
  - 3 Techniques: Antenna, Hardware and Digital Cancellation
- Analyzing Antenna Cancellation
- Performance Results
- Implications to Wireless Networks
- Limitations of Design, Future Work

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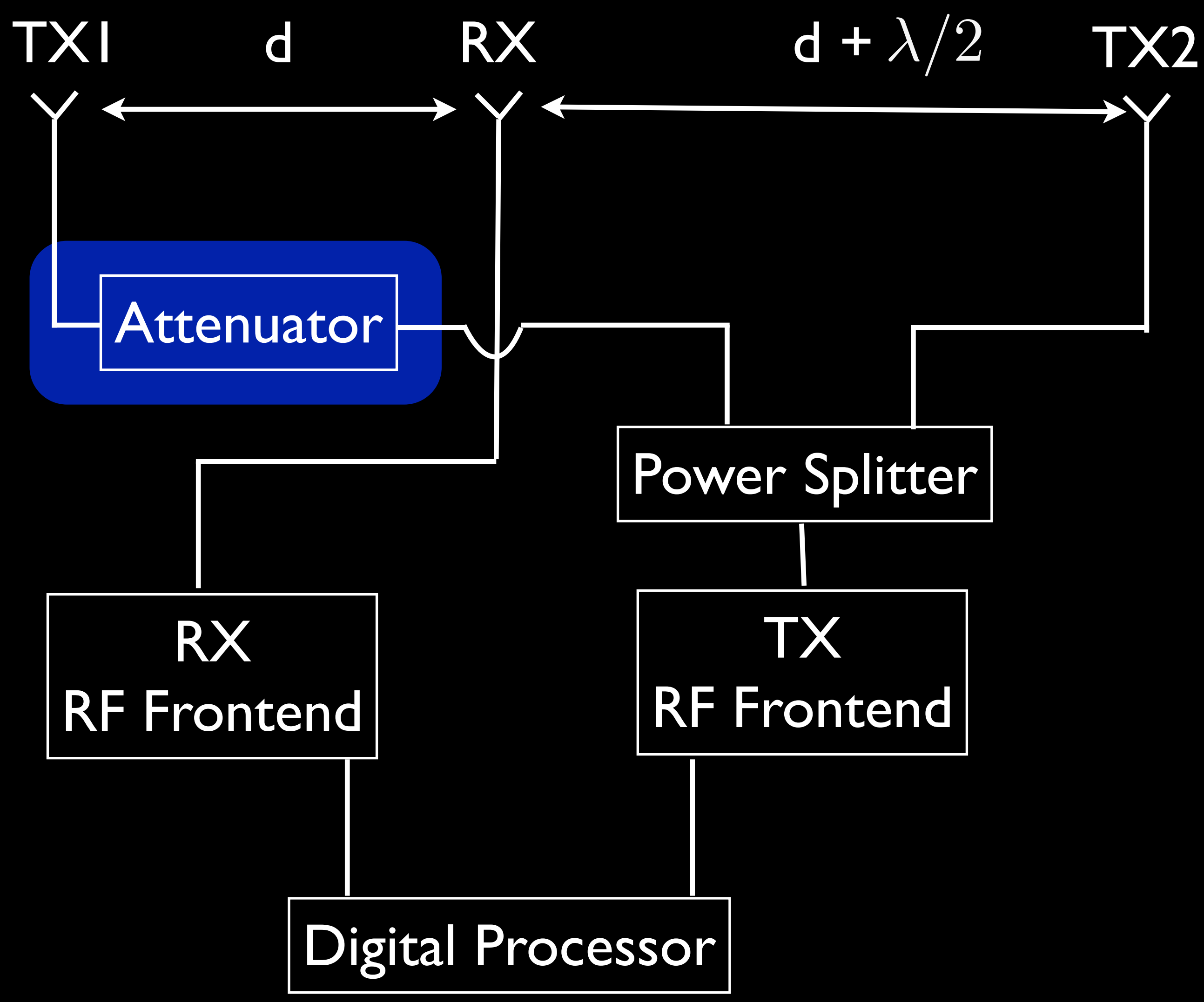
Three techniques give ~70dB cancellation

- Antenna Cancellation (~30dB)
- Hardware Cancellation (~25dB)
- Digital Cancellation (~15dB)

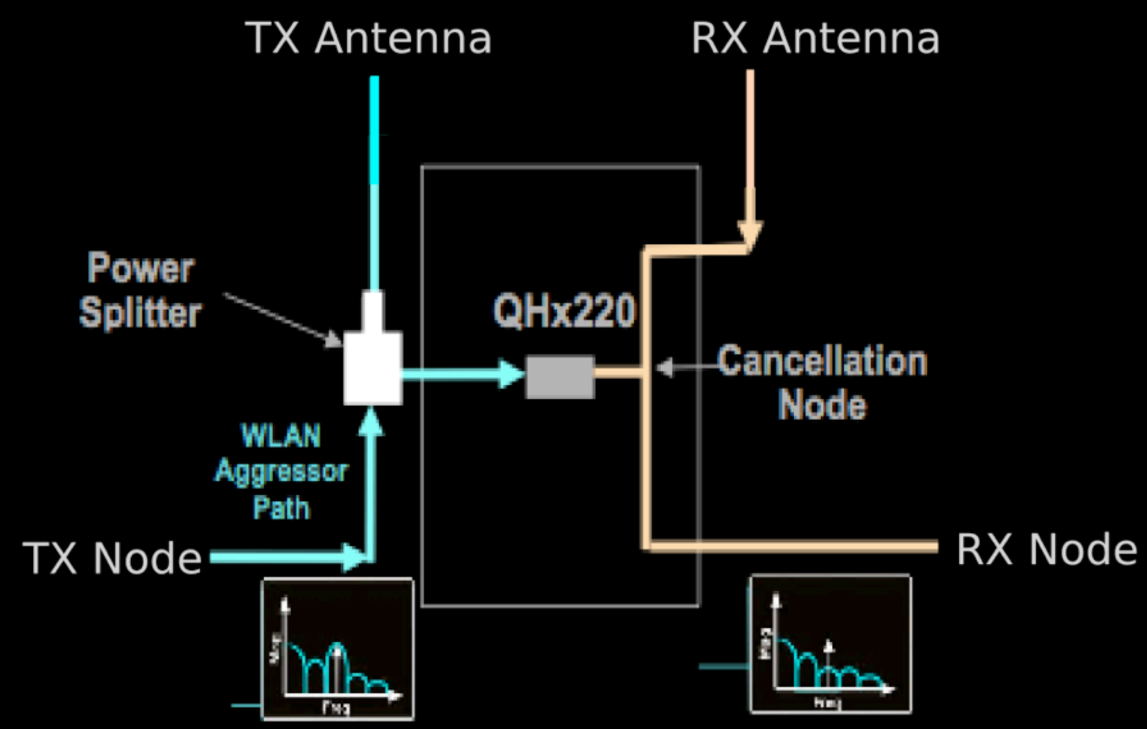
Antenna Cancellation: Block Diagram



Hardware and Digital Cancellation

Hardware Cancellation

- Use existing interference cancellation circuits (QHx220)*

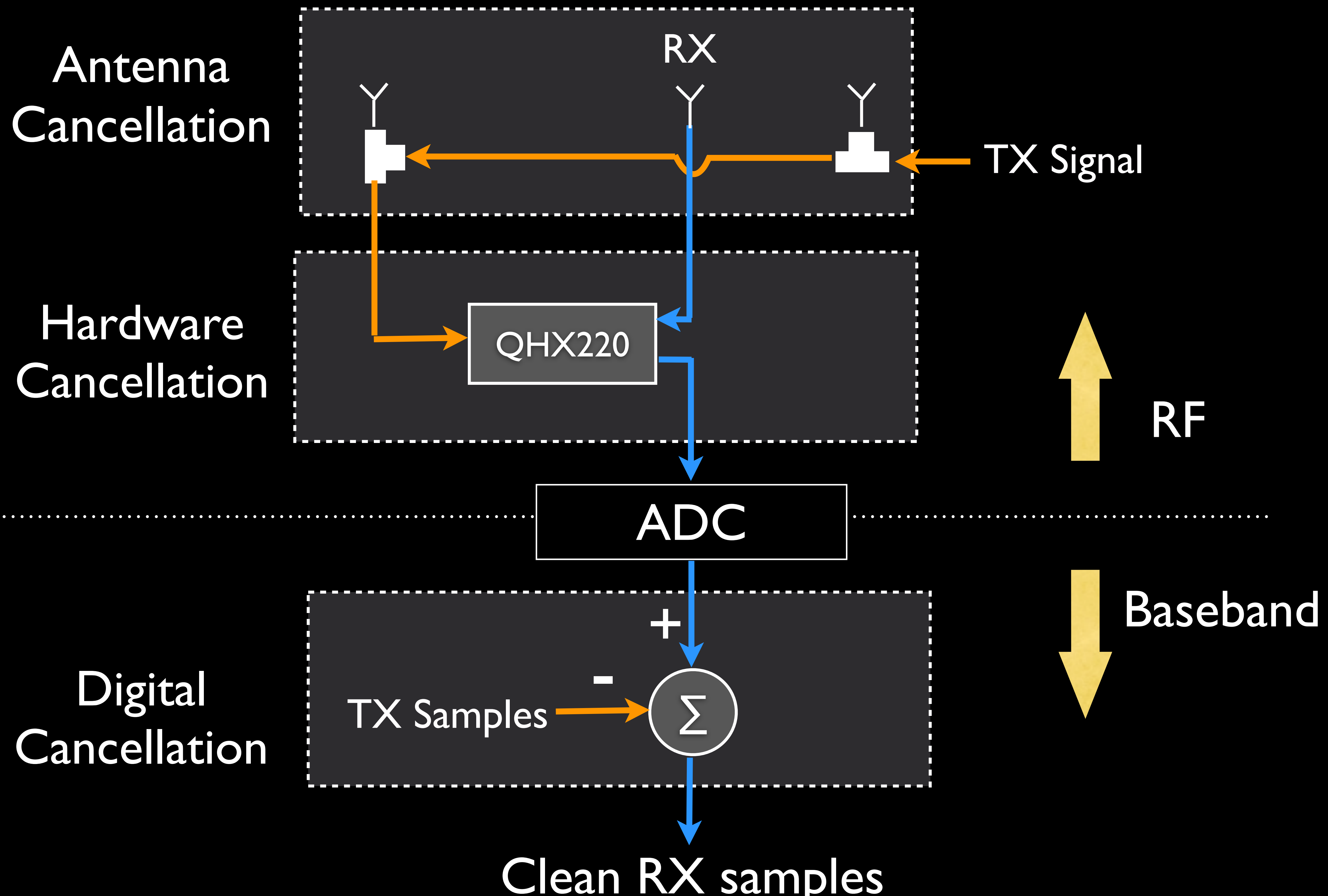


Digital Cancellation

- Subtract known transmit samples from received digital samples

* Radunovic et al. , "Rethinking Indoor Wireless: Lower Power, Low Frequency, Full-duplex", MSR Tech Report, 2009

Bringing It Together



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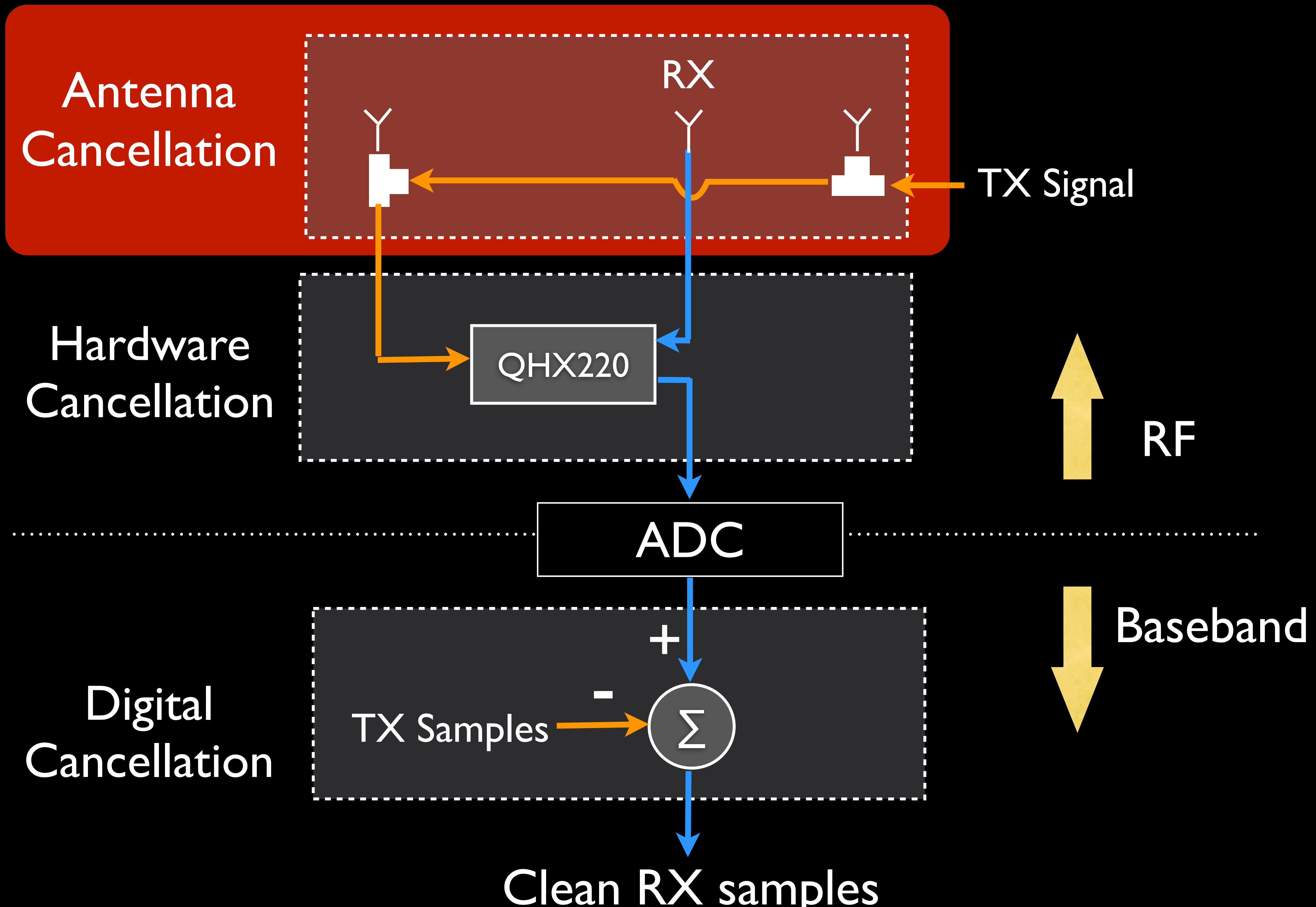

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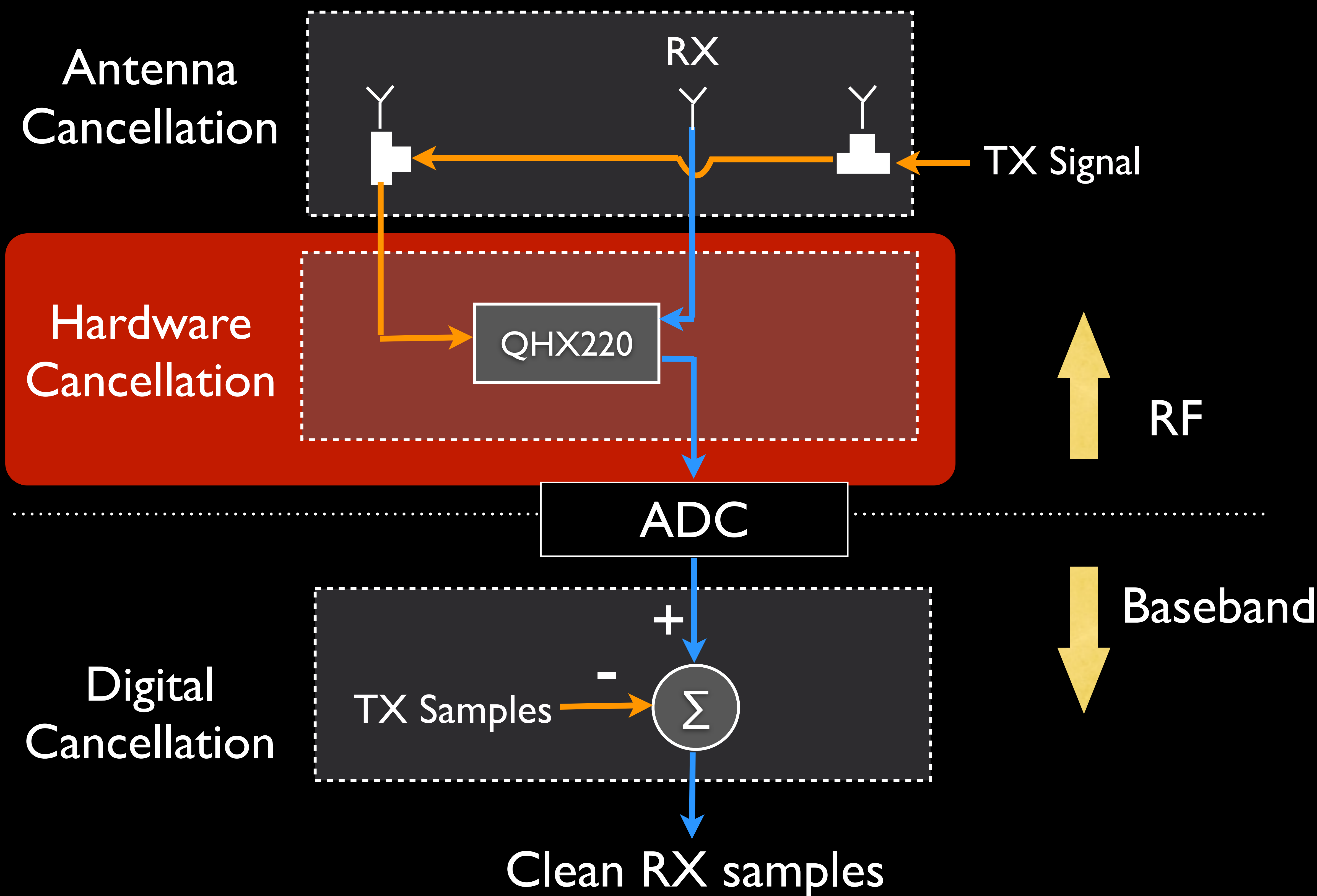

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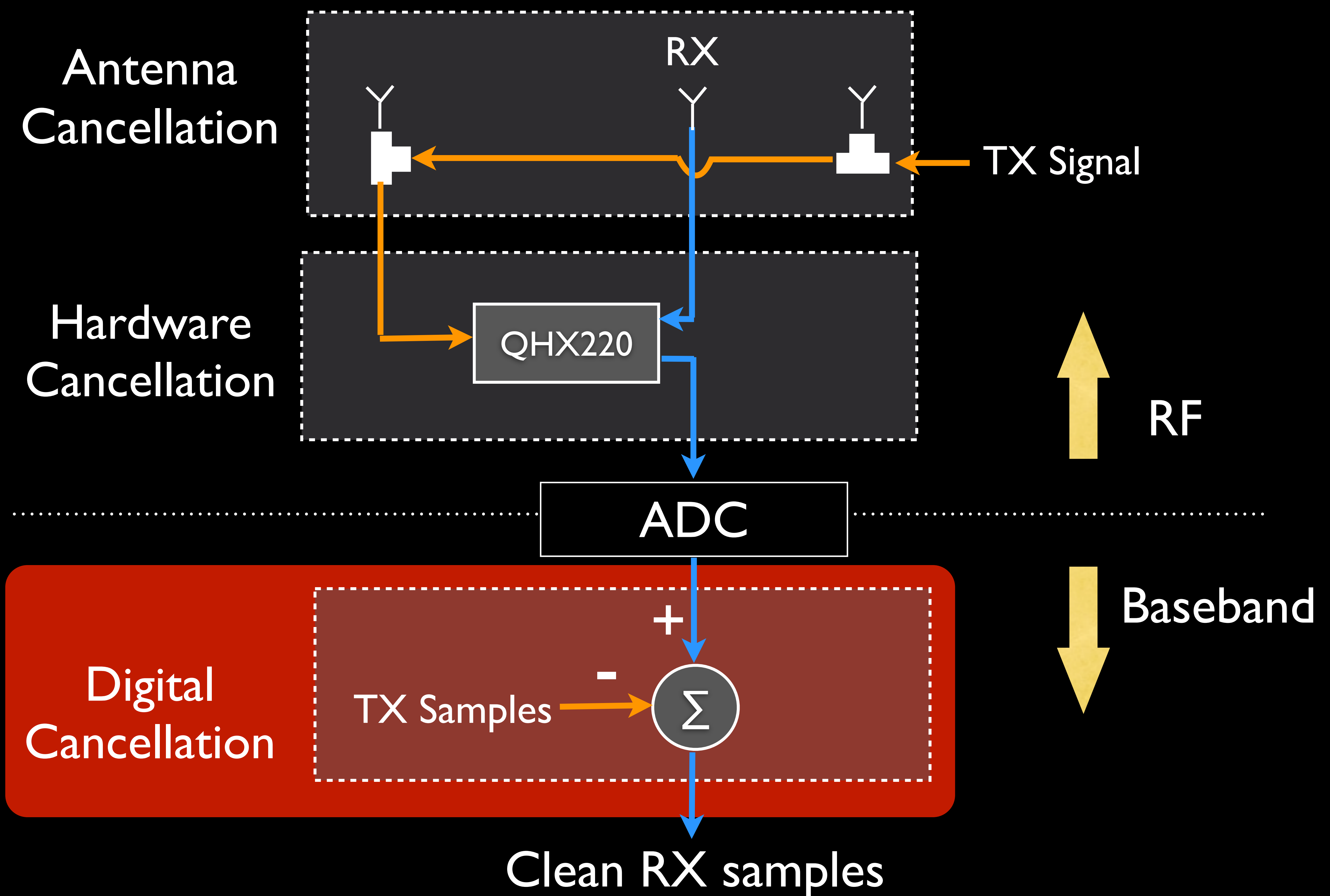
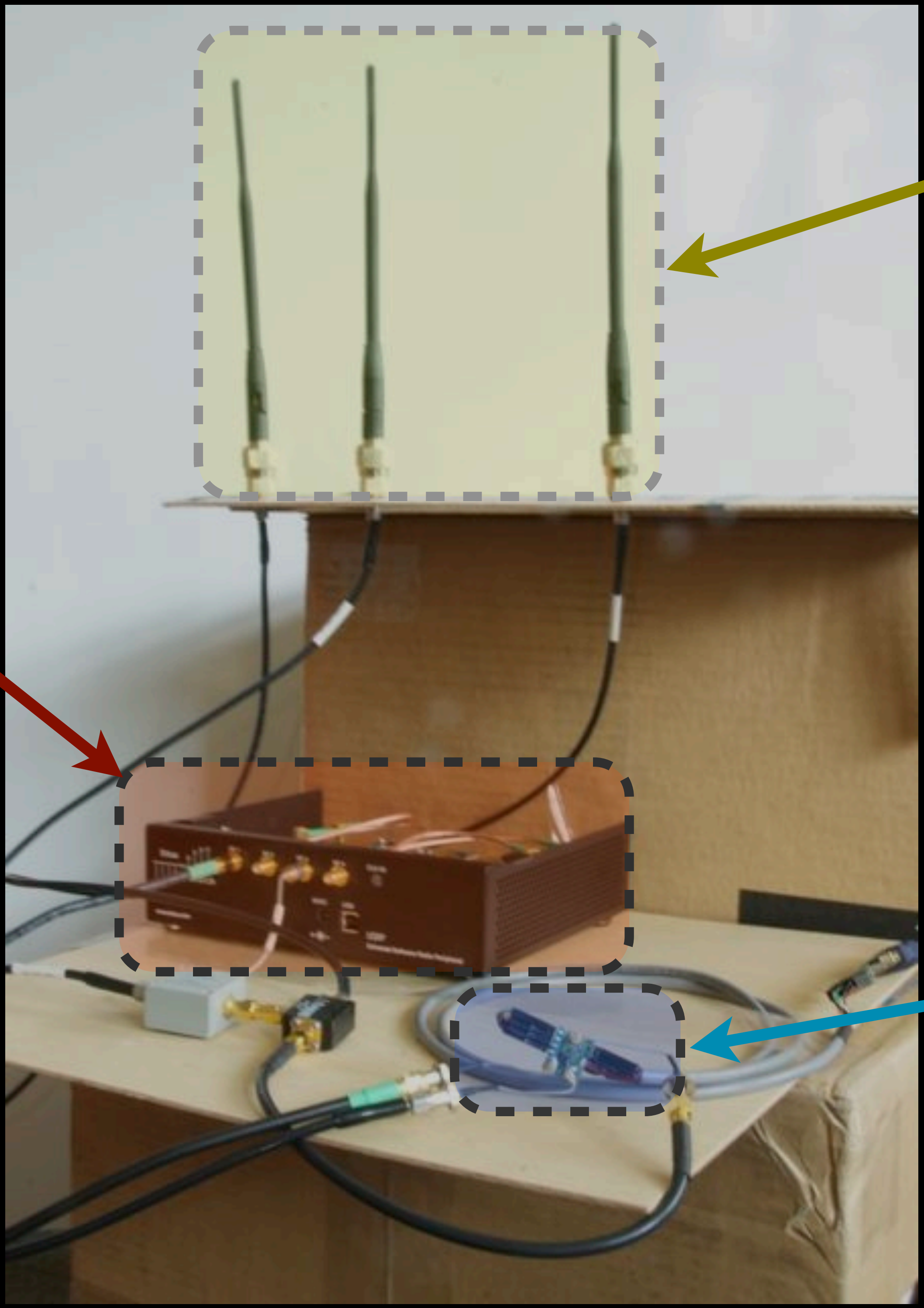


Our Prototype



Antenna Cancellation

Digital Interference Cancellation

Hardware Cancellation

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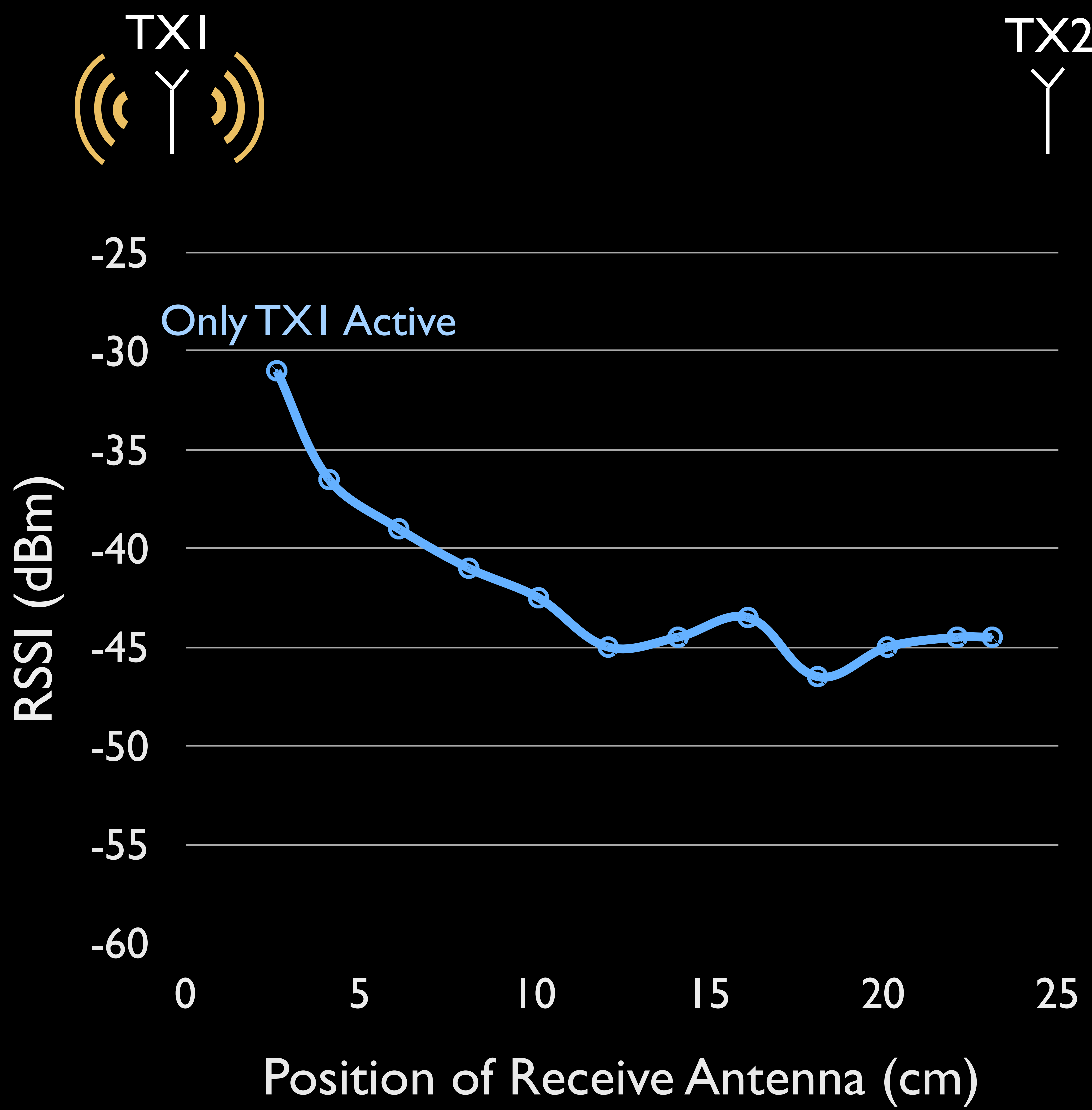
Antenna Cancellation: Performance



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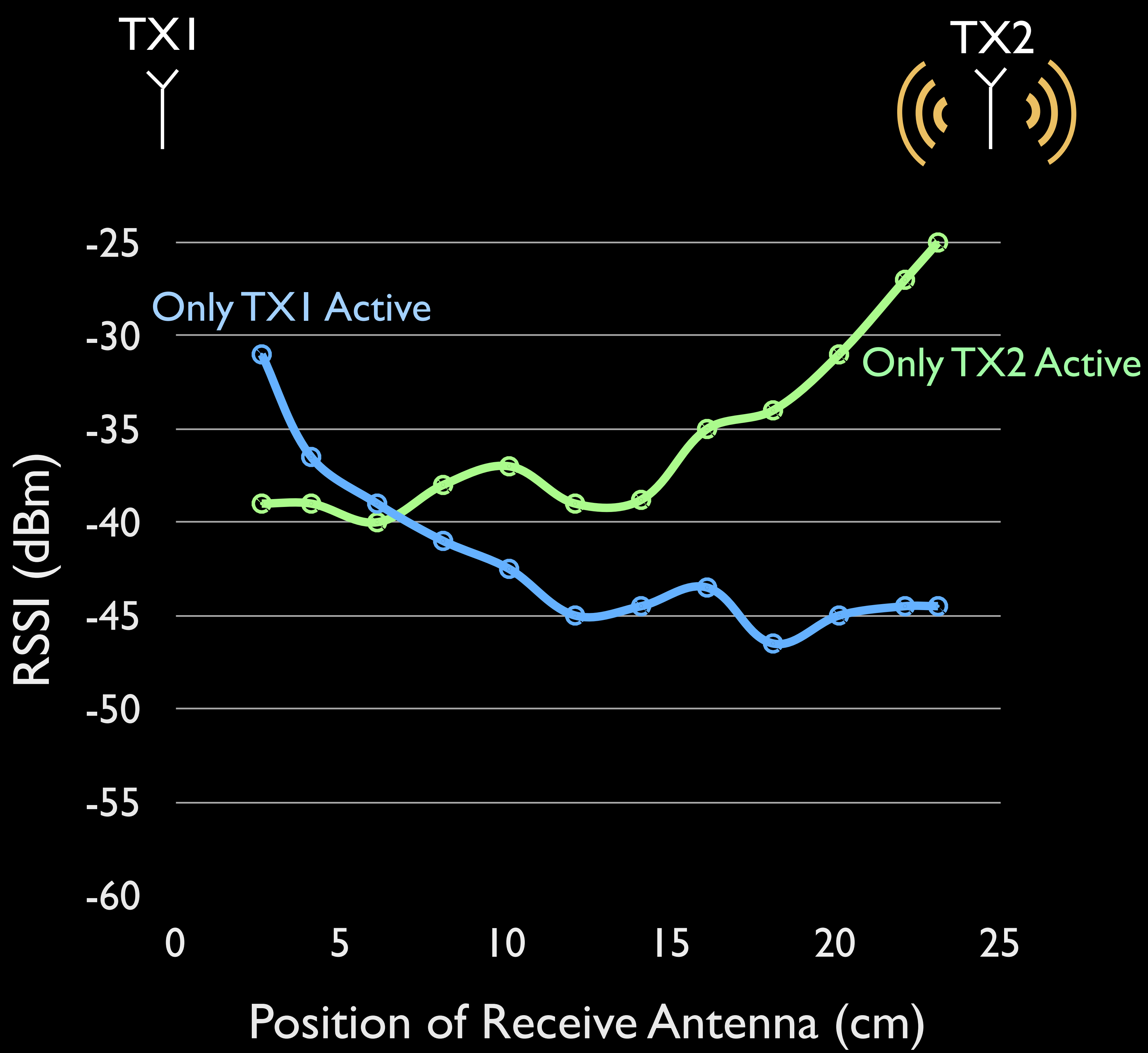

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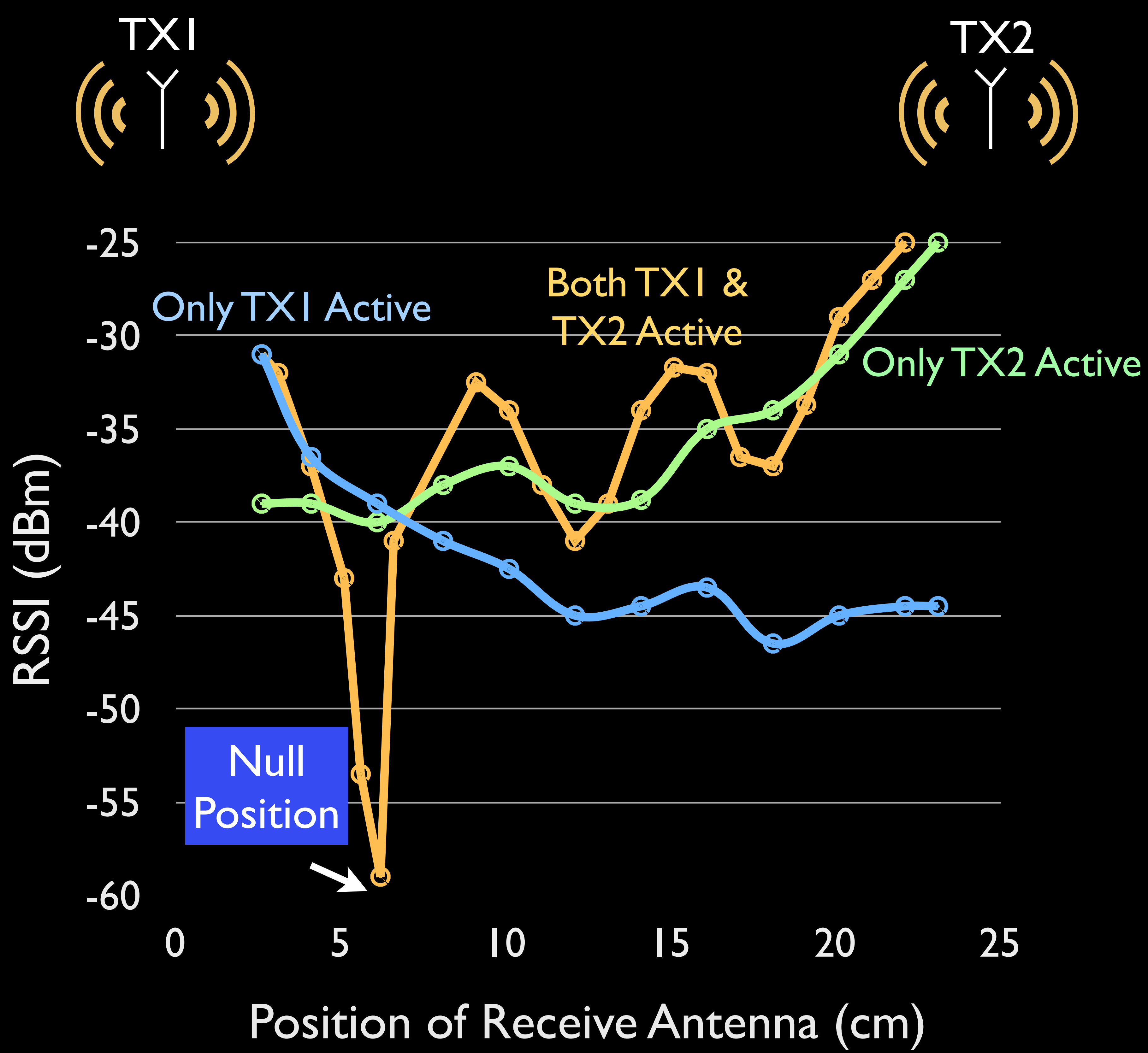

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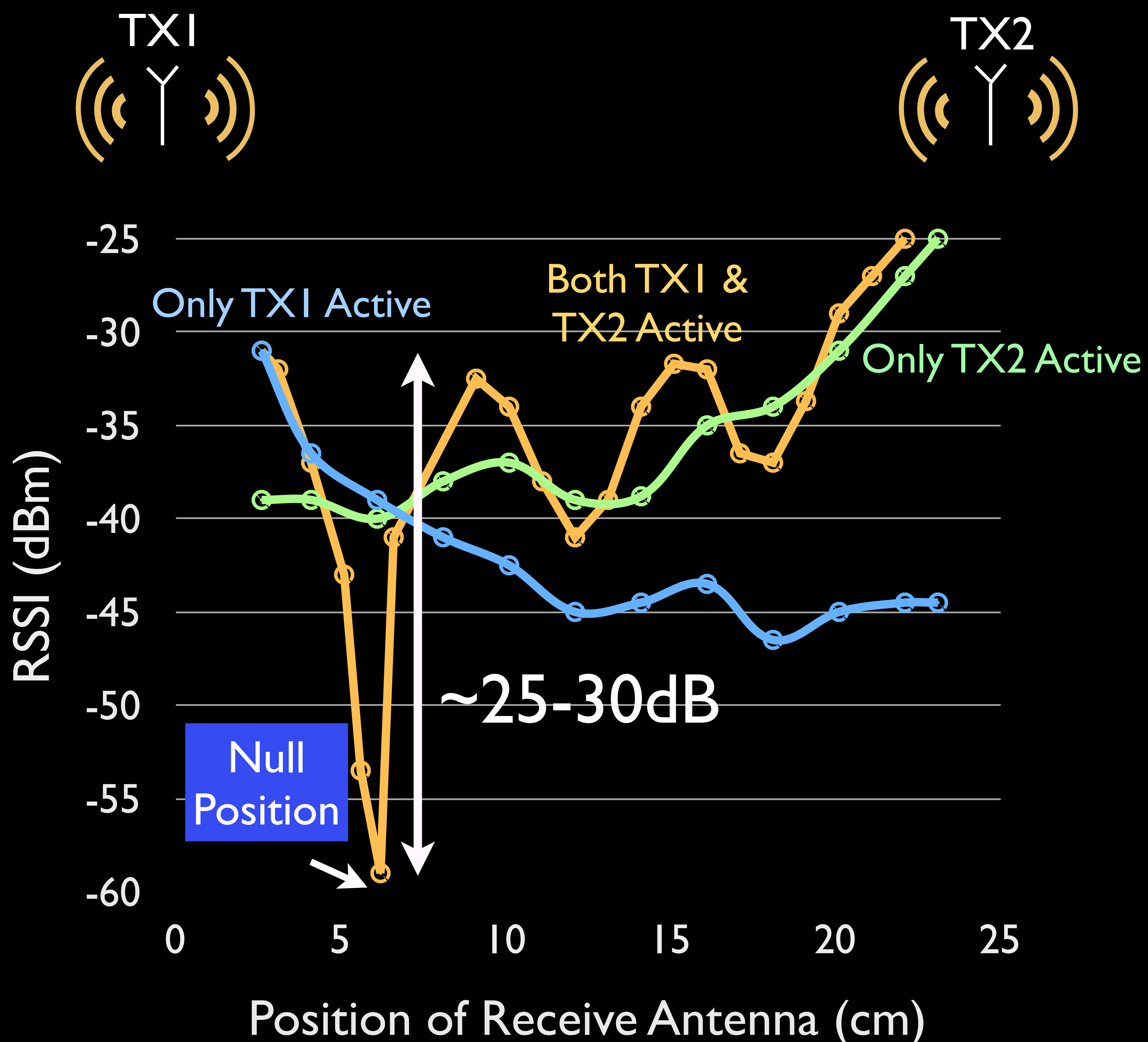
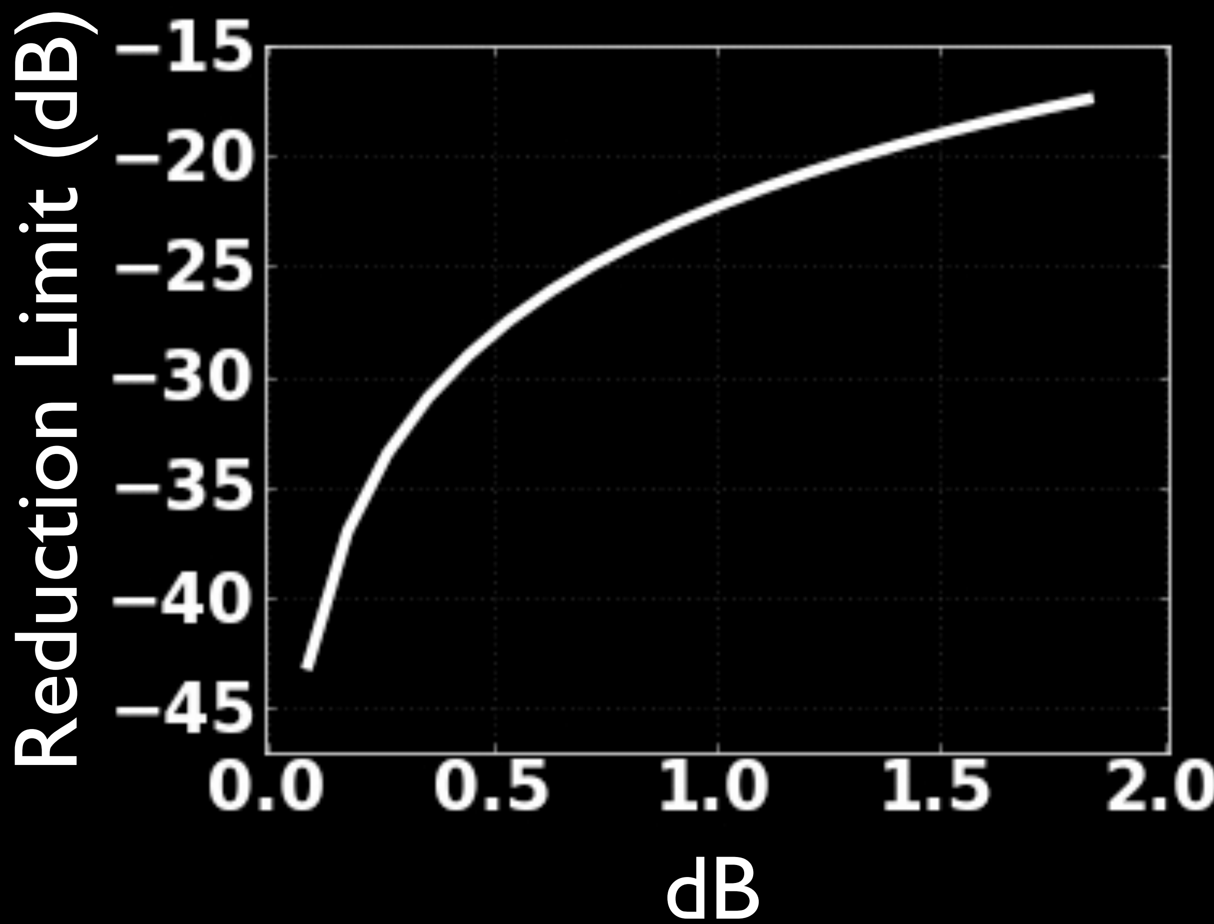
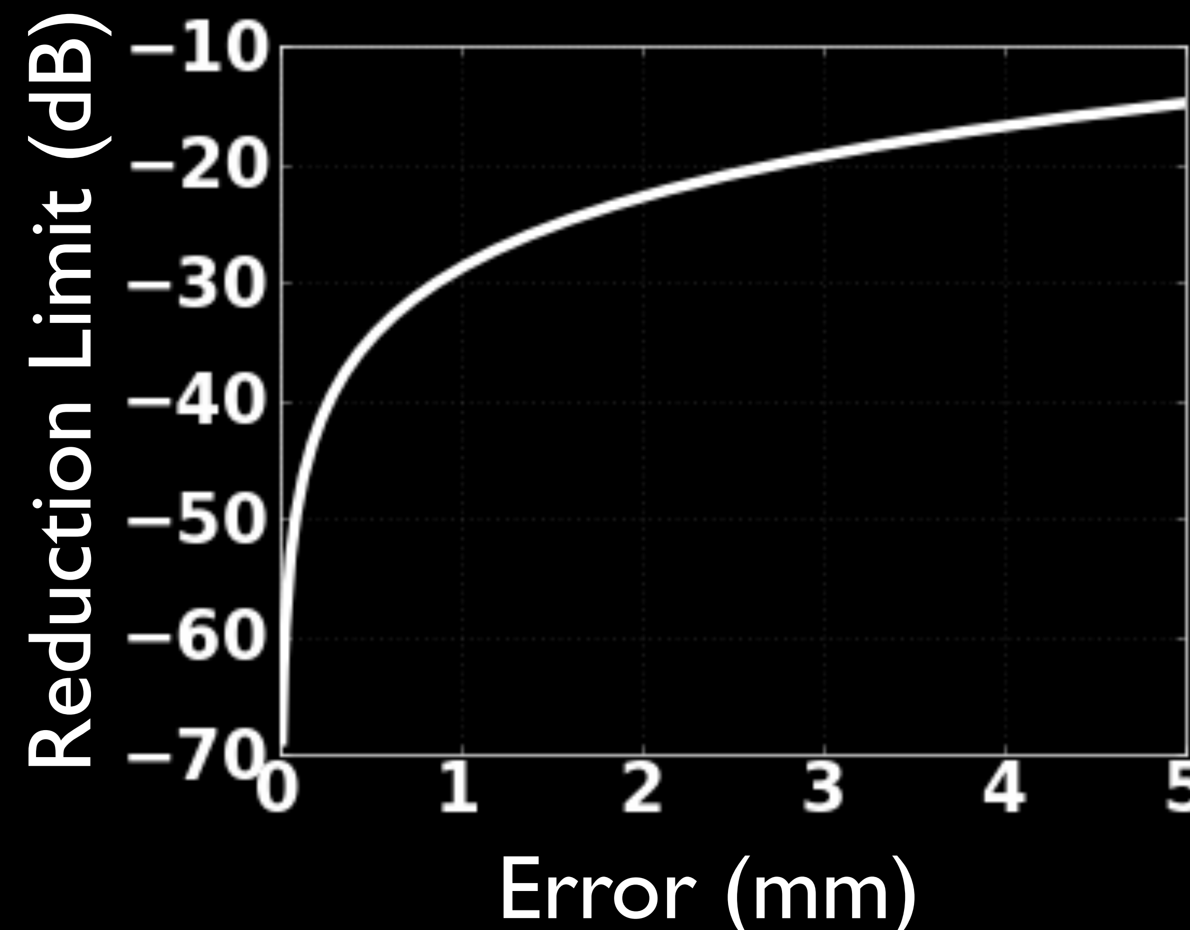


Sensitivity of Antenna Cancellation

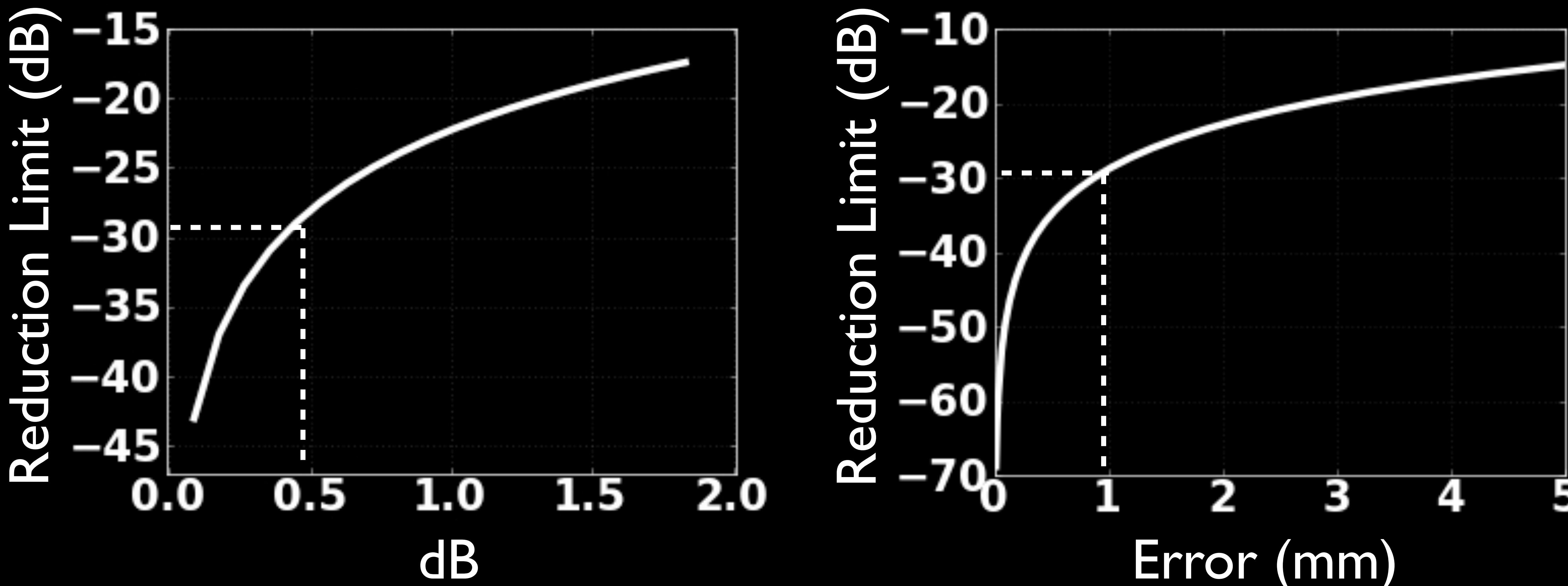


Amplitude Mismatch
between TX1 and TX2



Placement Error
for RX

Sensitivity of Antenna Cancellation



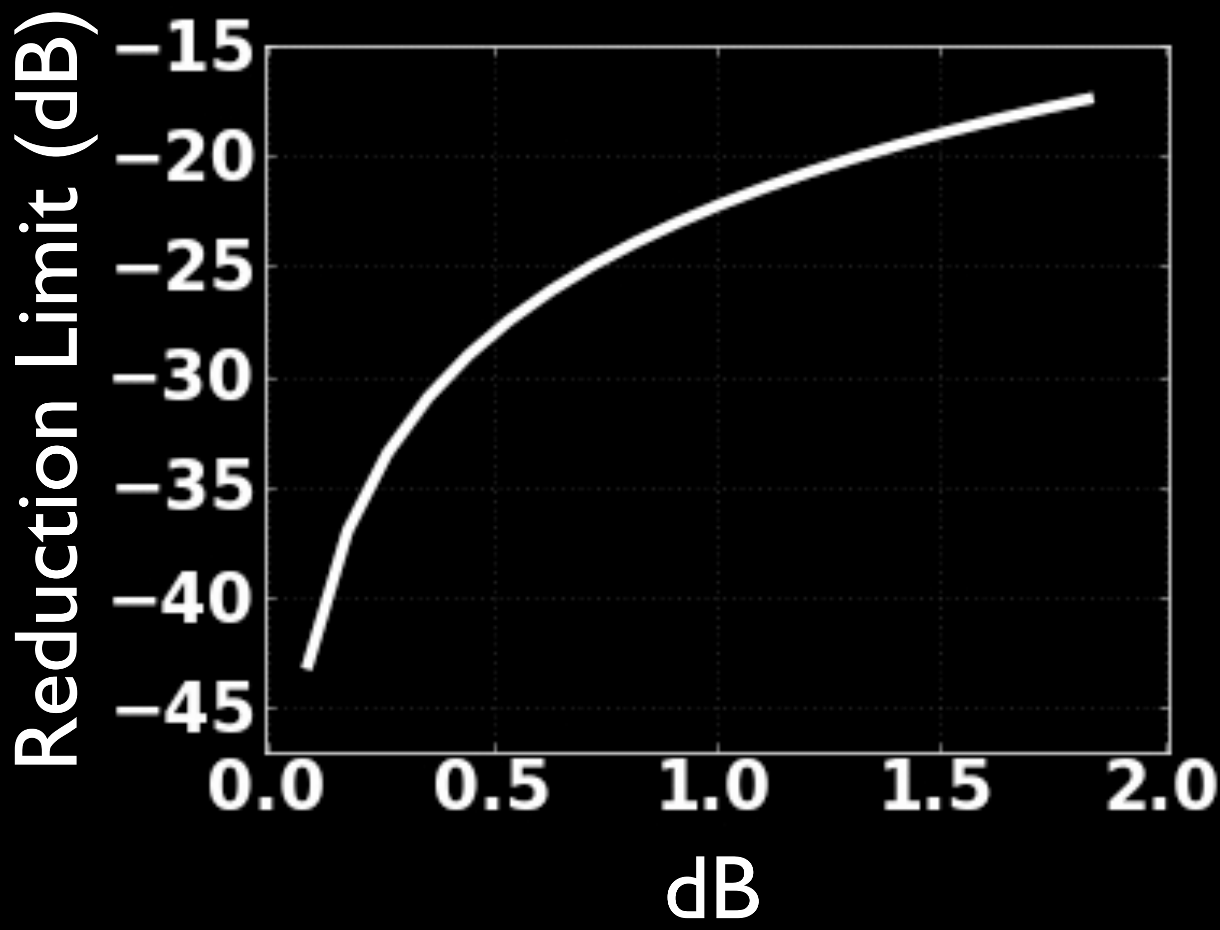
Amplitude Mismatch between TX1 and TX2

Placement Error for RX

30dB cancellation < 5% (~0.5dB) amplitude mismatch

< 1mm distance mismatch

Sensitivity of Antenna Cancellation



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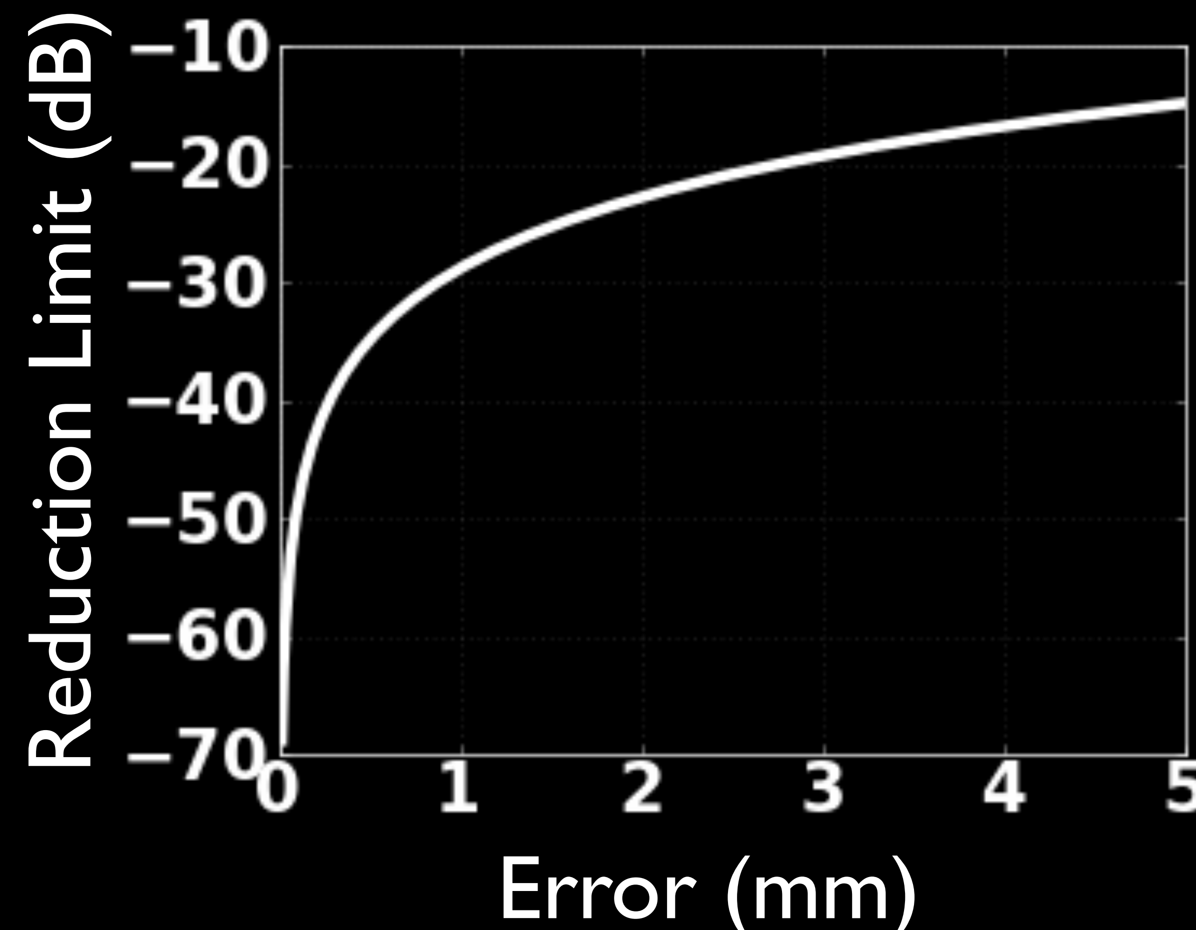
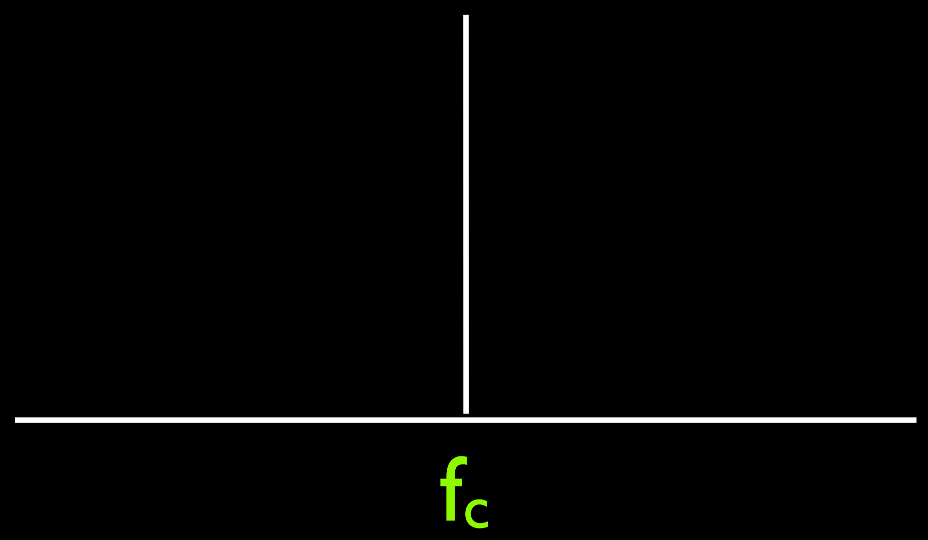


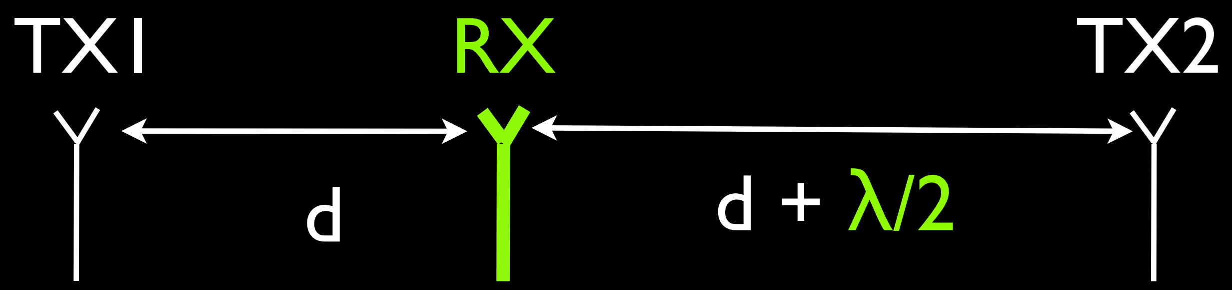
Placement Error for RX

- Rough prototype good for 802.15.4
- More precision needed for higher power systems (802.11)

Bandwidth Constraint

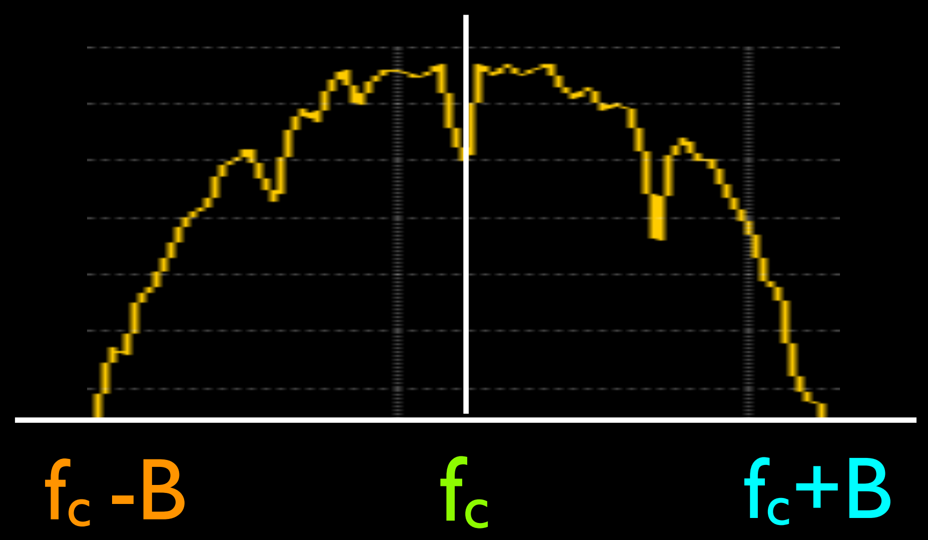
A λ/2 offset is precise for one frequency

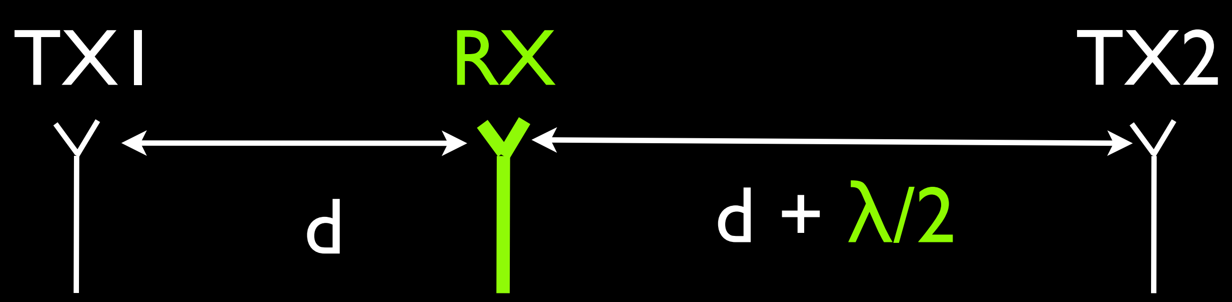




Bandwidth Constraint

A λ/2 offset is precise for one frequency not for the whole bandwidth





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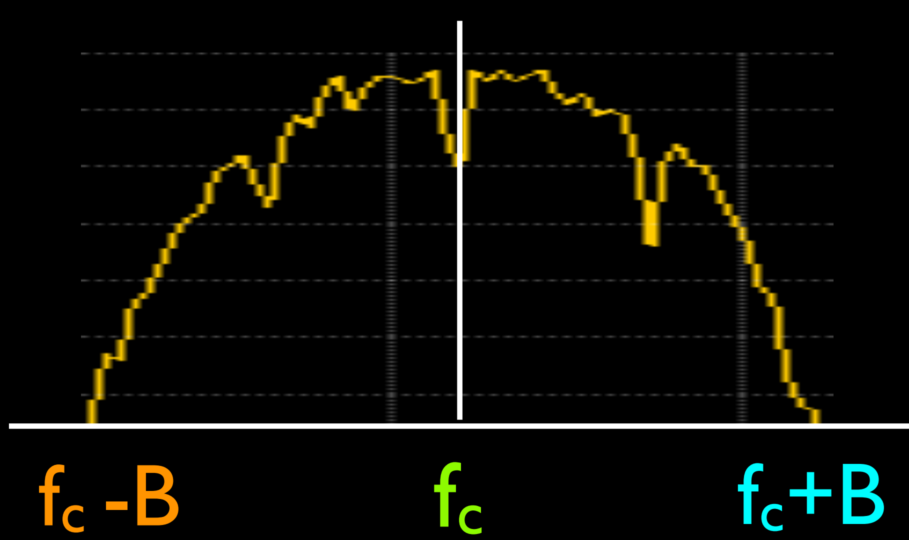

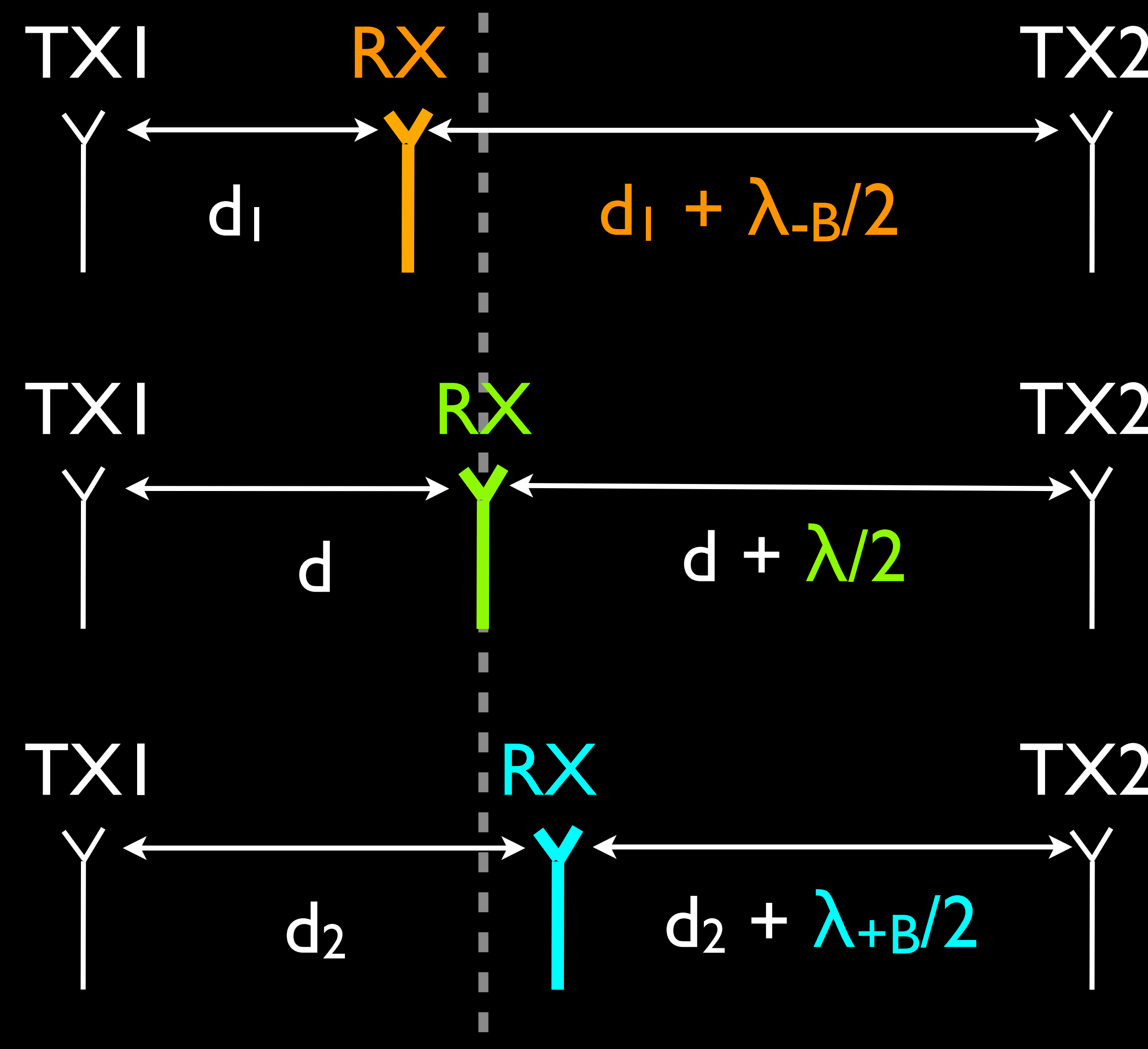

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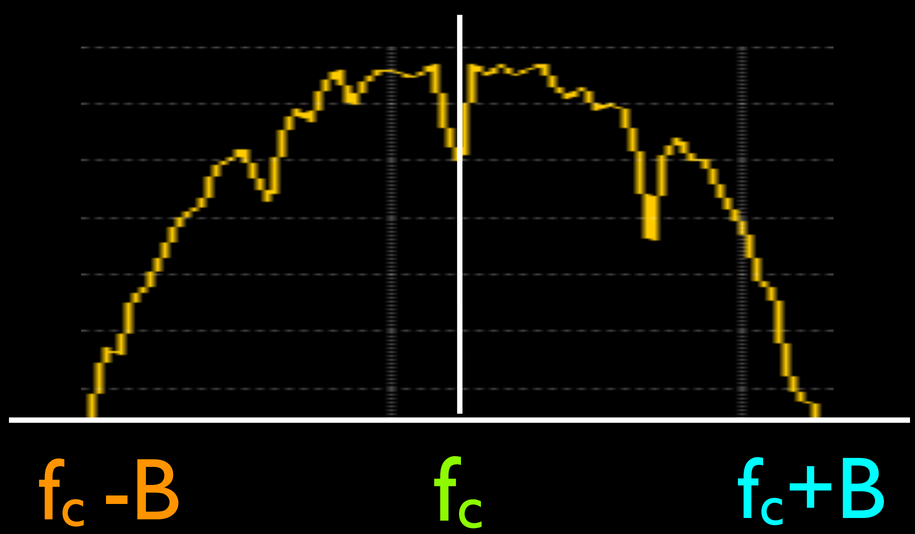
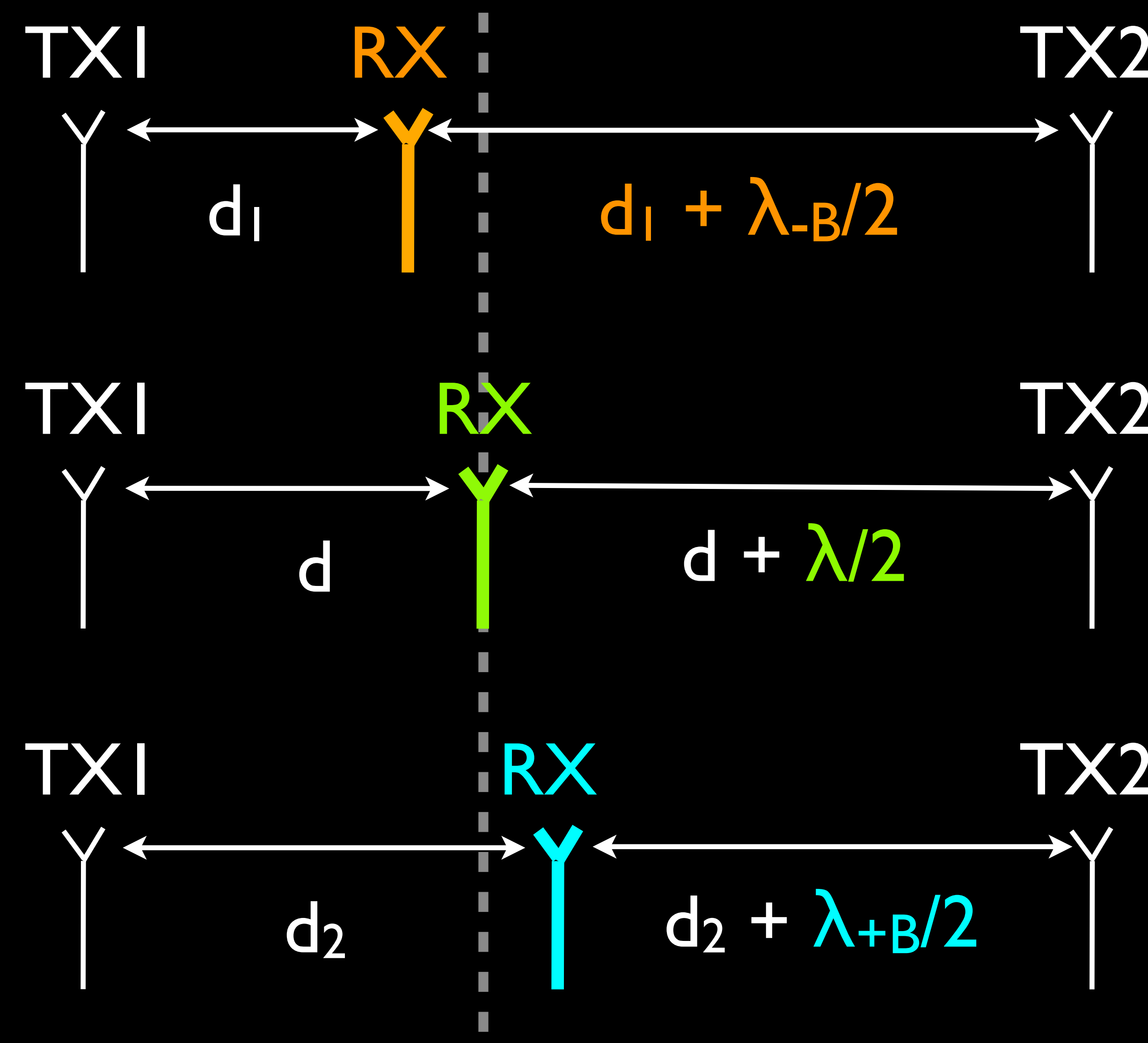
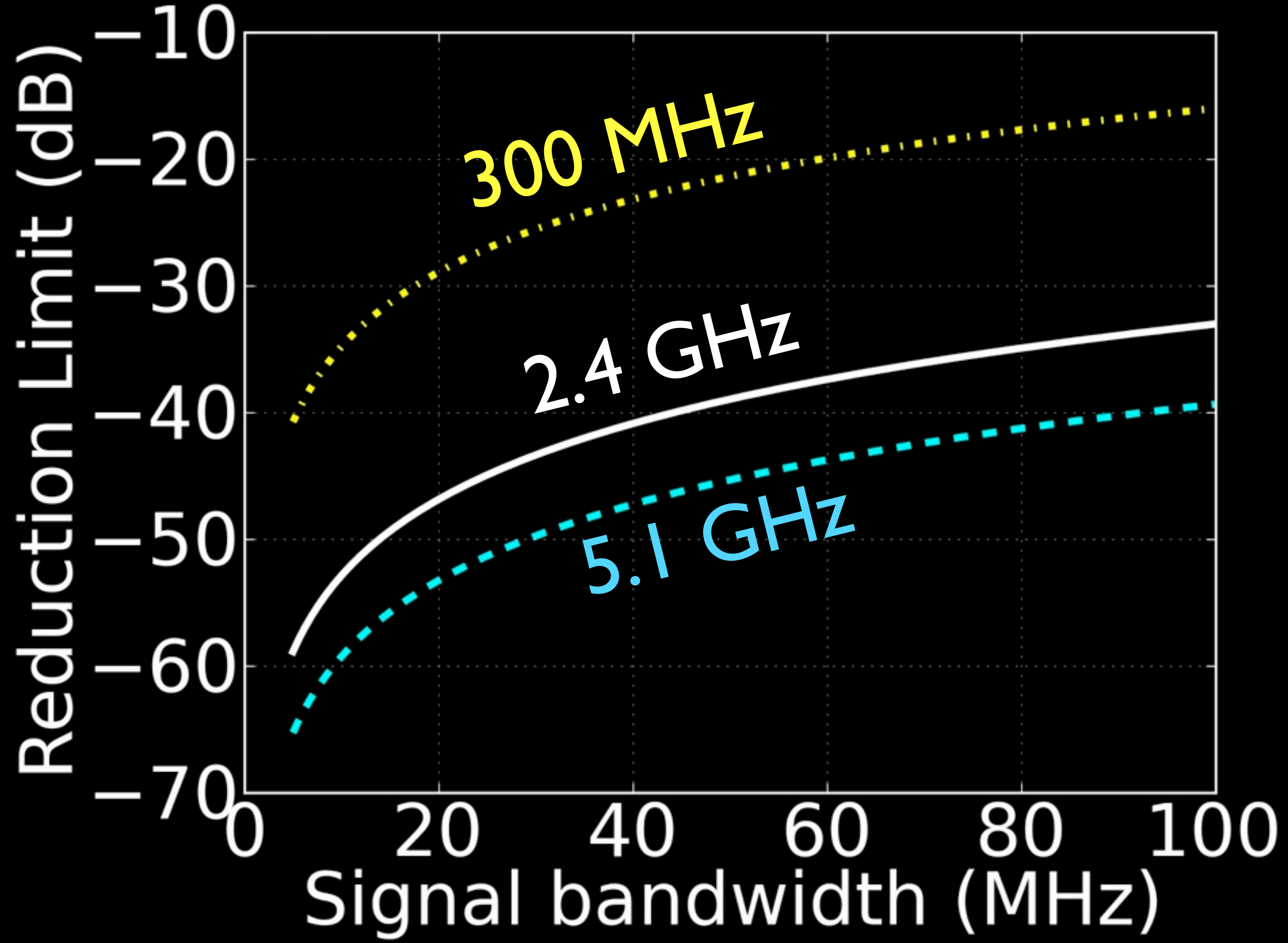




WiFi (2.4G, 20MHz) => ~0.26mm precision error

Bandwidth Constraint



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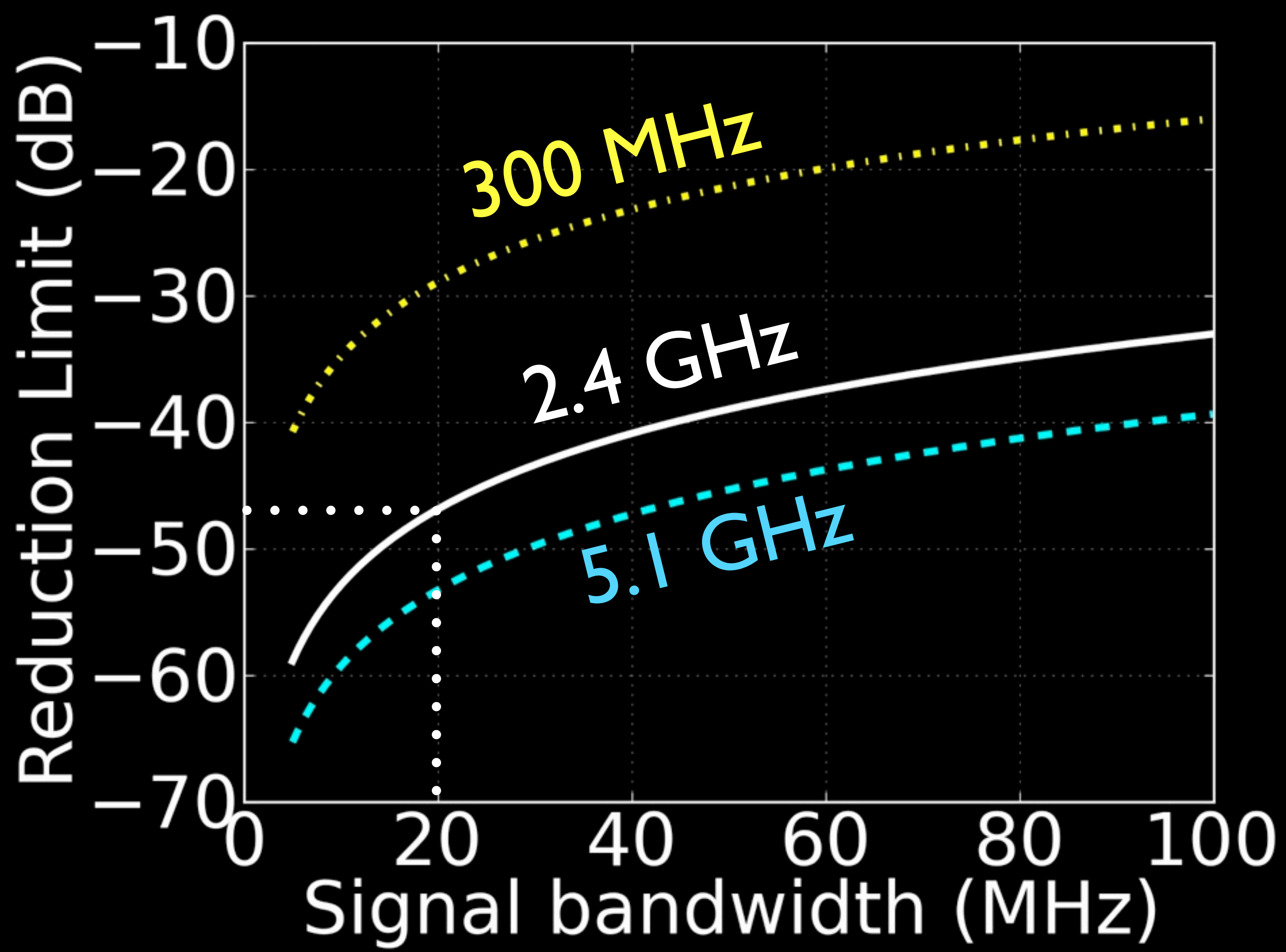

- WiFi (2.4GHz, 20MHz): Max 47dB reduction
- Bandwidth ↑ => Cancellation ↓
- Carrier Frequency ↑ => Cancellation ↑

What about attenuation at intended receivers?
Destructive interference can affect this signal too!

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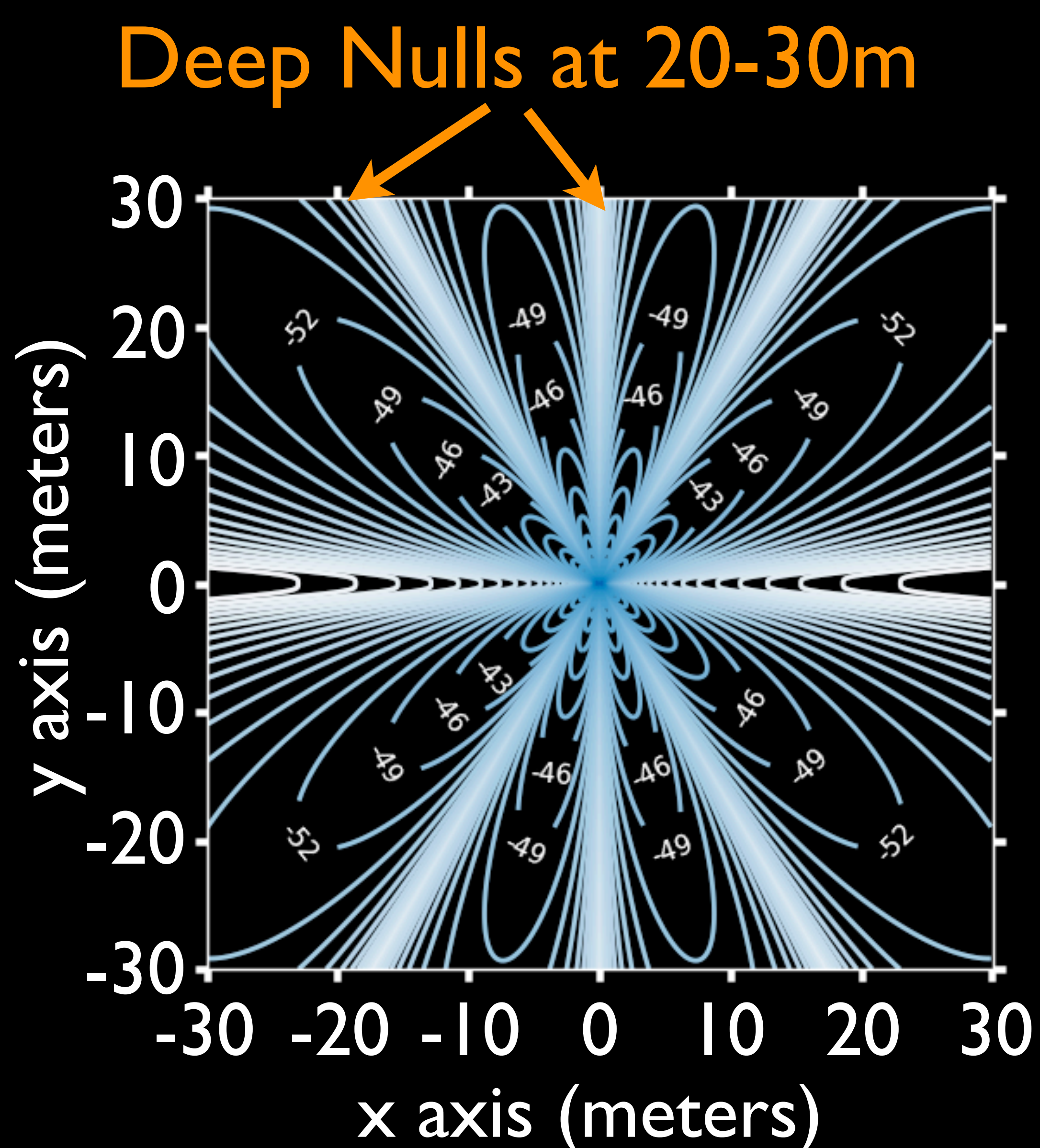
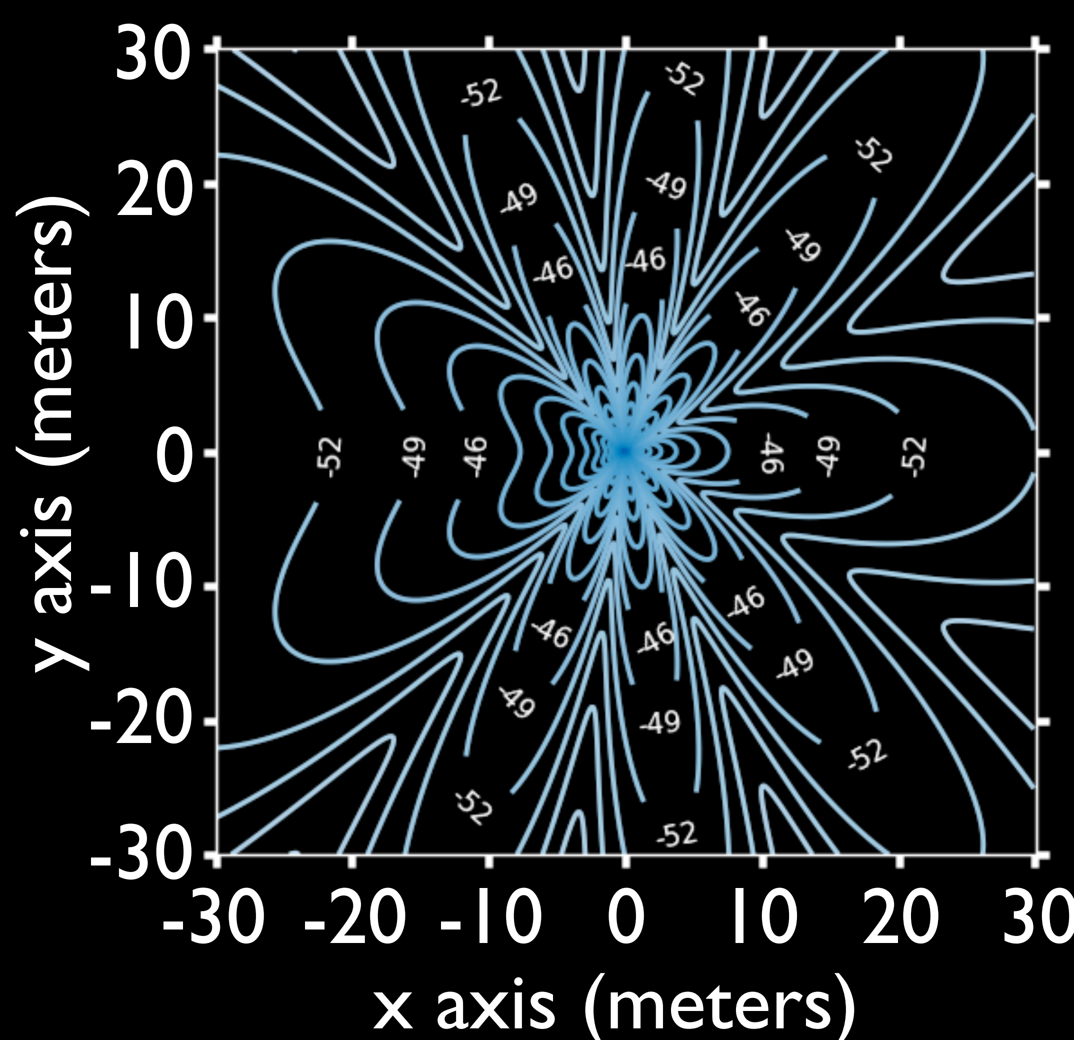
- Different transmit powers for two TX helps



Equal Transmit Power



Unequal Transmit Power

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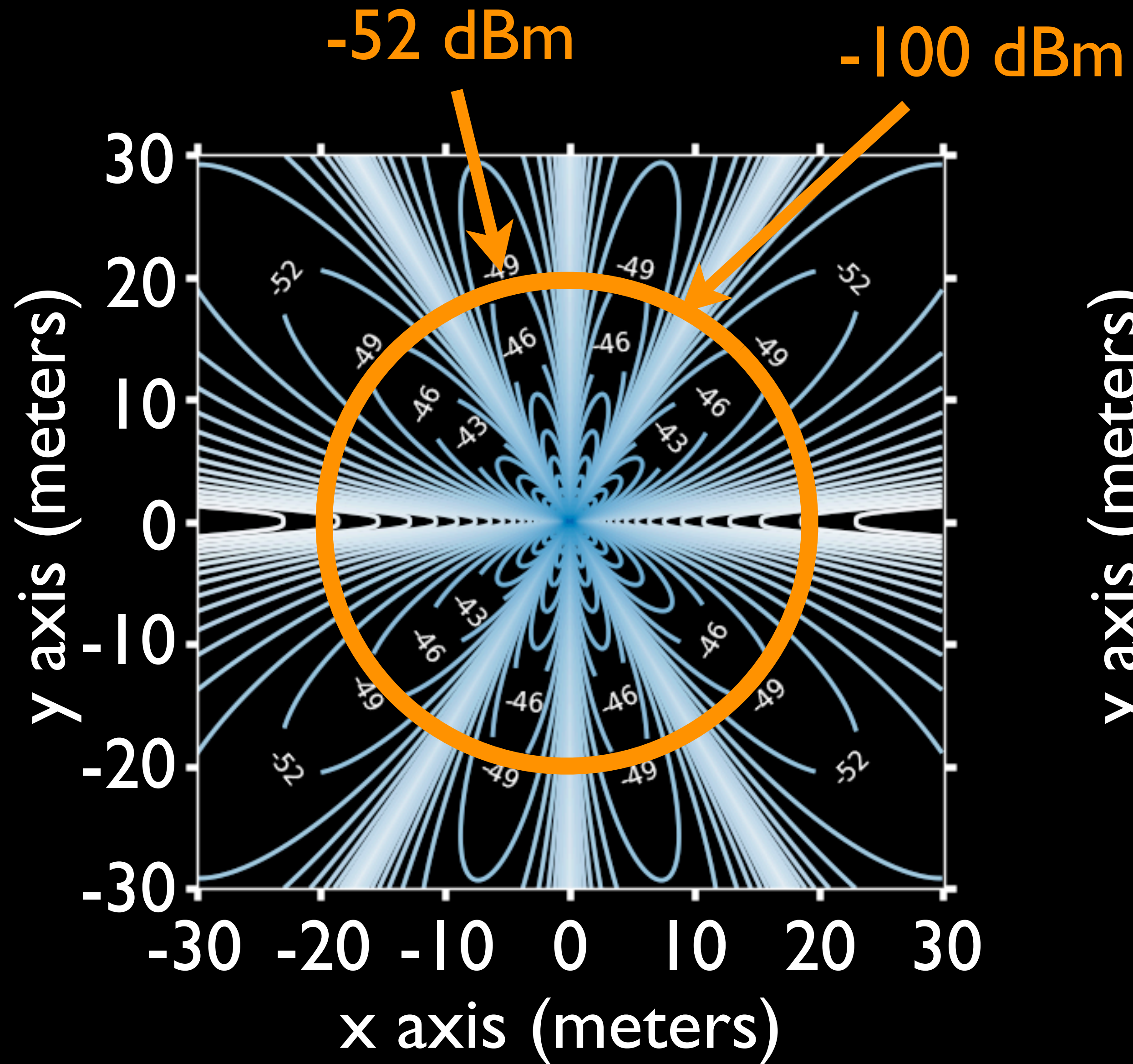

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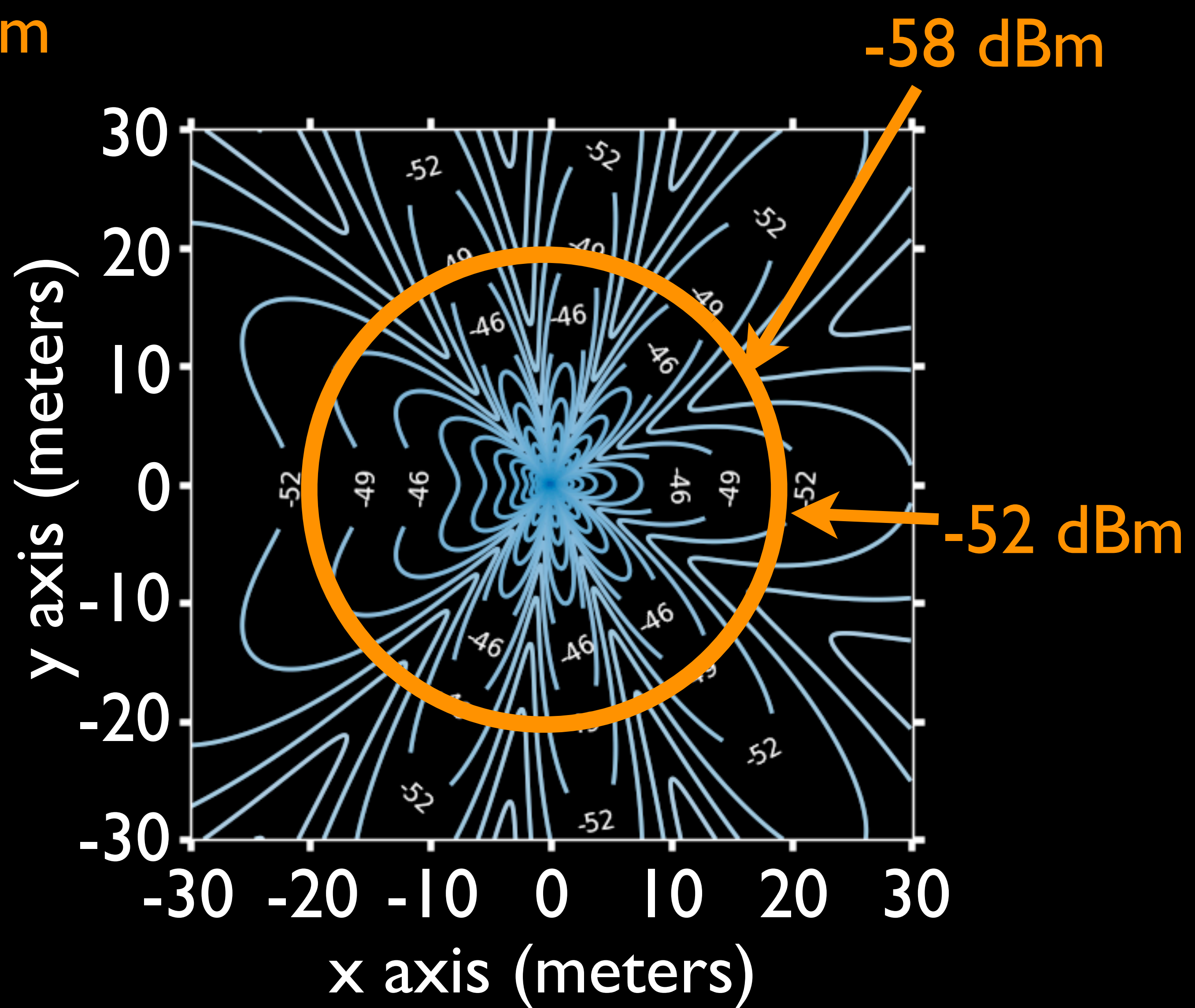

Unequal Transmit Power

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Destructive interference can affect this signal too!

- Different transmit powers for two TX helps
- Diversity gains in indoor environments

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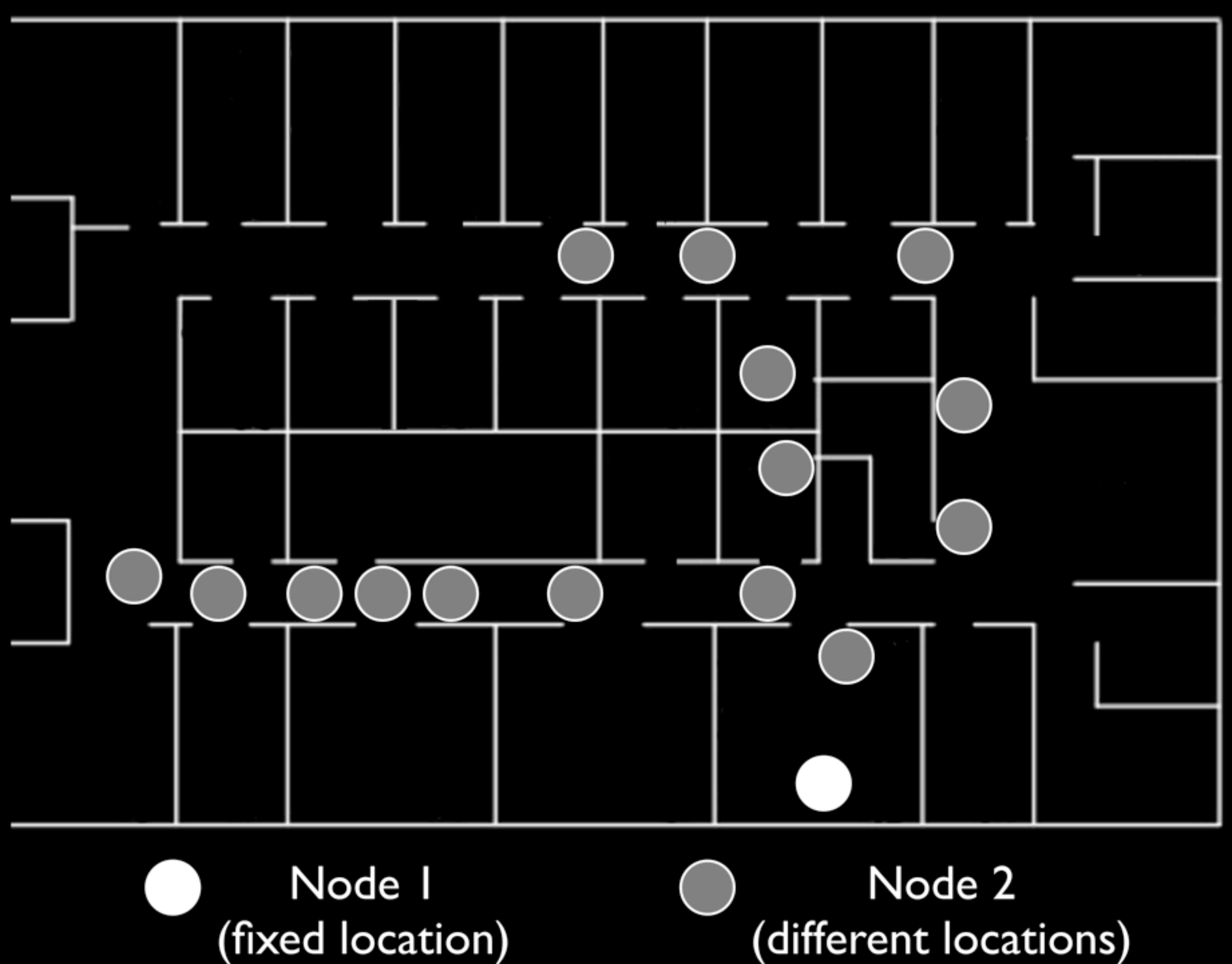
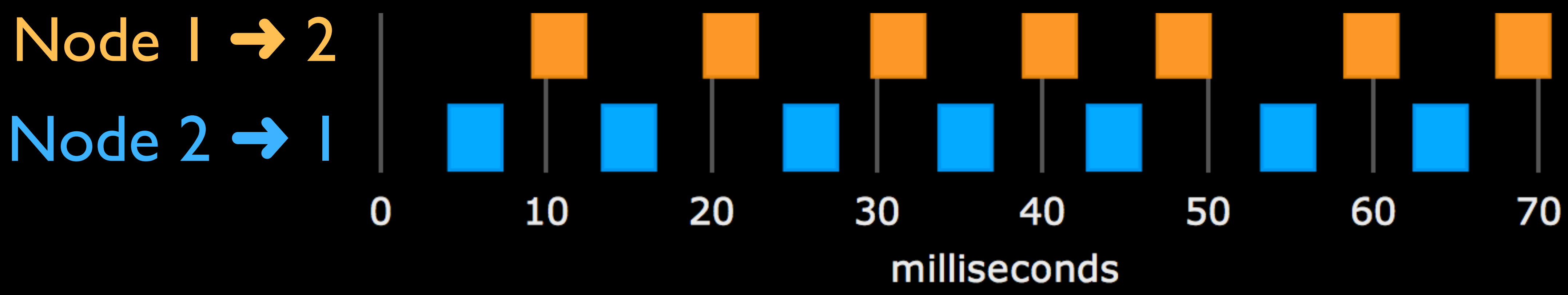
Experimental Setup

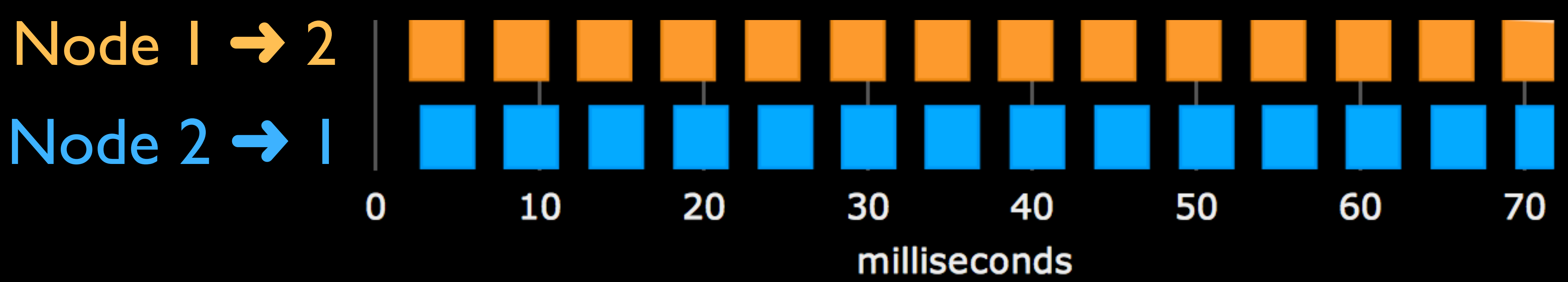
- 802.15.4 based signaling on USRP nodes
- Two nodes at varying distances placed in an office building room and corridor



Half-Duplex :- Nodes interleave transmissions

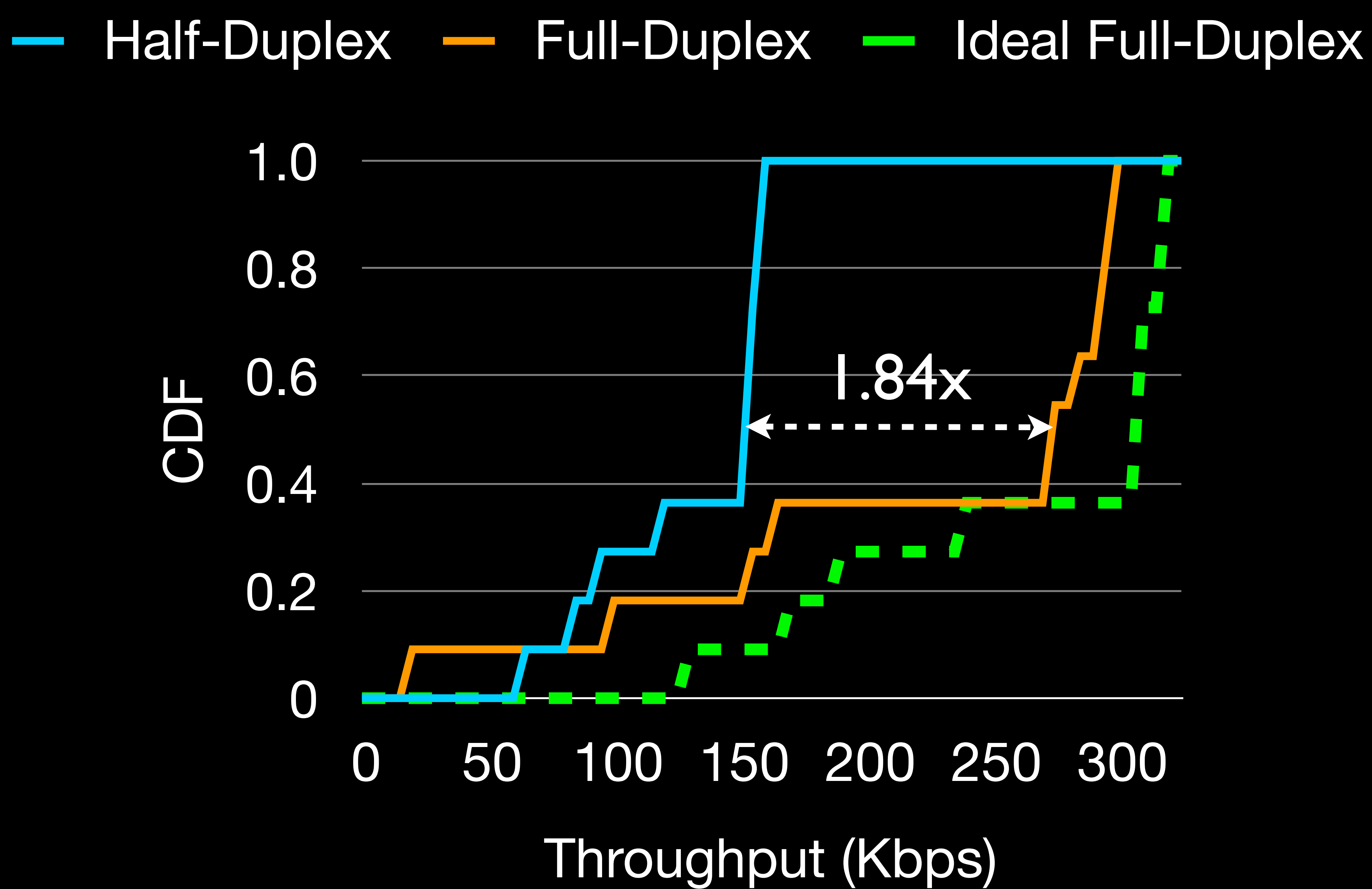


Full-Duplex :- Nodes transmit concurrently



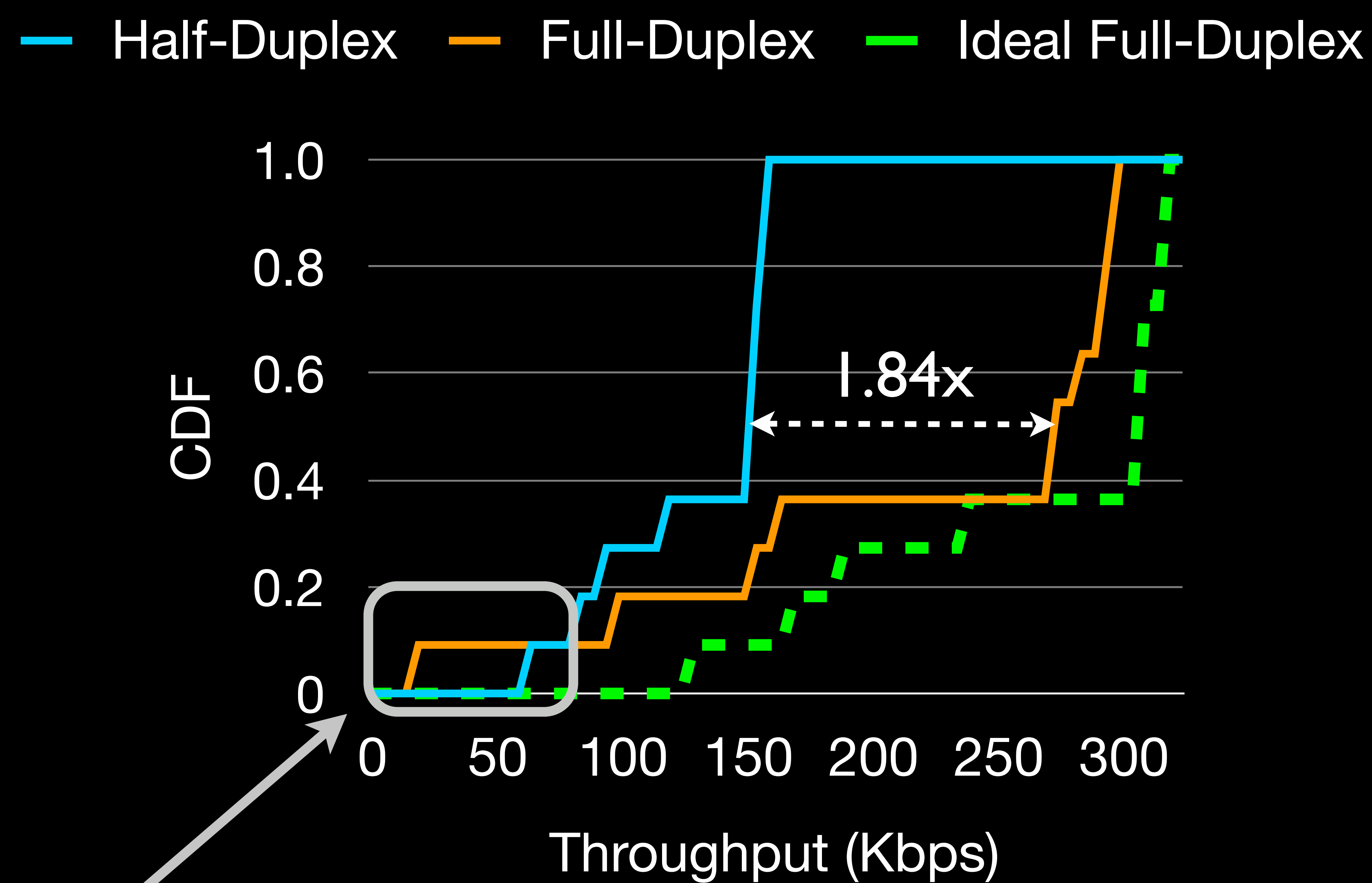
- Full-duplex should double aggregate throughput

Throughput



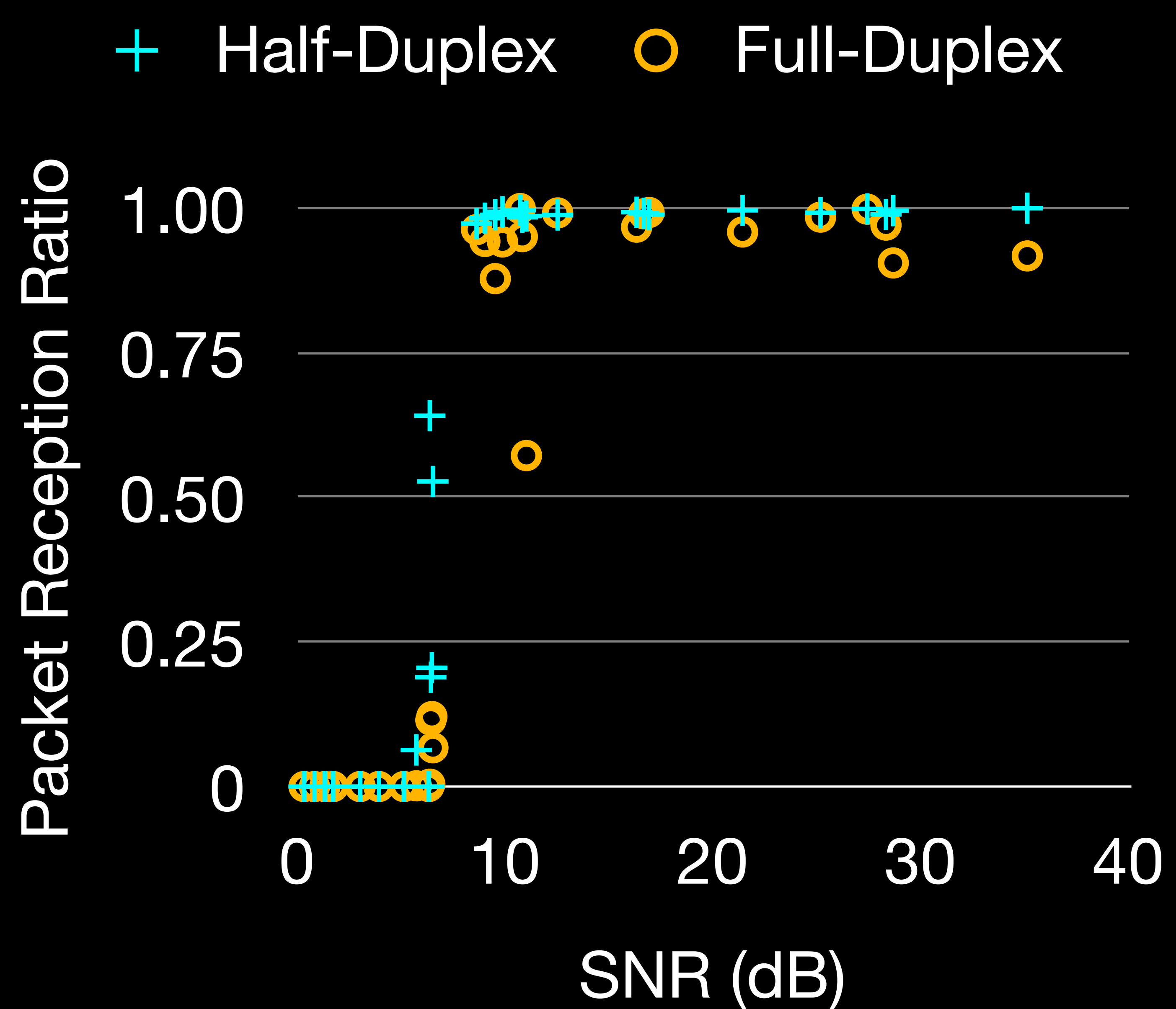
Median throughput 92% of ideal full-duplex

Throughput



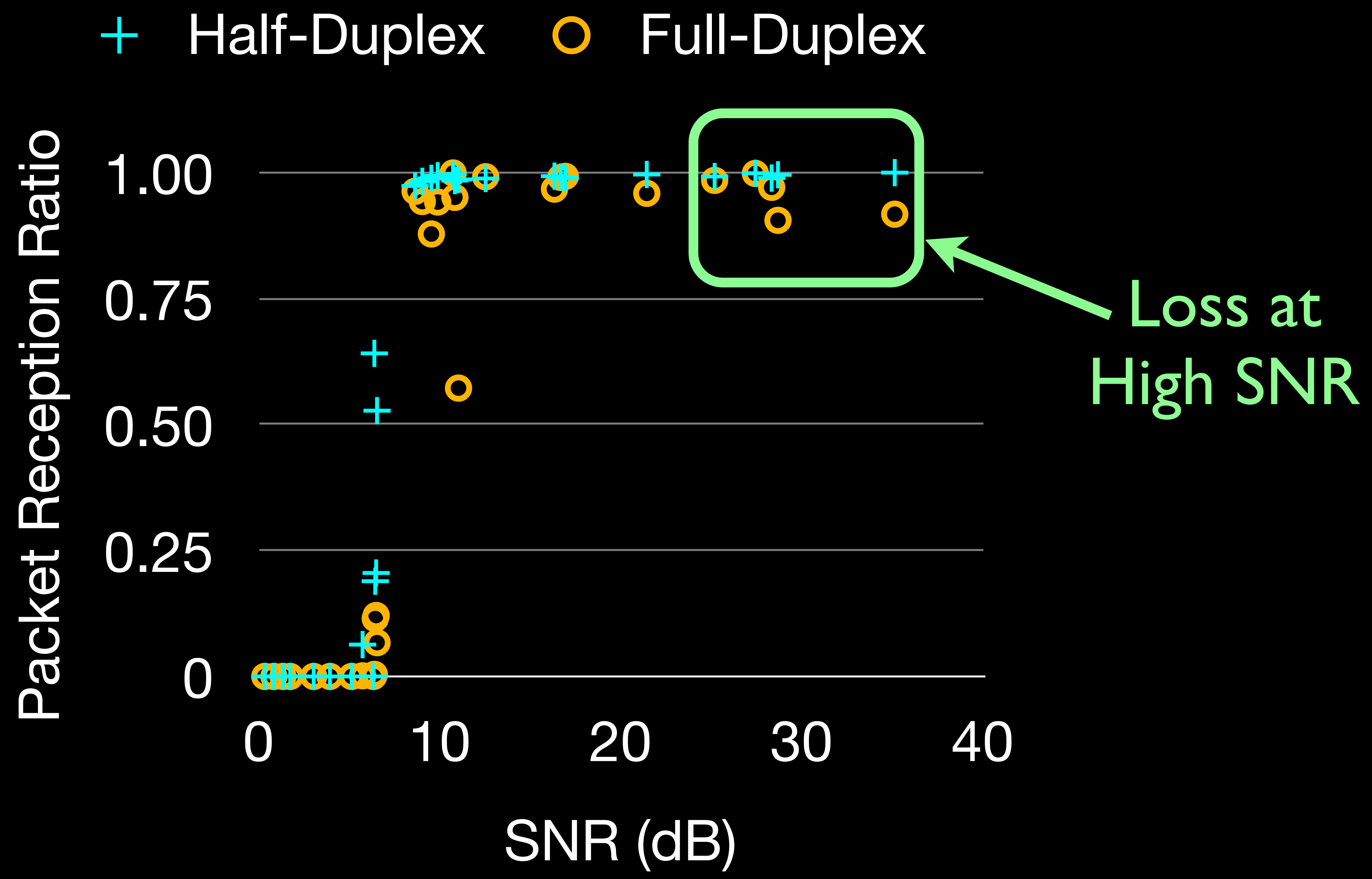
Performance loss
at low SNR

Link Reception Ratio



Little loss in link reliability: 88% of half-duplex on average

Link Reception Ratio



- Loss at High SNR: Due to spurious signal peaks in USRP

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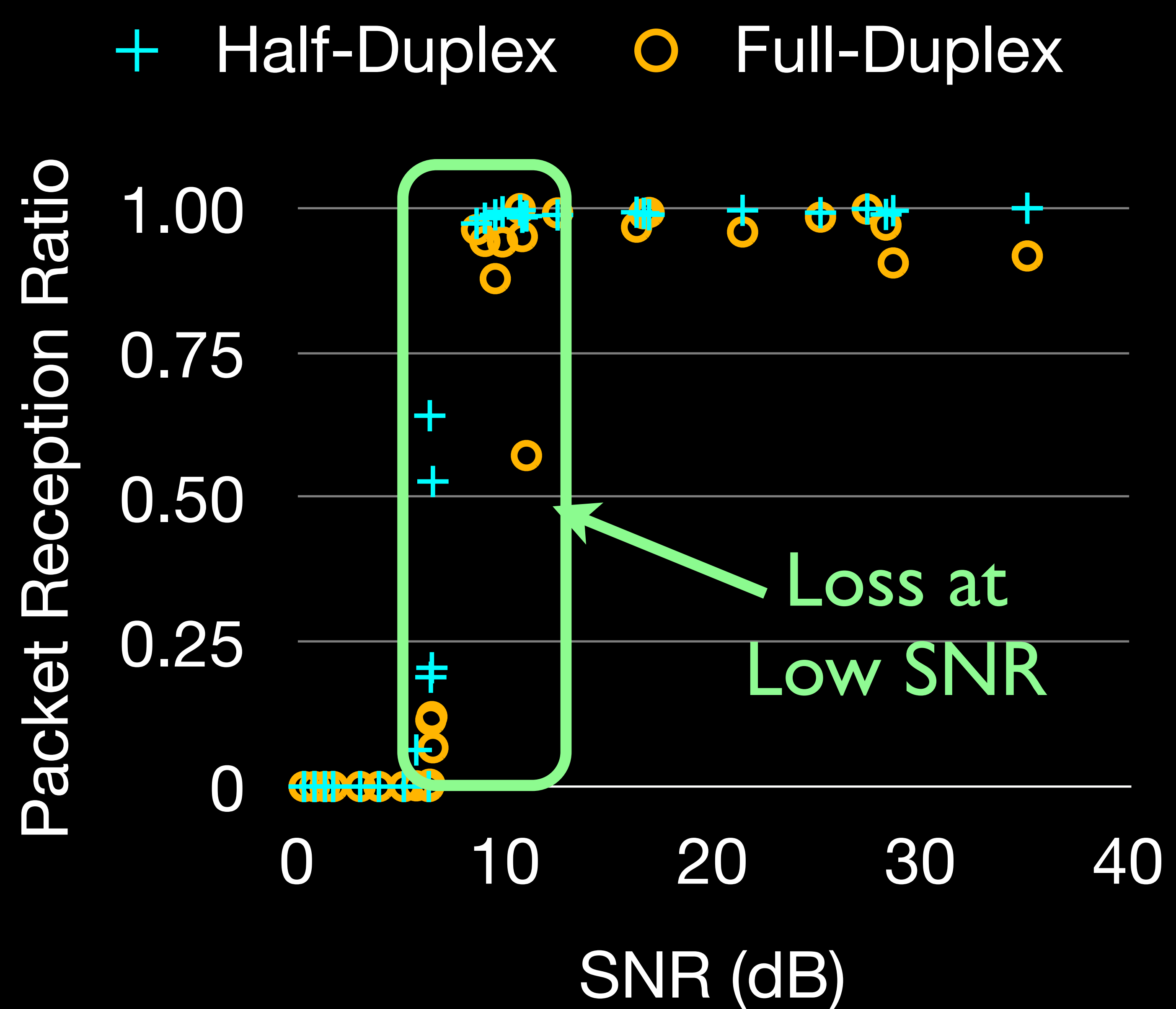

- Loss at High SNR: Due to spurious signal peaks in USRP
- Loss at low SNR: Due to imprecisions in prototype

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The prototype gives 1.84x throughput gain with two radios compared to half-duplex with a single radio

So what? PHY gains similar to 2x2 MIMO

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So what? PHY gains similar to 2x2 MIMO

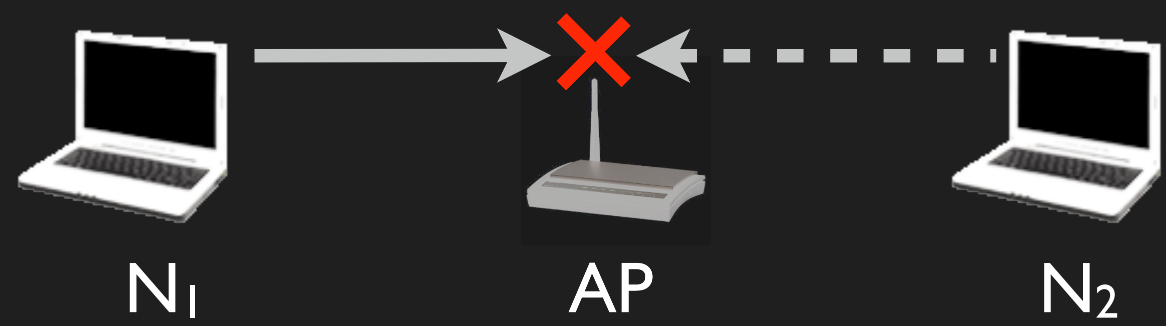
True benefit lies beyond the physical layer

Implications to Wireless Networks

- Breaks a basic assumption in wireless
- Can solve some fundamental problems with wireless networks today
  - Hidden terminals
  - Primary detection in whitespaces
  - Network congestion and WLAN fairness
  - Excessive latency in multihop wireless

Mitigating Hidden Terminals

Current networks have hidden terminals



- CSMA/CA can't solve this
- Schemes like RTS/CTS introduce significant overhead

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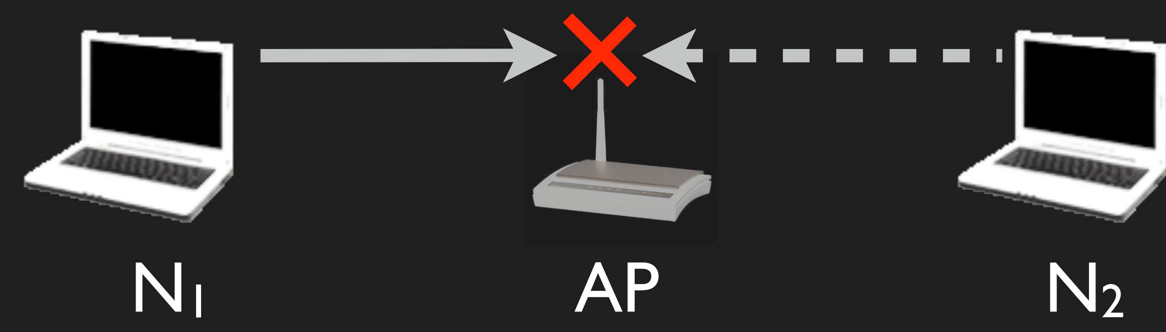

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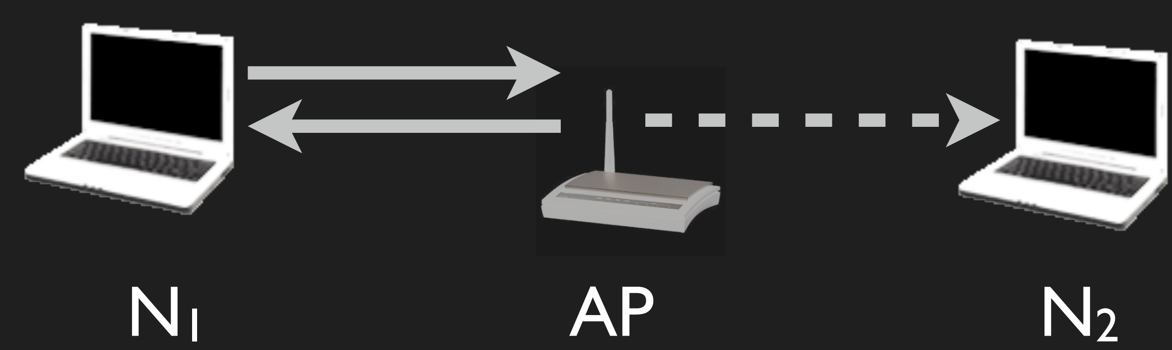
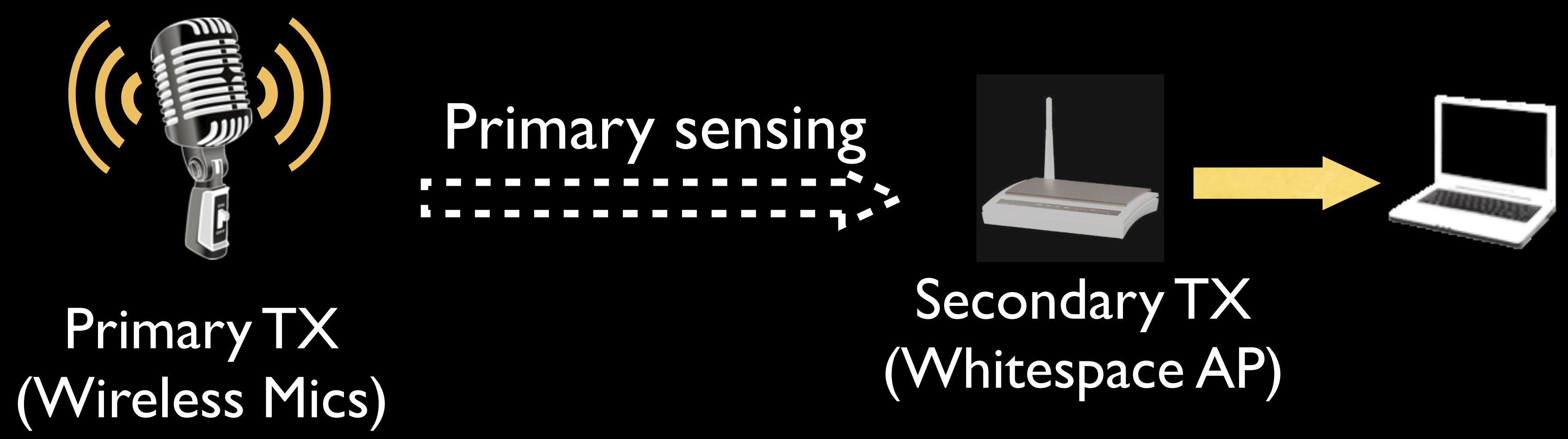
Full Duplex solves hidden terminals



Since both sides transmit at the same time, no hidden terminals exist

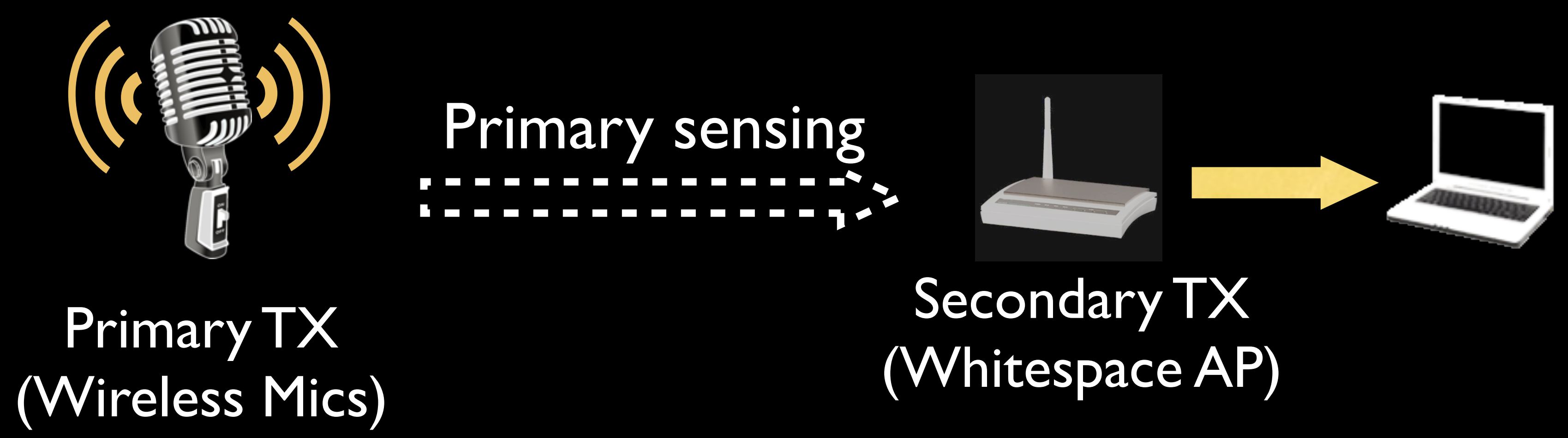
Primary Detection in Whitespaces



Secondary transmitters should sense for primary transmissions before channel use

Traditional nodes may still interfere during transmissions

Primary Detection in Whitespaces



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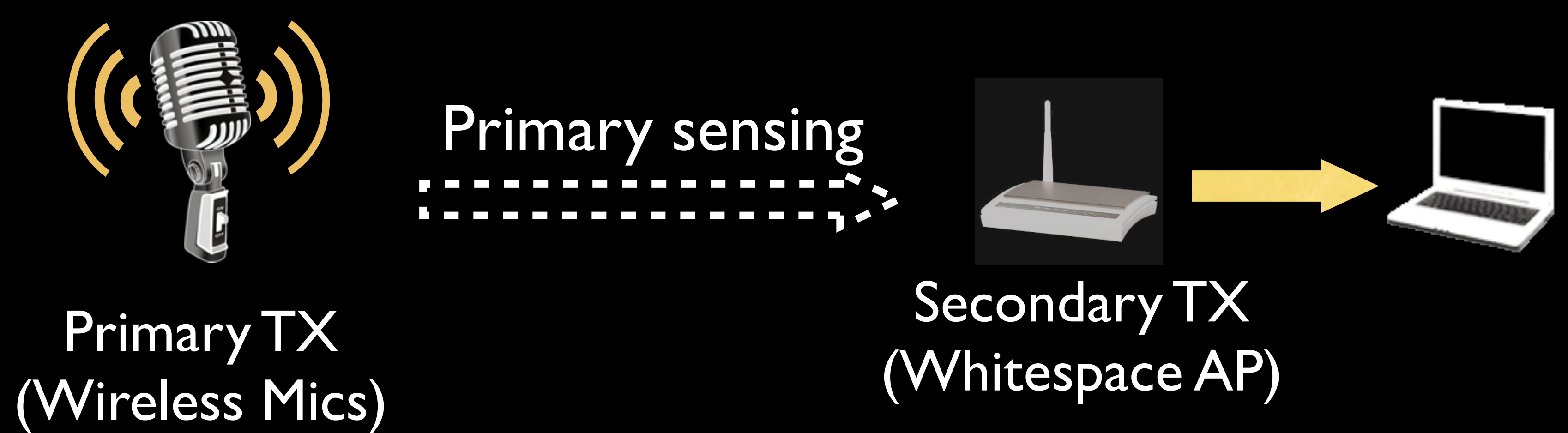
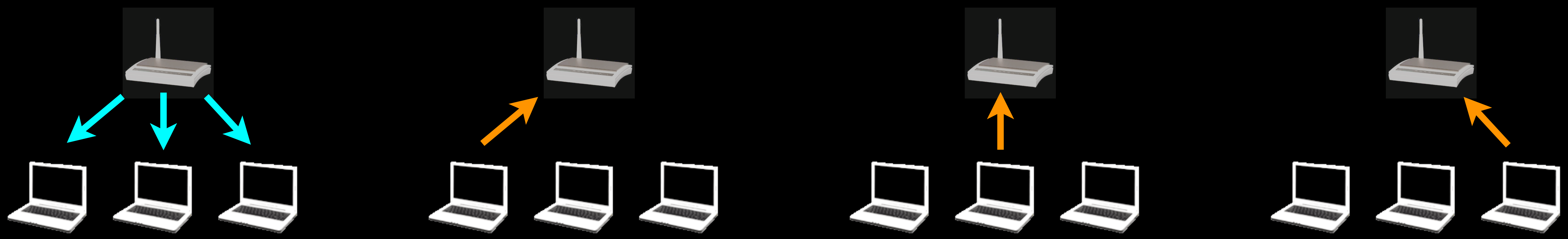


Full-duplex nodes can sense and send at the same time

Network Congestion and WLAN Fairness

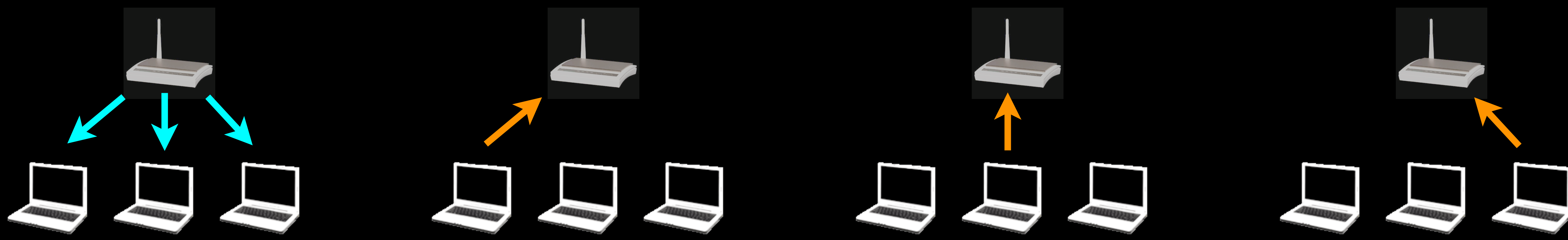


Without full-duplex:

- 1/n bandwidth for each node in network, including AP

Downlink Throughput = 1/n   Uplink Throughput = (n-1)/n

Network Congestion and WLAN Fairness



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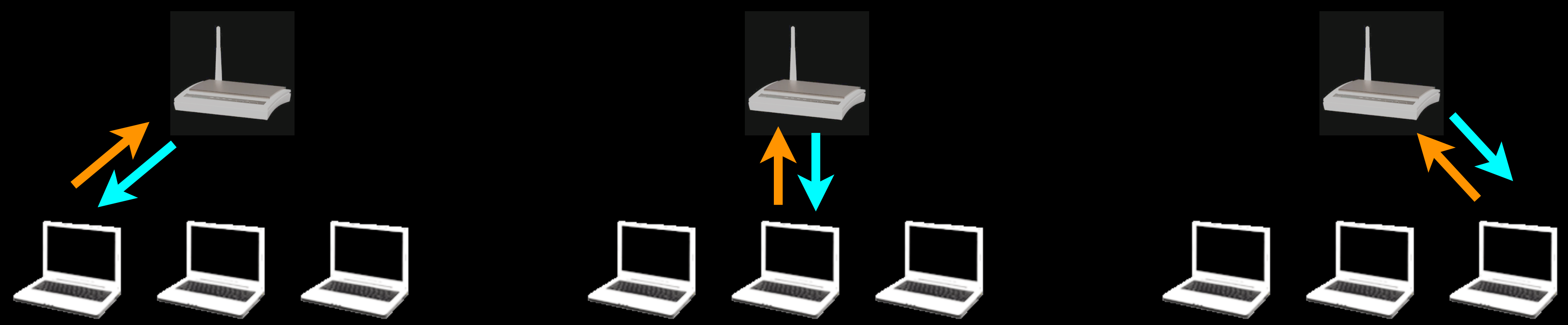


With full-duplex:

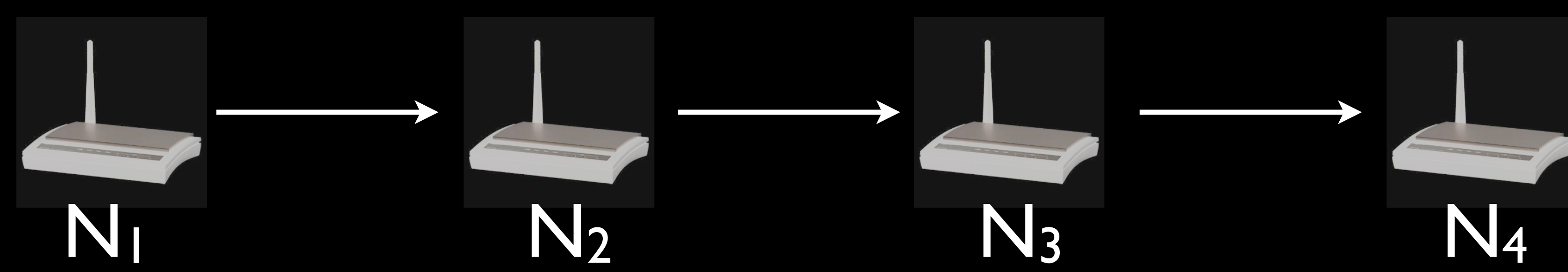
- AP sends and receives at the same time

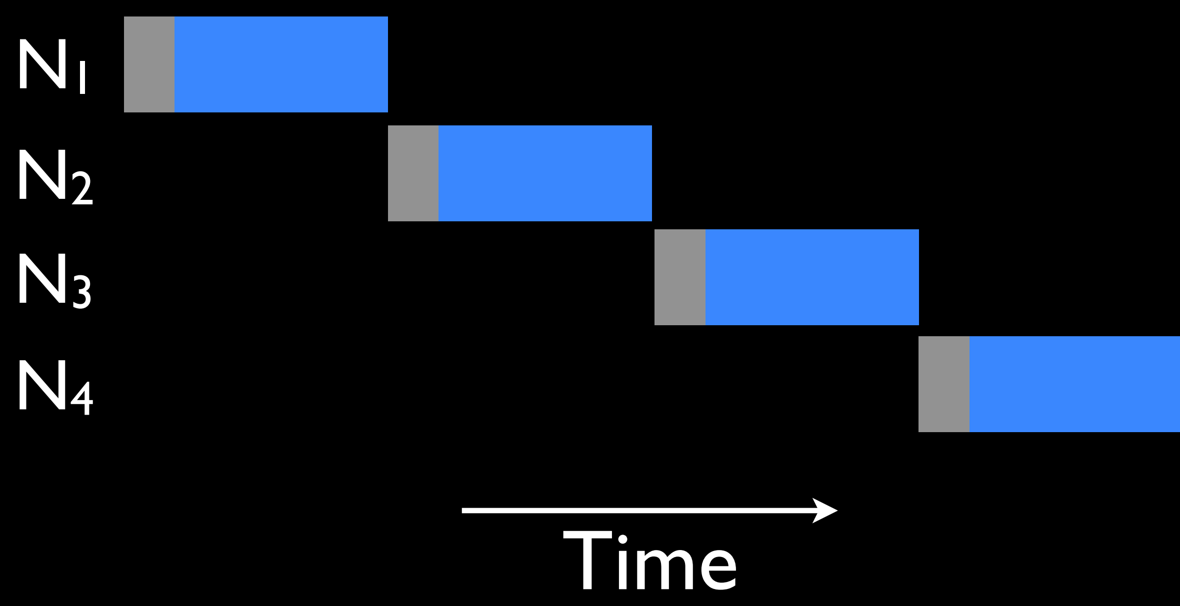
Downlink Throughput = 1   Uplink Throughput = 1

Reducing Round-Trip Times

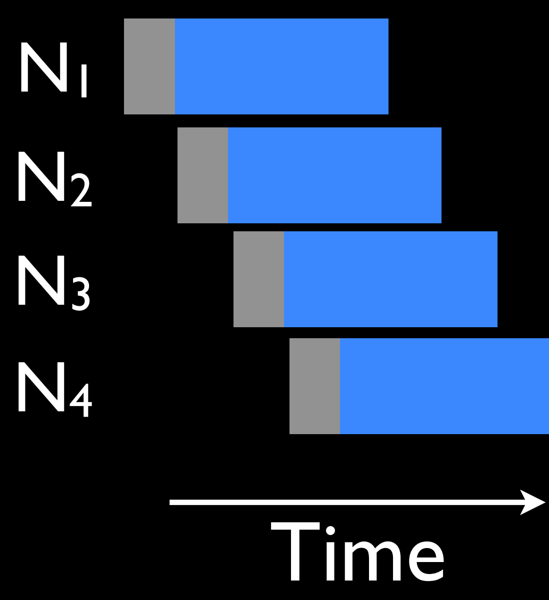
Long delivery and round-trip times in multi-hop networks

Solution: Wormhole routing





Half-duplex



Full-duplex

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- Bandwidth Constraint

  Working on a frequency independent signal inversion technique

- Time-varying wireless channel

  Auto-tuning of the hardware cancellation circuit

- Multi-path

  Estimate and incorporate in digital cancellation: Some existing work does this

- Single stream

  Extension to MIMO-like systems

Summary

- Prototype for achieving in-band full-duplex wireless
- Constraints of current prototype can be overcome with some neat ideas and careful engineering
- Rethinking of wireless networks
  - We've discussed some applications like mitigating hidden terminals and WLAN fairness
  - Many more possibilities

From 3 antennas to 2 antennas

➜ solves bandwidth problem

Demo on Wednesday

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PS: We're looking for jobs starting mid-2011 :)

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