Practical, Real-time, Full-Duplex Wireless

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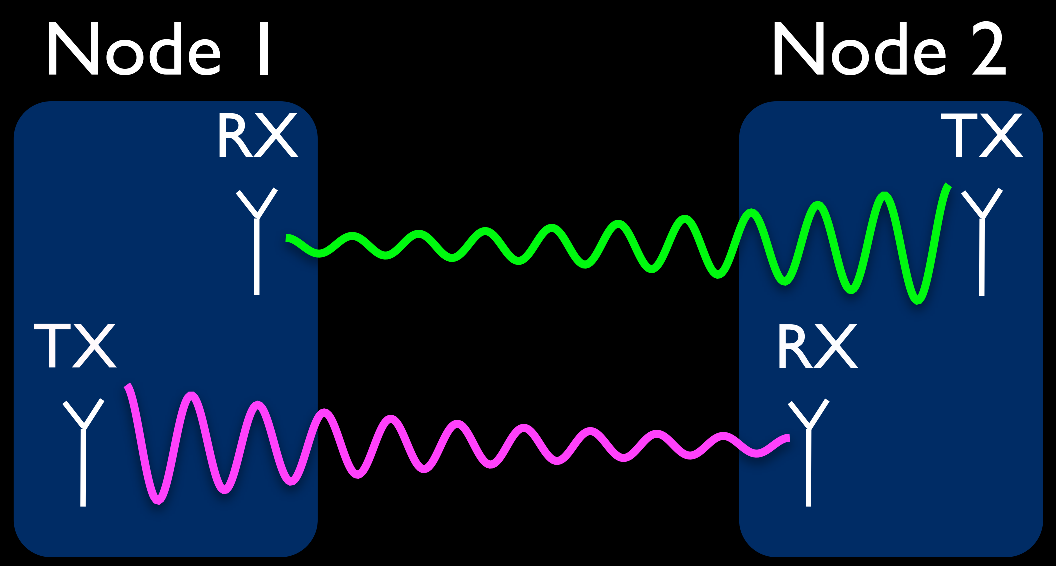
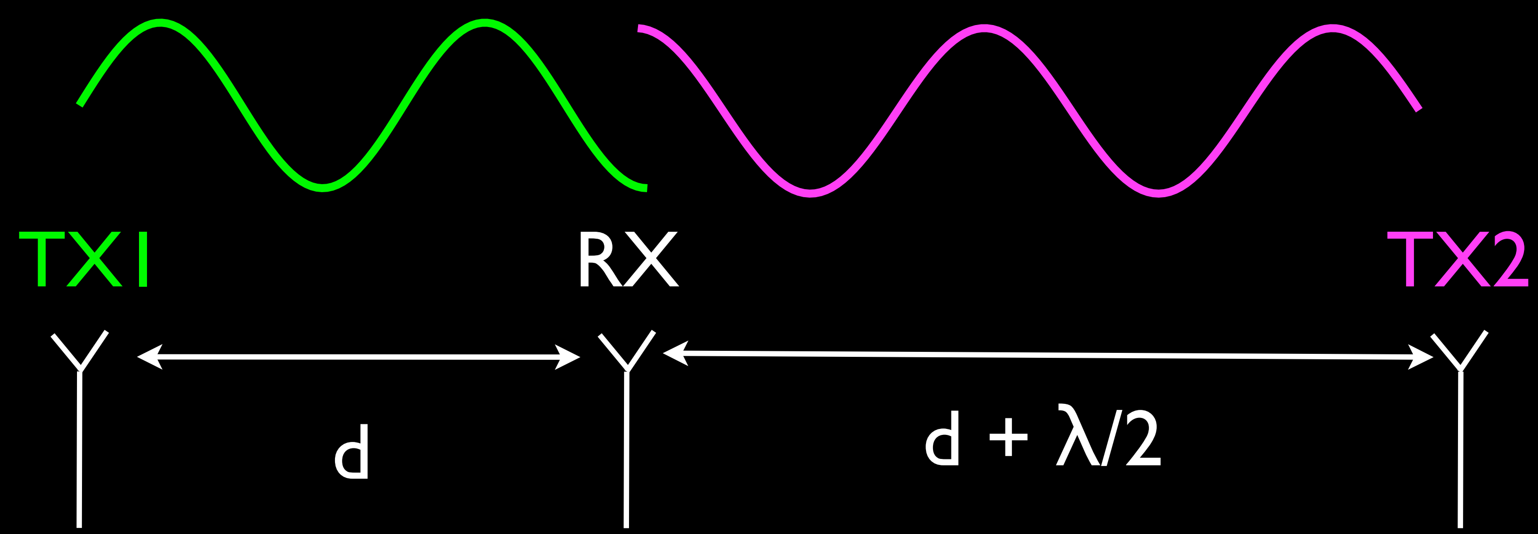
Single channel full-duplex



The story so far...

Mobicom'10[1]:

Antenna Cancellation + other techniques



[1] Choi et al. "Achieving single channel, full duplex wireless communication", Mobicom 2010

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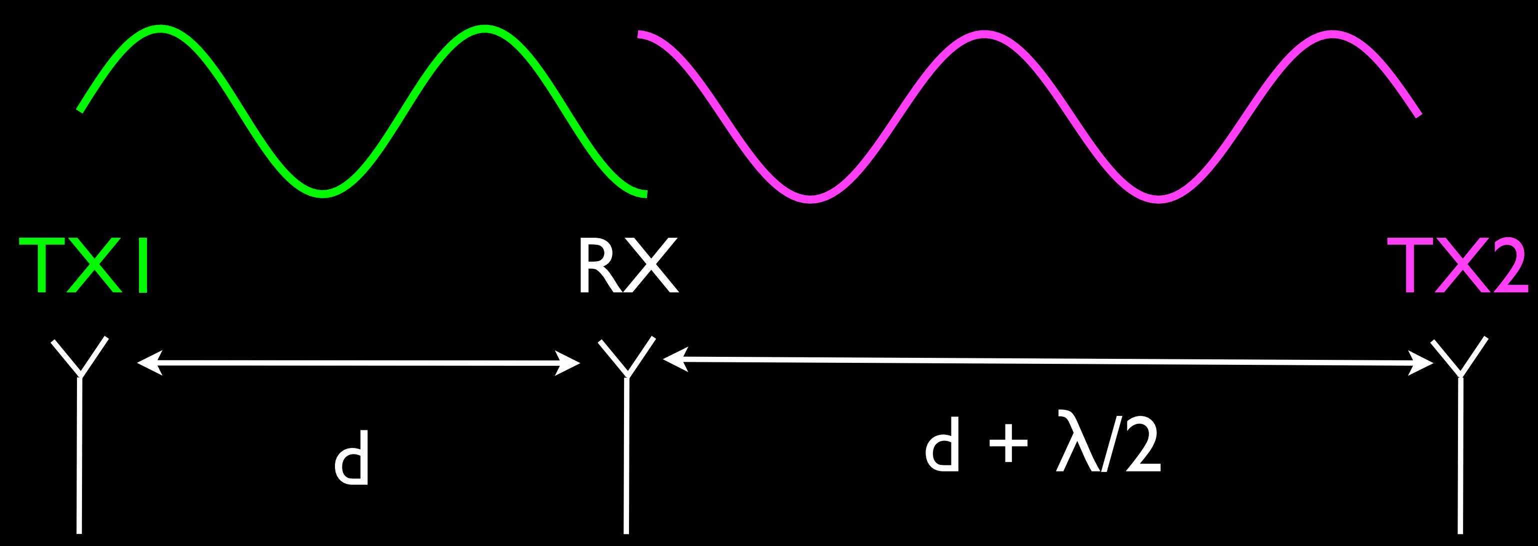

- Frequency dependent, narrowband
- Requires manual tuning
- Two transmit antennas cause complex far-field behavior

Contributions

- New full-duplex radio design: signal inversion cancellation
  - Wideband, frequency independent
  - Adaptive
  - One transmit antenna design
- Real-time full-duplex MAC layer implementation
  - Show MAC layer gains with full-duplex

Talk Outline

- RF Design using Signal Inversion
- Adaptive RF Cancellation
- System Performance
- Implications to Wireless Networks
- Open Questions

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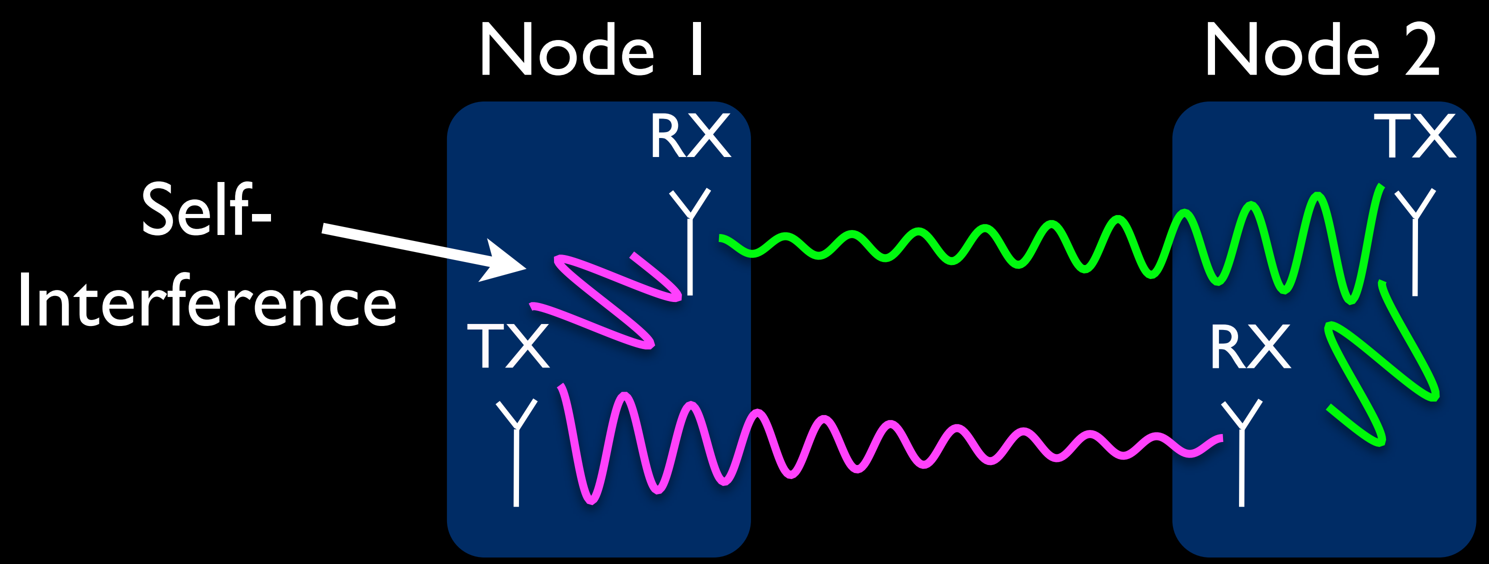
The challenge of full-duplex

→ Very strong self-interference: ~70dB for 802.11



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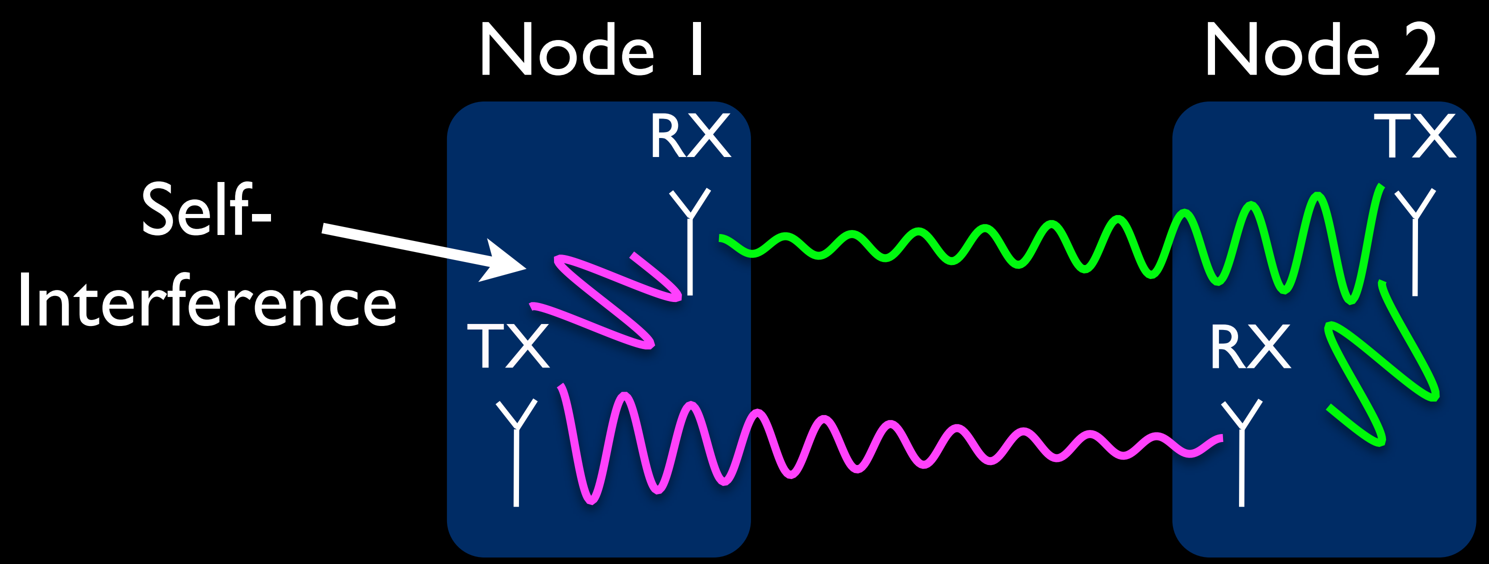
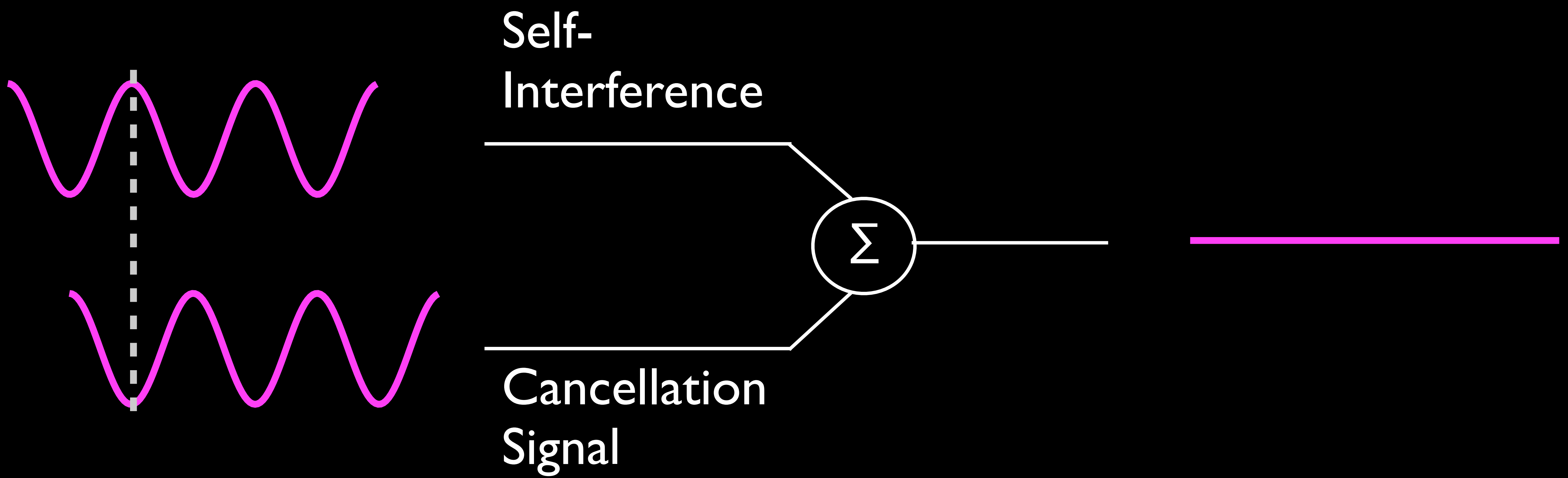


Combine RF and digital techniques for cancellation

Cancellation using Phase Offset



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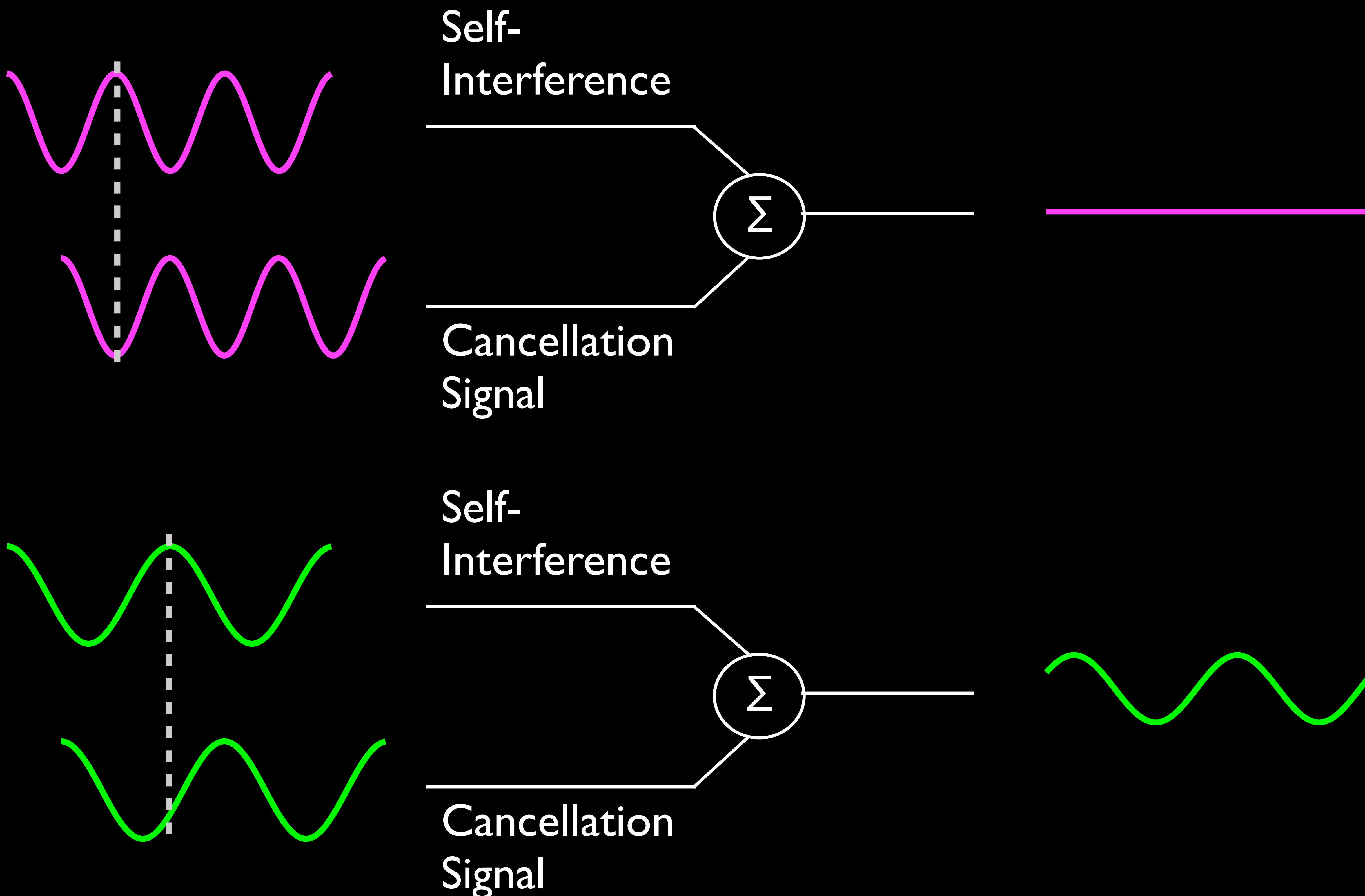
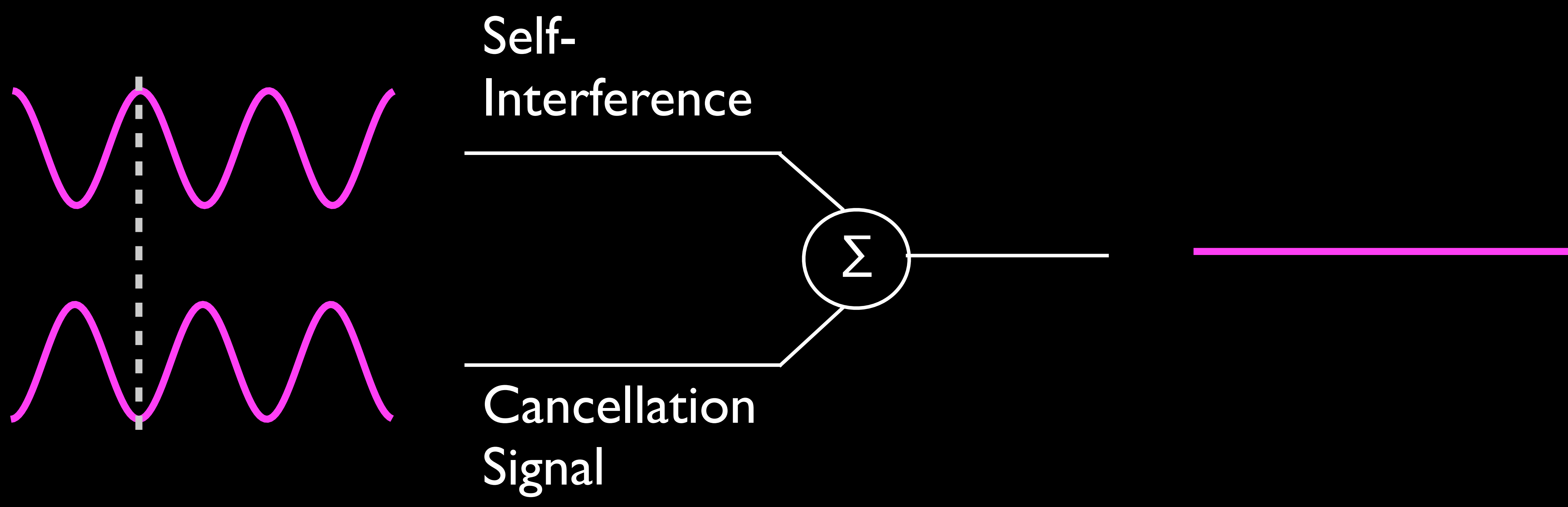
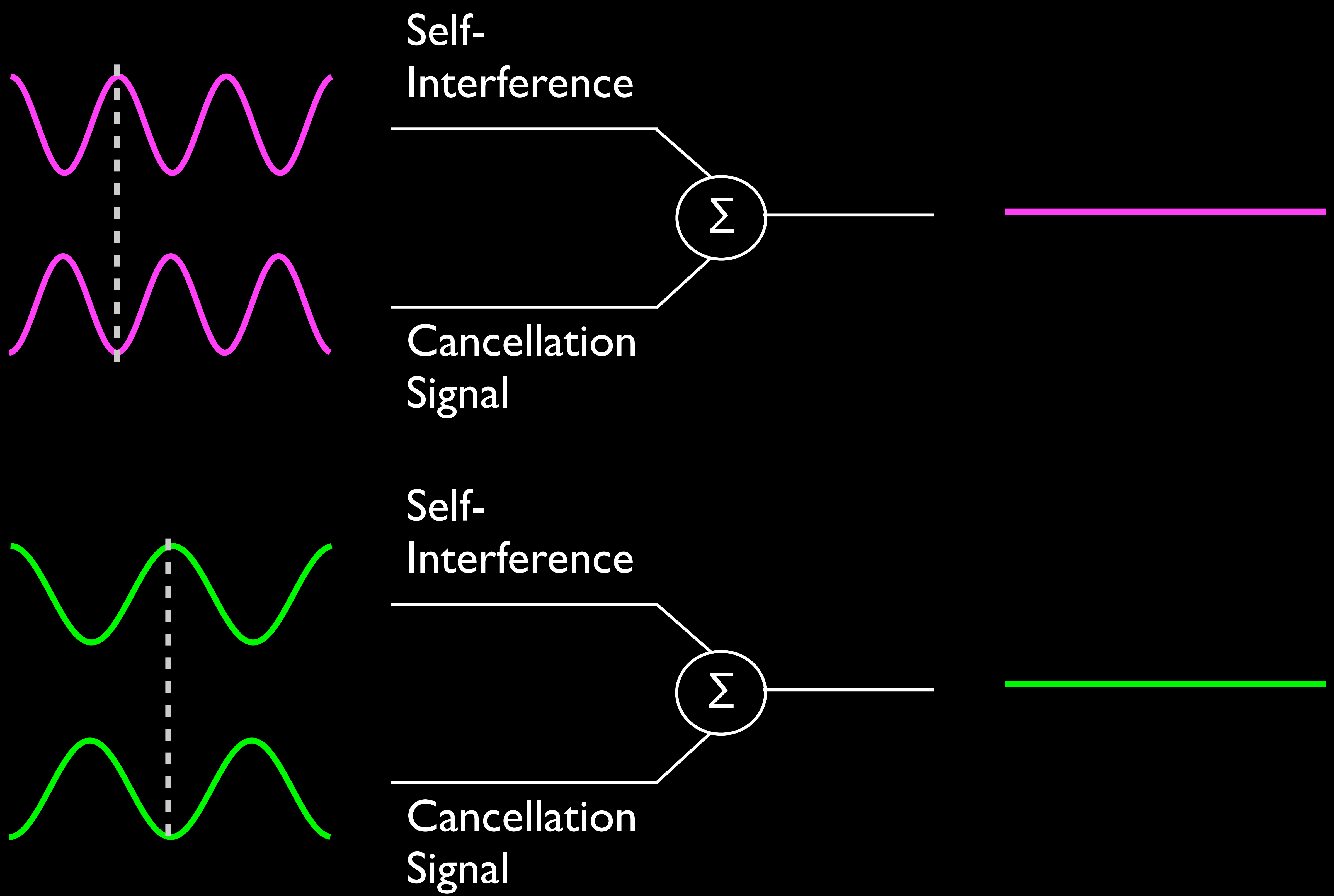


Frequency dependent, narrowband

Cancellation using Signal Inversion

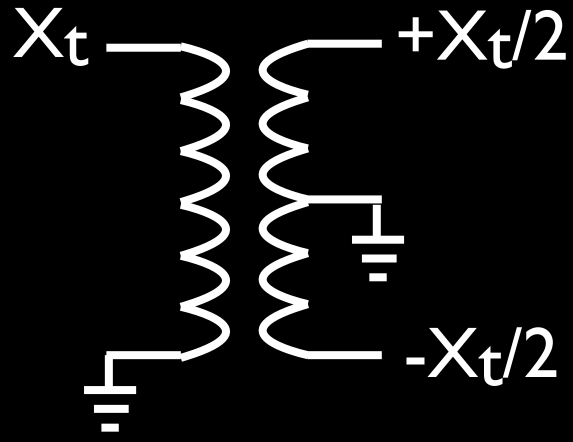


Cancellation using Signal Inversion



Frequency and bandwidth independent

BALUN : Balanced to Unbalanced Conversion



BALUN

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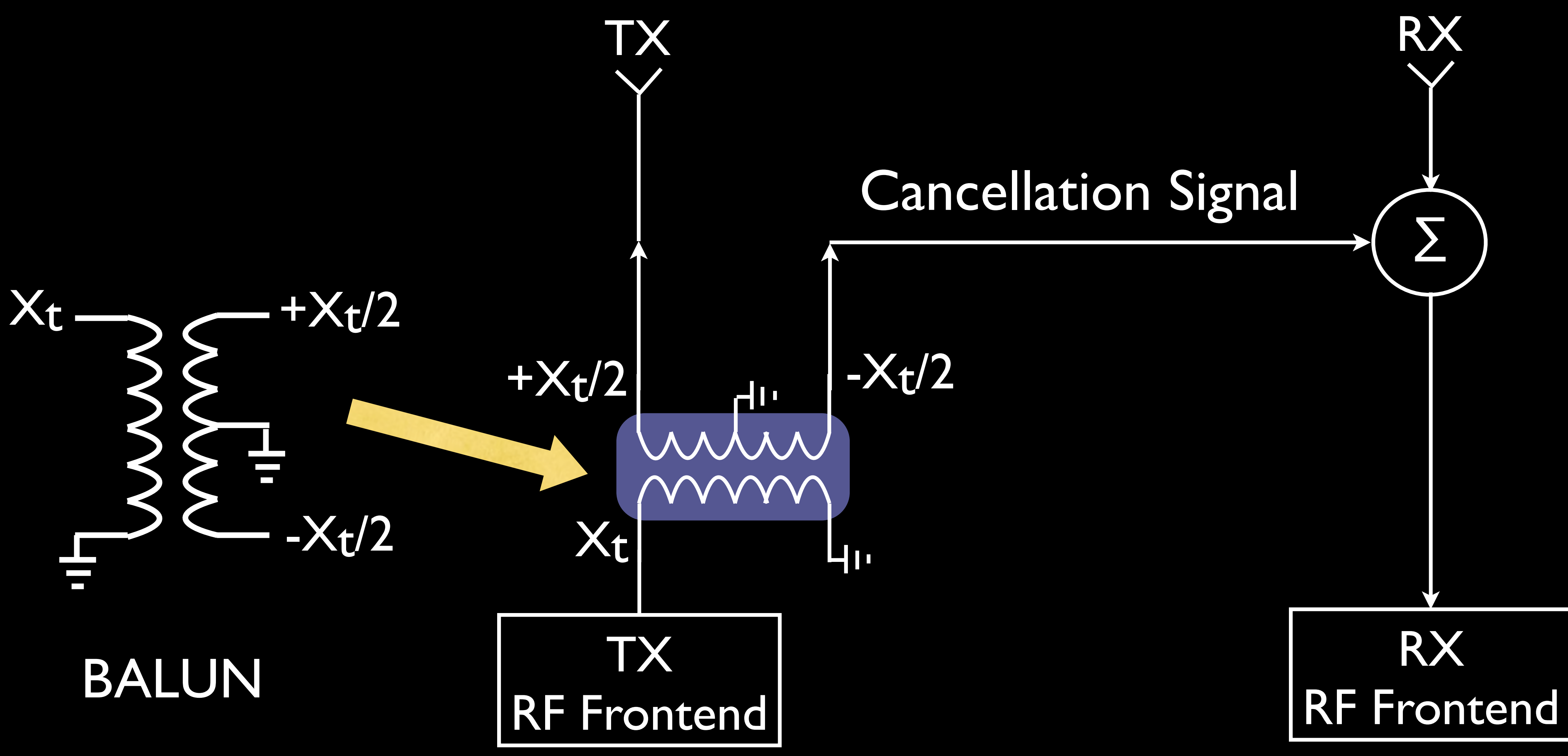
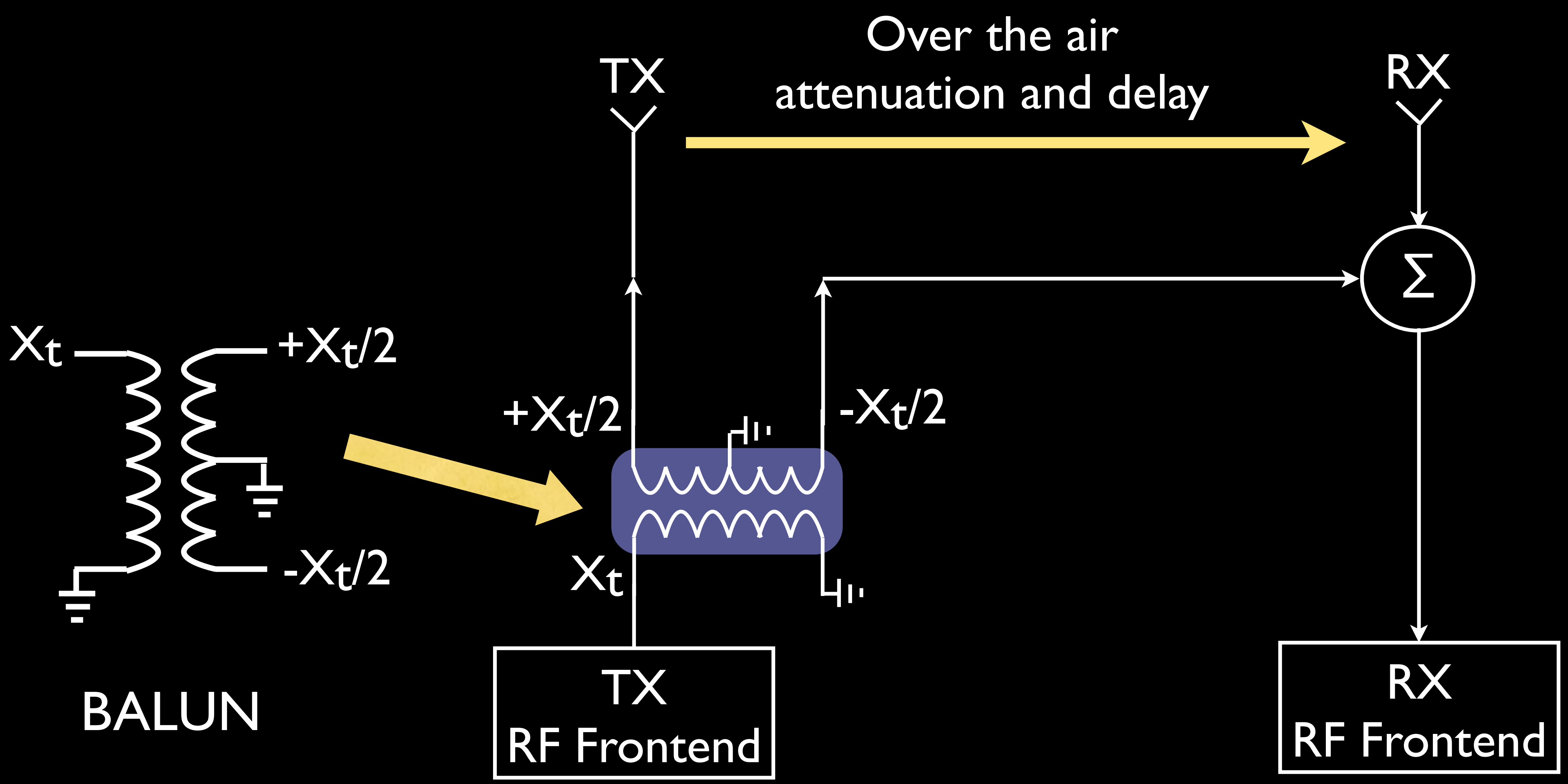
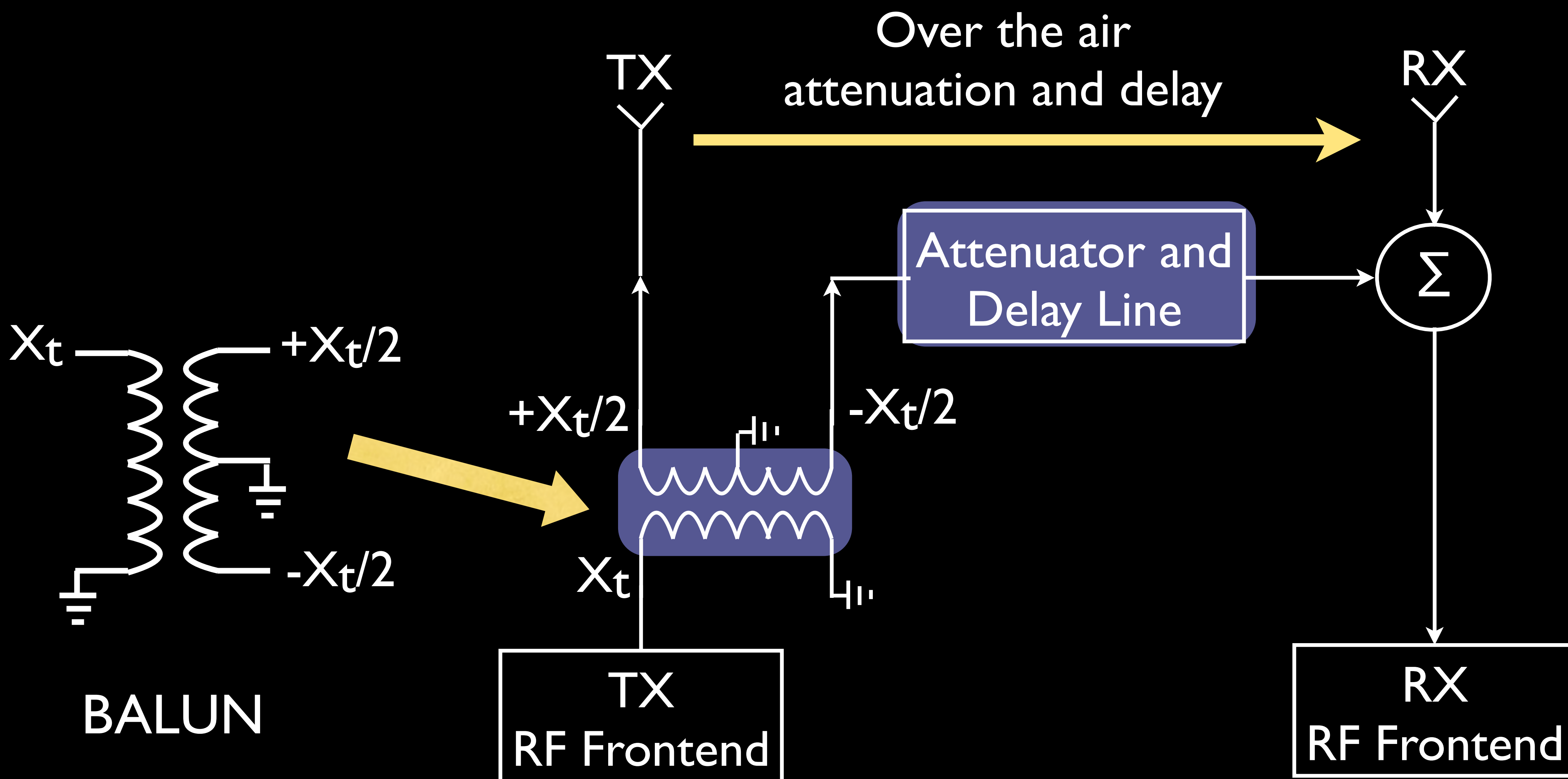




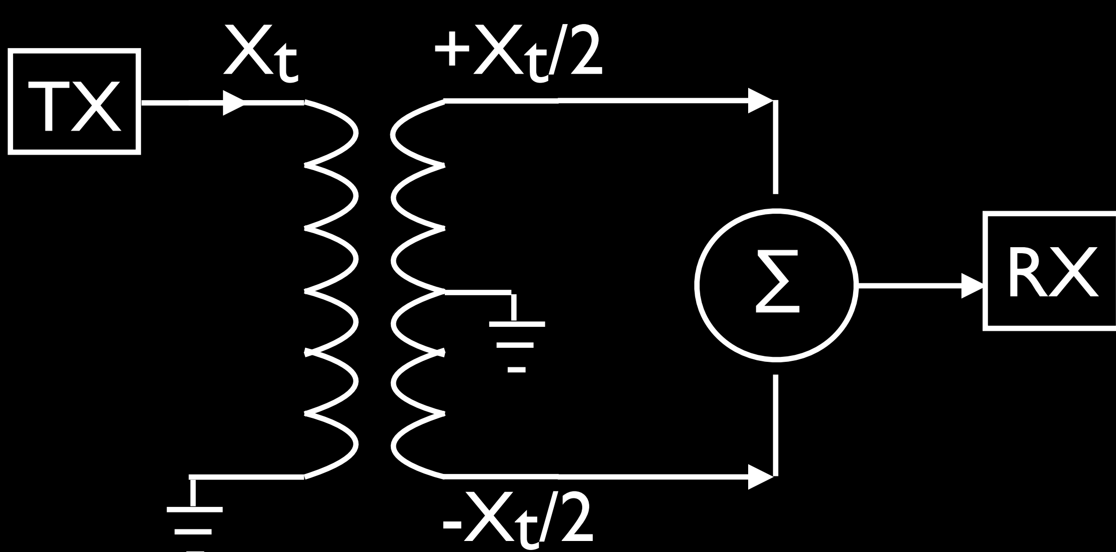
Over the air
attenuation and delay
TX
RX
Σ
Xt
+Xt/2
-Xt/2
BALUN
+Xt/2
-Xt/2
Xt
TX
RF Frontend
RX
RF Frontend

Signal Inversion Cancellation

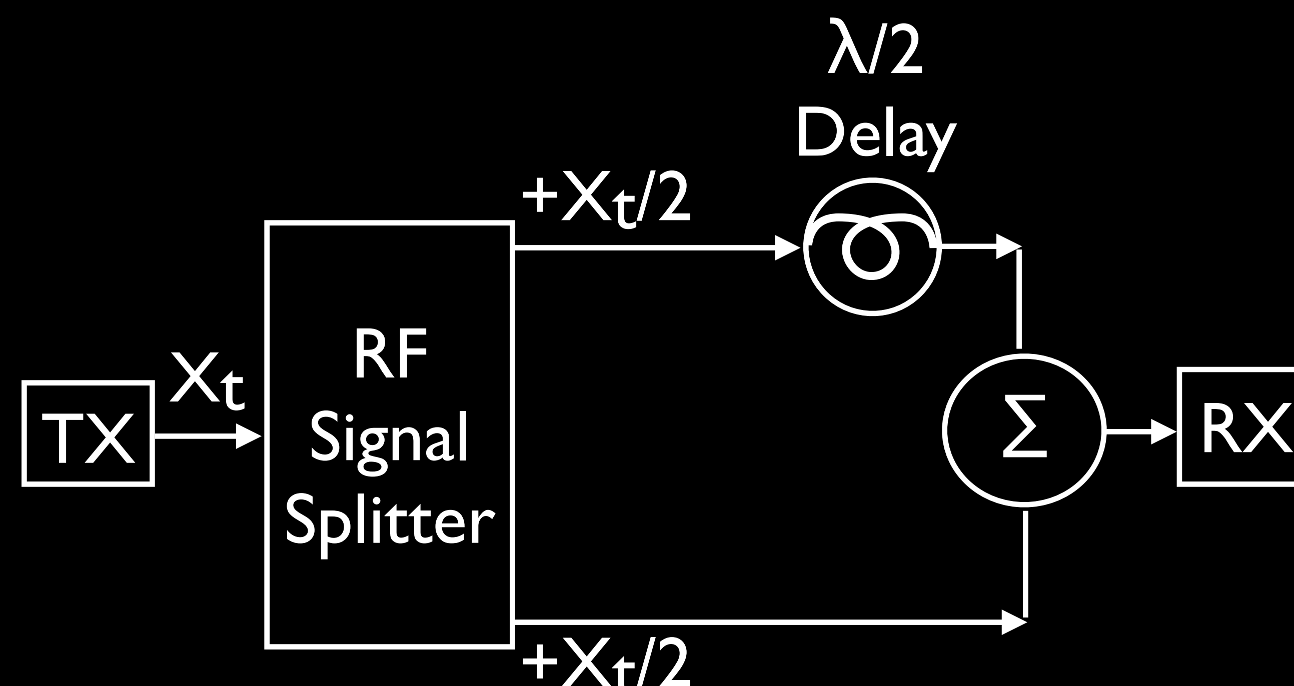


Signal Inversion Cancellation: Wideband Evaluation

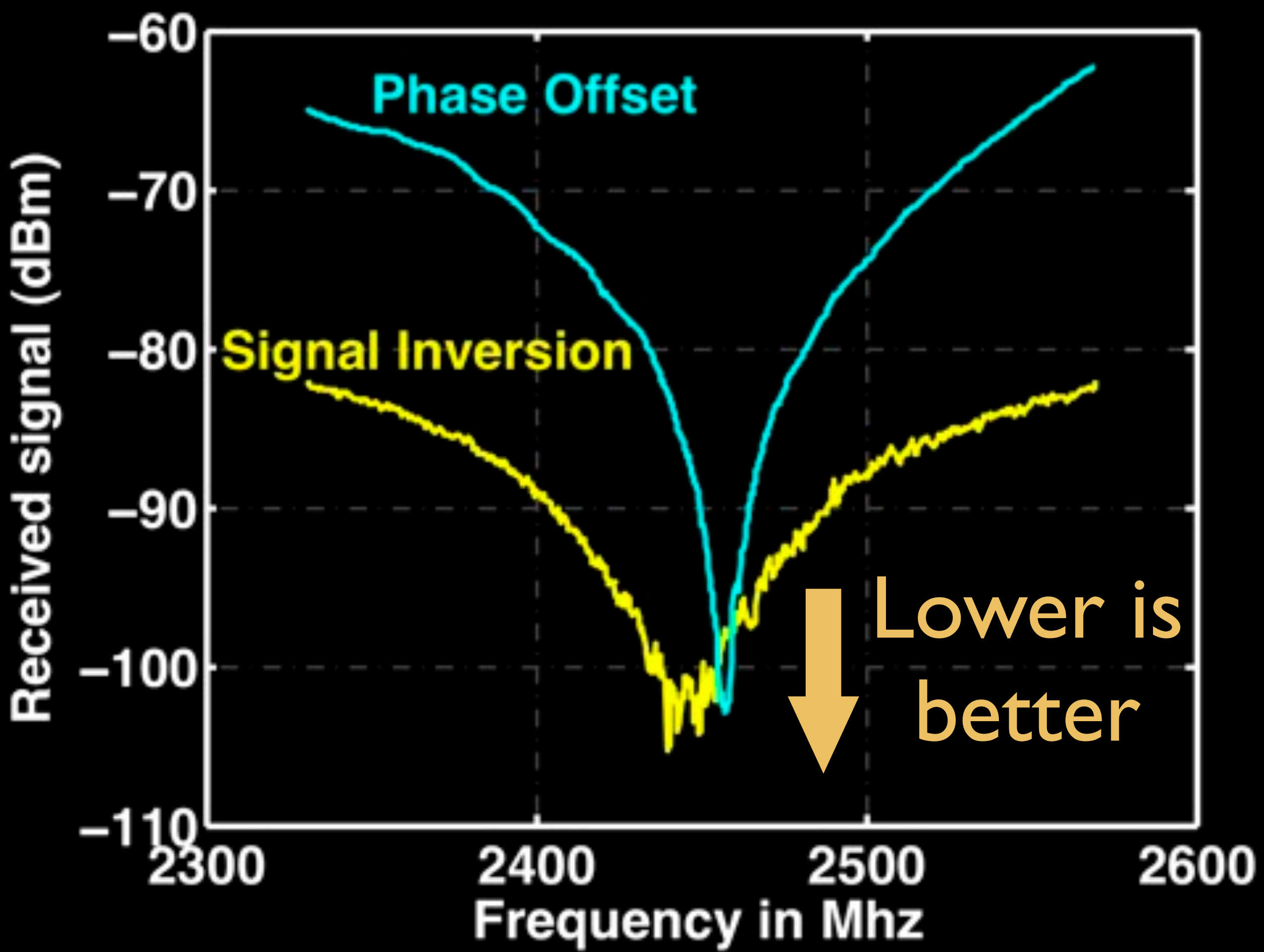
- Measure wideband cancellation
- Wired experiments
- 240MHz chirp at 2.4GHz to measure response



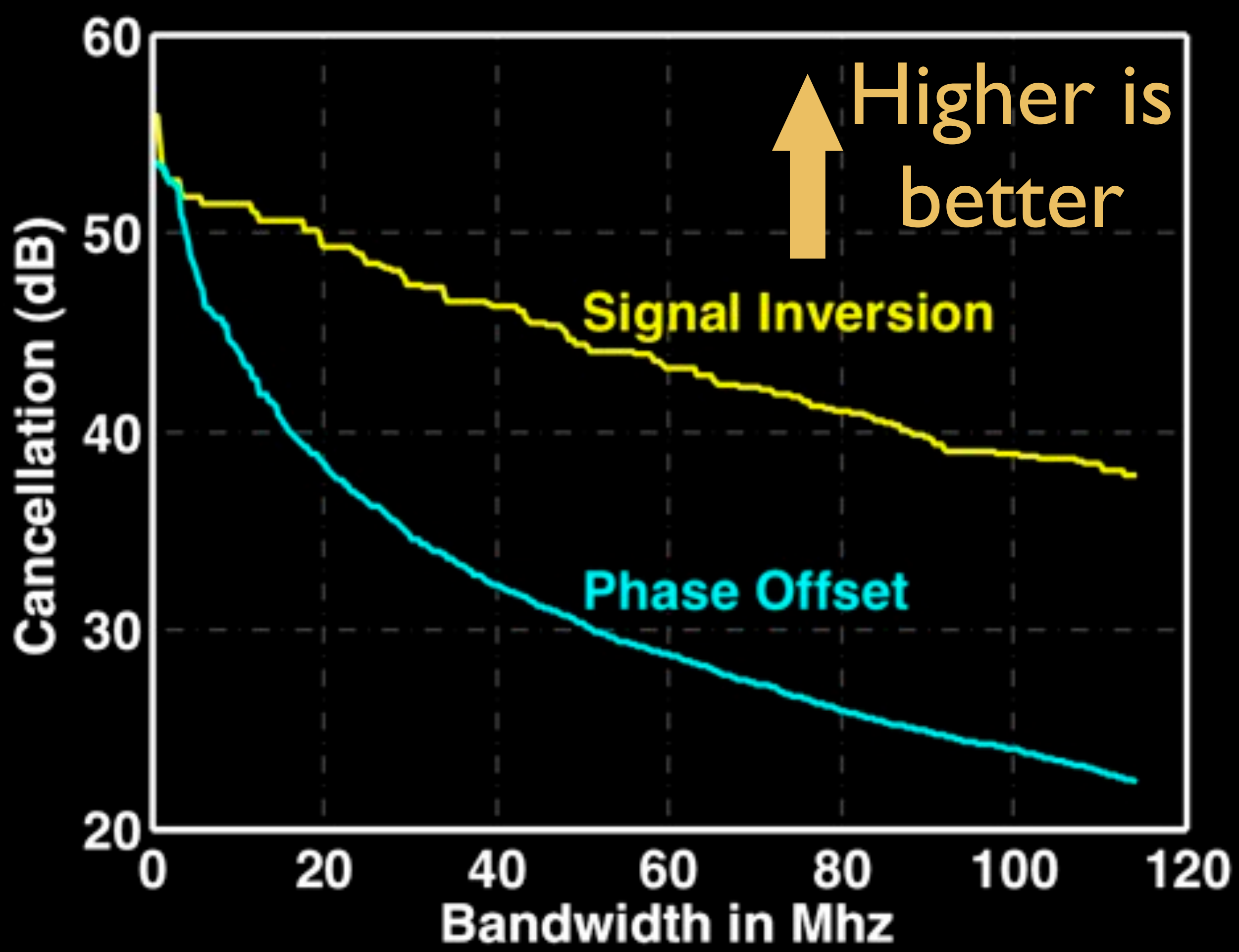
Signal Inversion Cancellation Setup



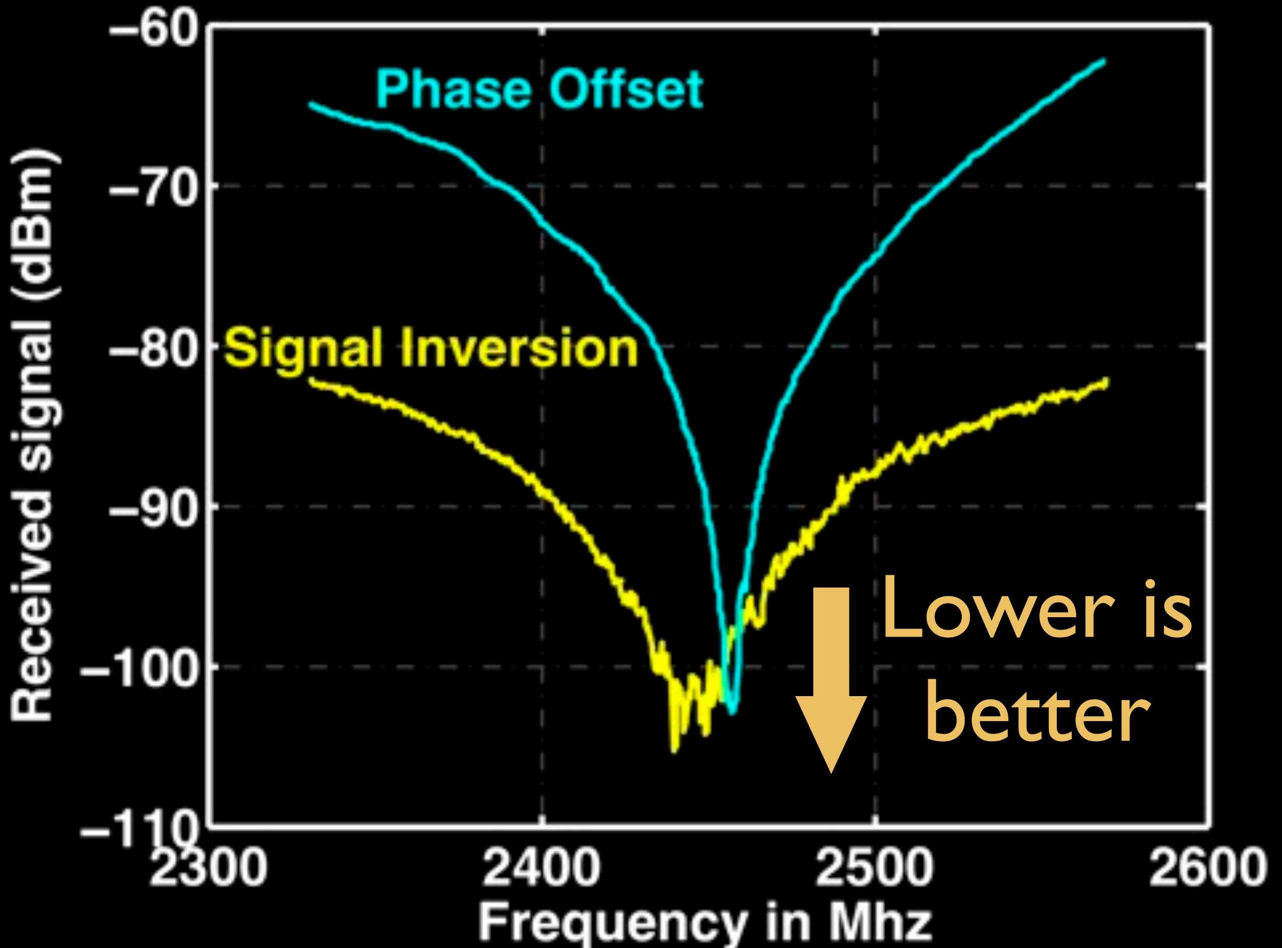
Phase Offset Cancellation Setup

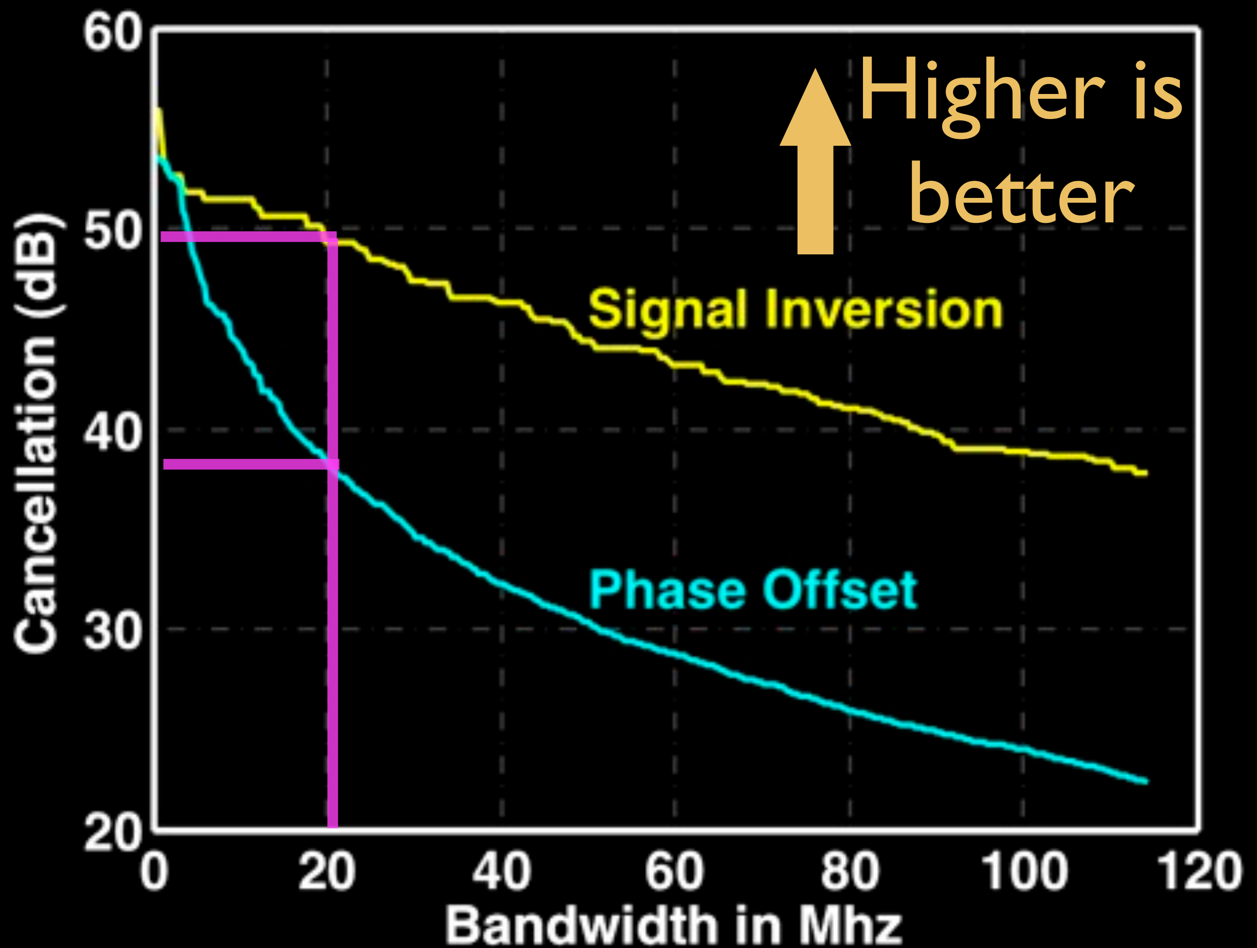


Phase Offset
Signal Inversion
Lower is better
Received signal (dBm)
Frequency in Mhz
−60
−70
−80
−90
−100
−110
2300
2400
2500
2600



Higher is better
Signal Inversion
Phase Offset
Cancellation (dB)
Bandwidth in Mhz
60
50
40
30
20
0
20
40
60
80
100
120

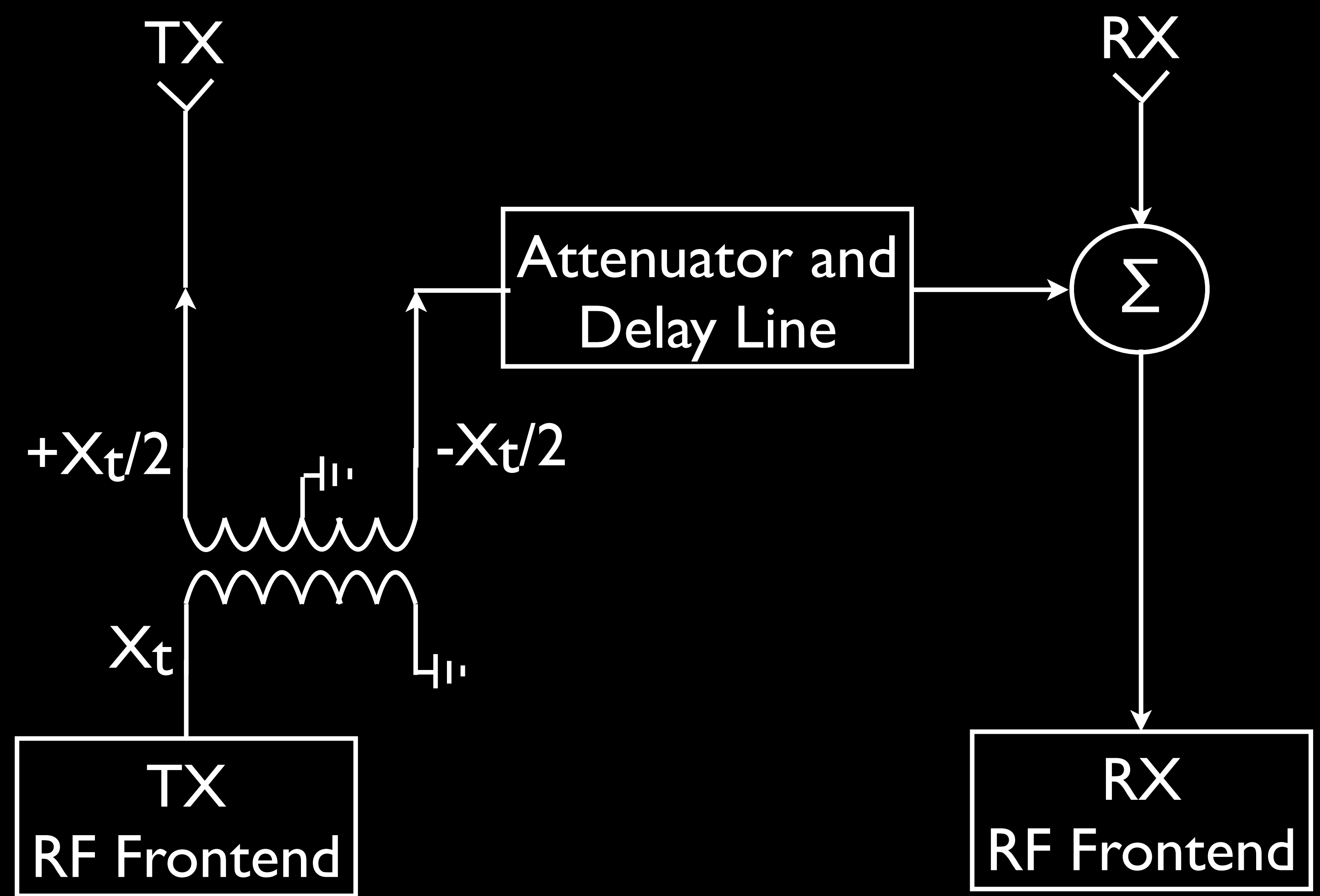




~50dB cancellation at 20MHz bandwidth with balun vs ~38dB with phase offset cancellation.

Significant improvement in wideband cancellation

Other advantages

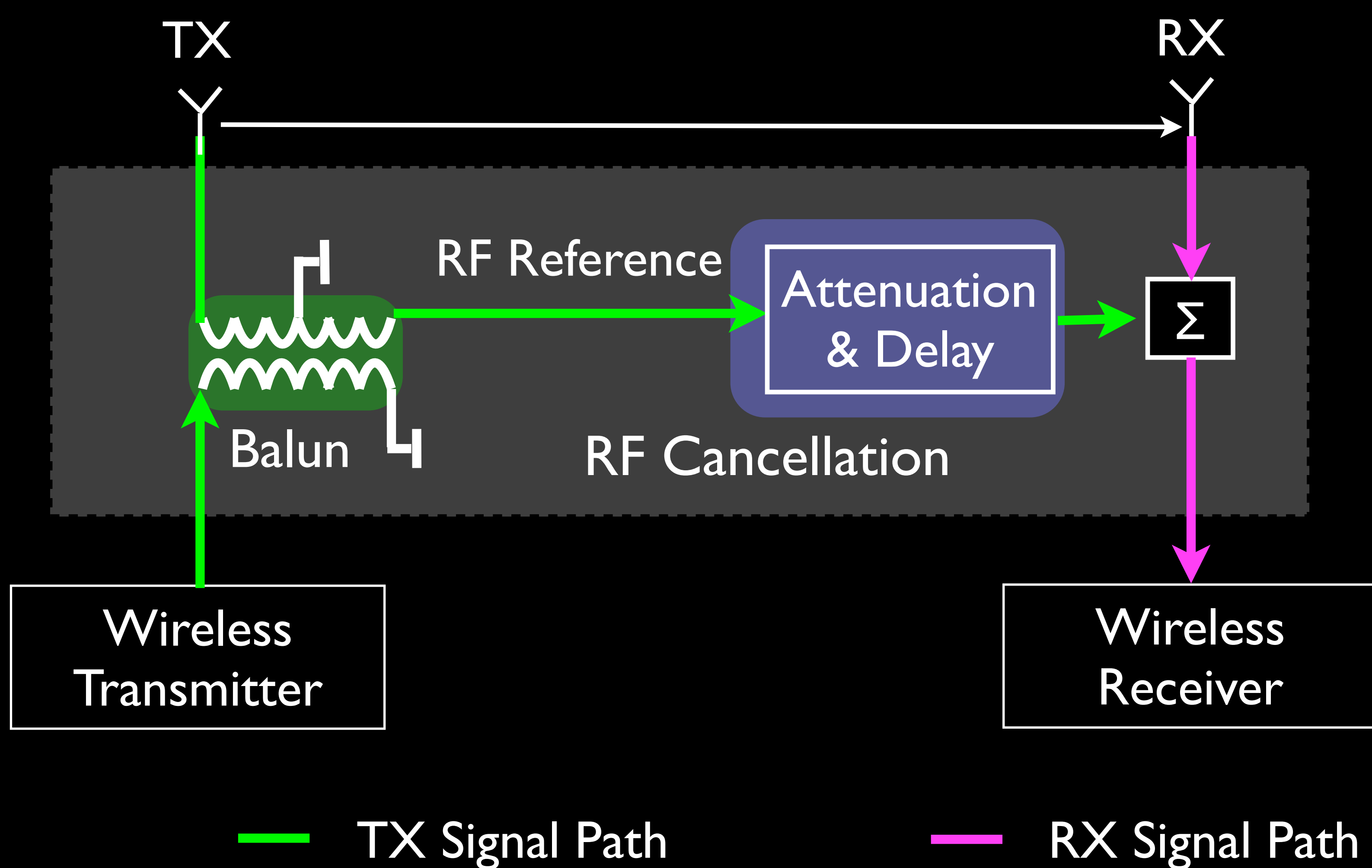


- From 3 antennas per node to 2 antennas
- Parameters adjustable with changing conditions

Talk Outline

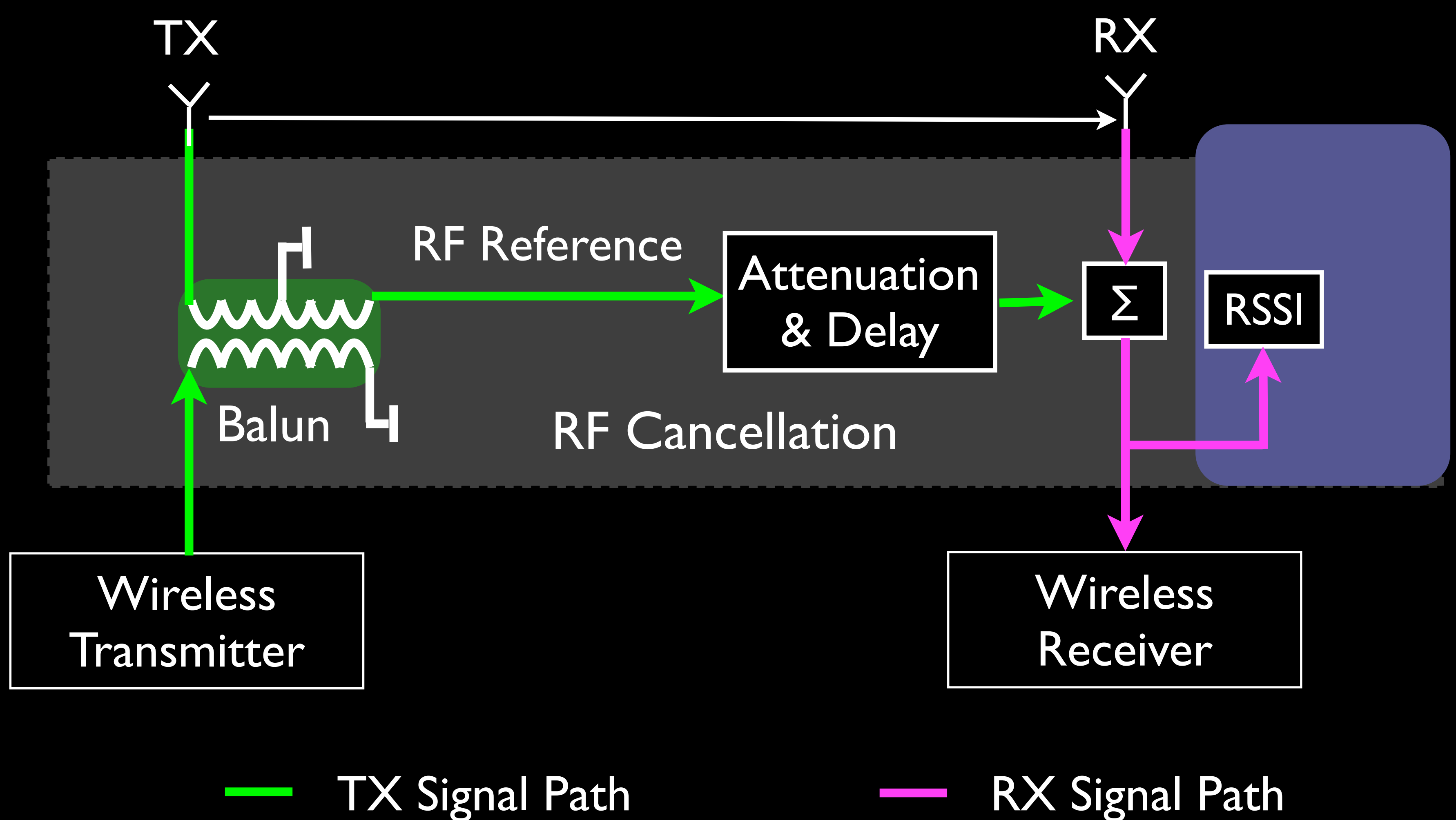
- RF Design using Signal Inversion: ~50dB for 20Mhz
- Adaptive RF Cancellation
- System Performance
- Implications to Wireless Networks
- Open Questions

Adaptive RF Cancellation



- Need to match self-interference power and delay
- Can’t use digital samples: Saturated ADC

Adaptive RF Cancellation



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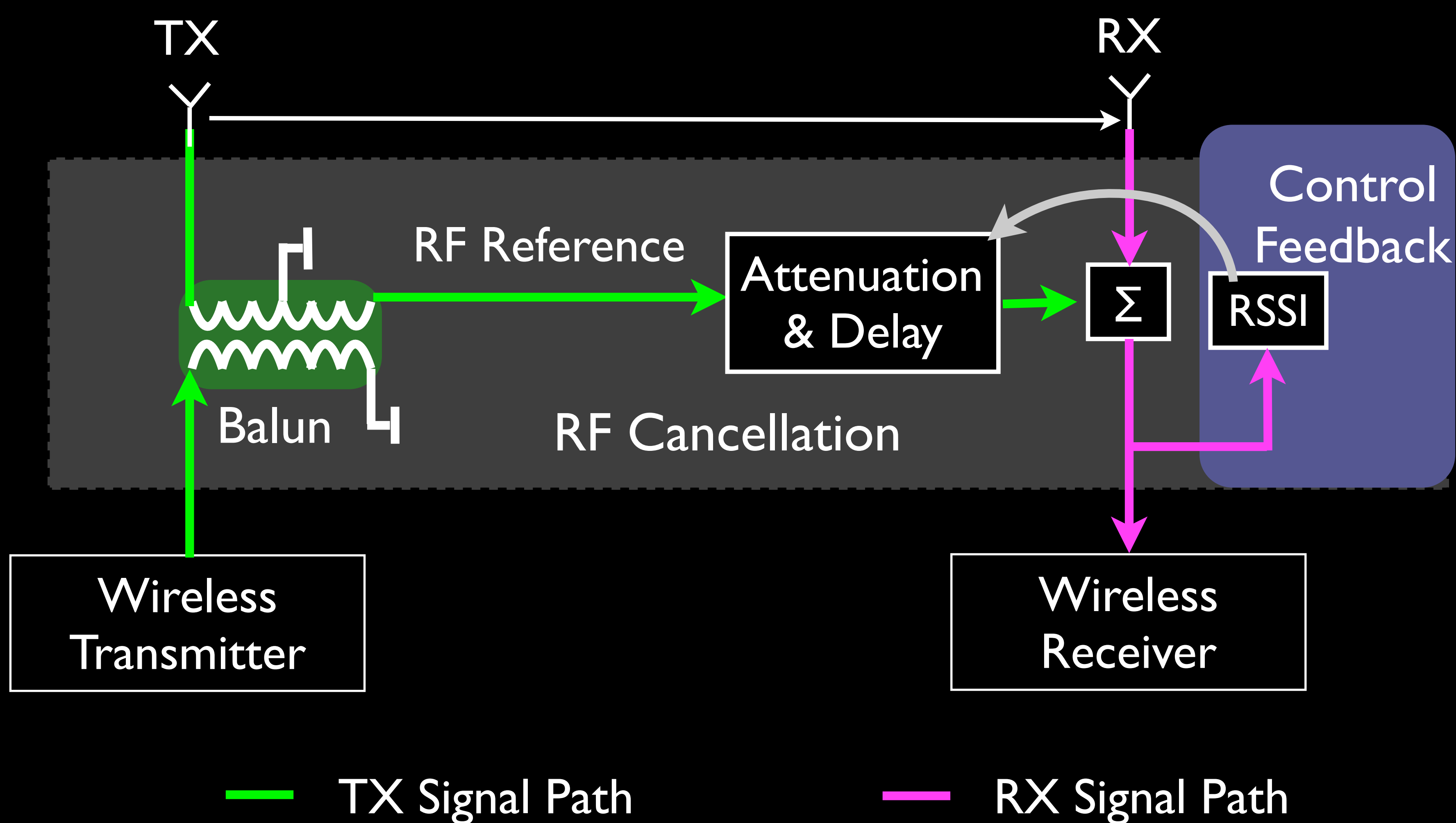
RSSI : Received Signal Strength Indicator

Adaptive RF Cancellation



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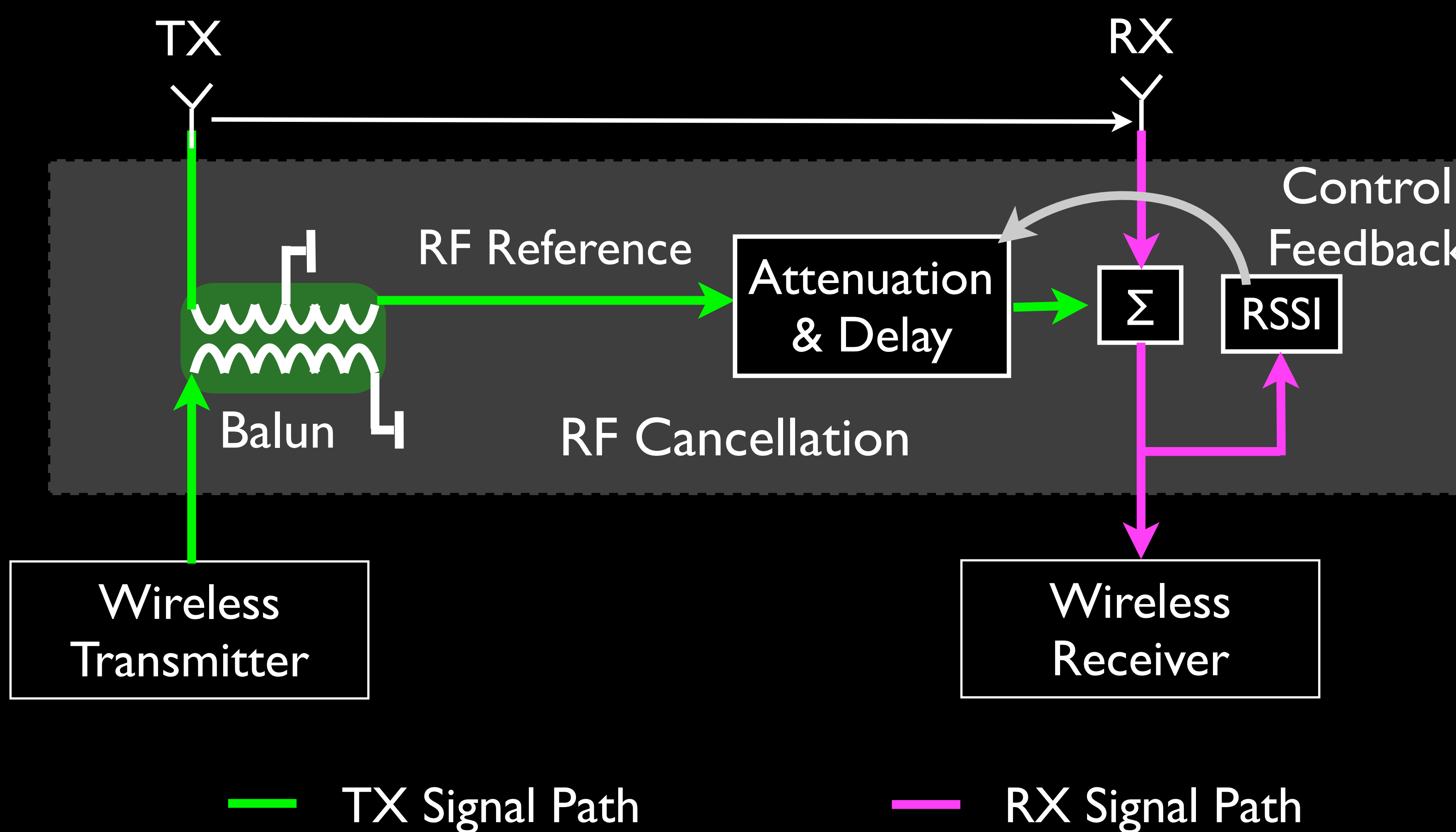
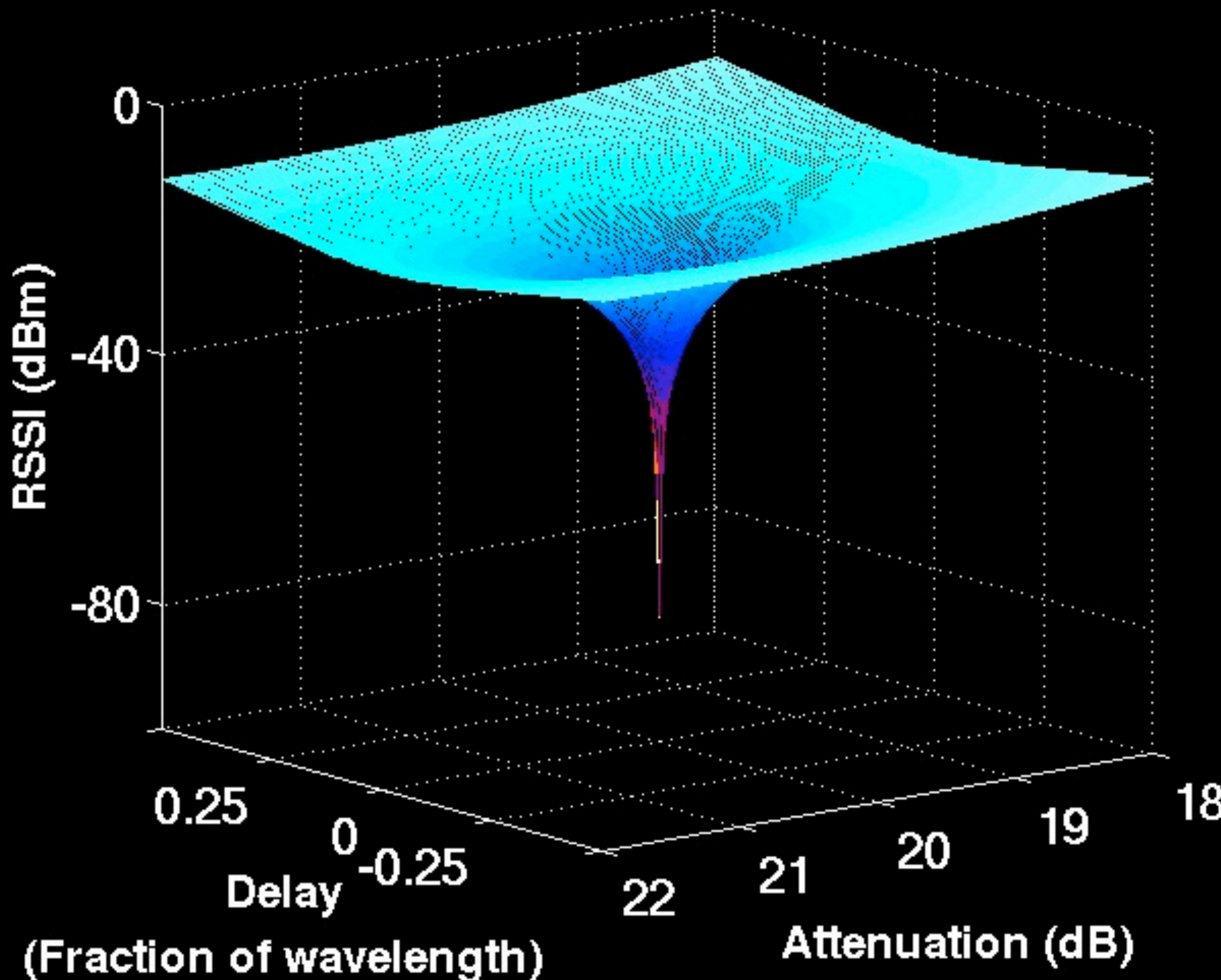
Use RSSI as an indicator of self-interference



Objective: Minimize received power

Control variables: Delay and Attenuation



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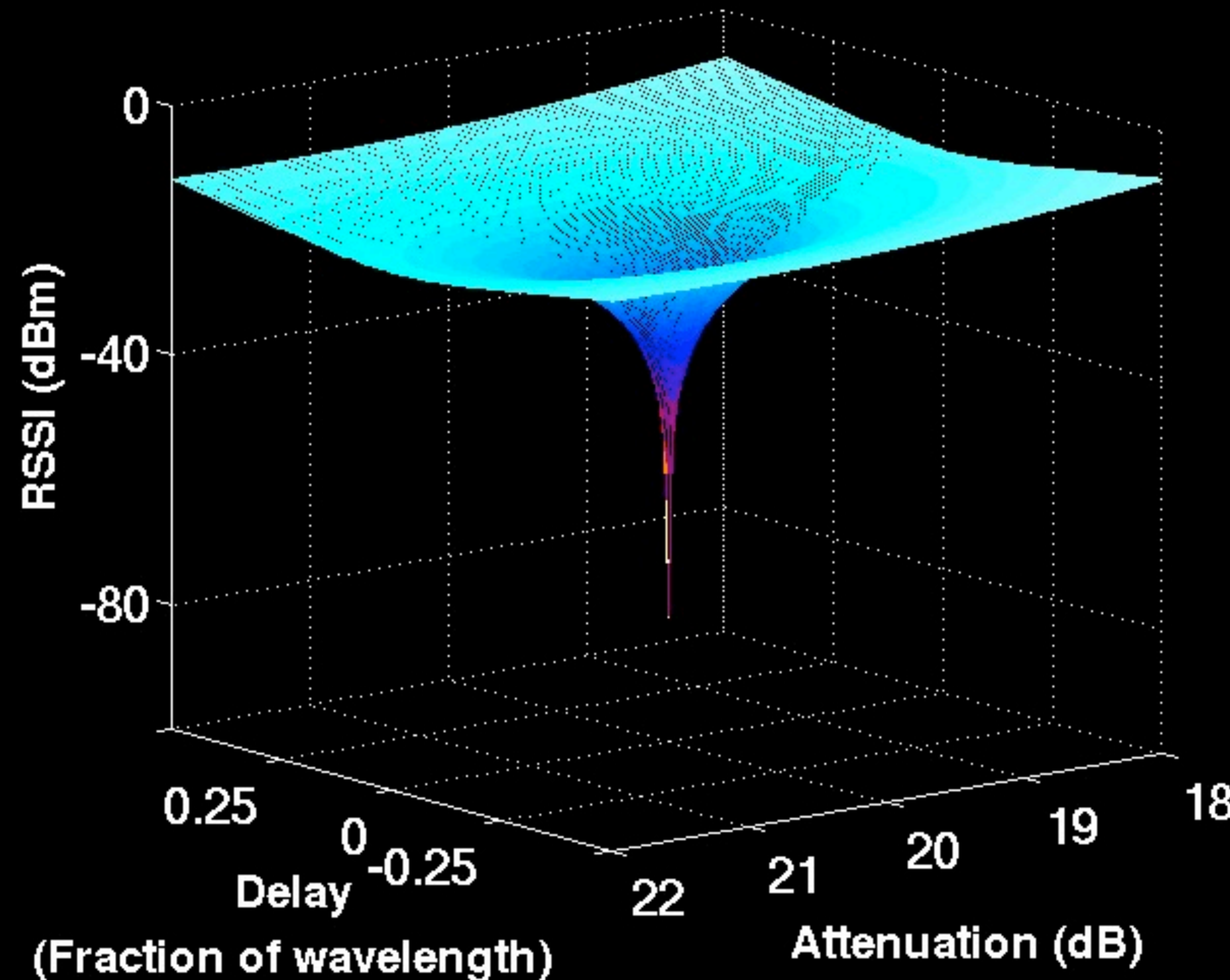
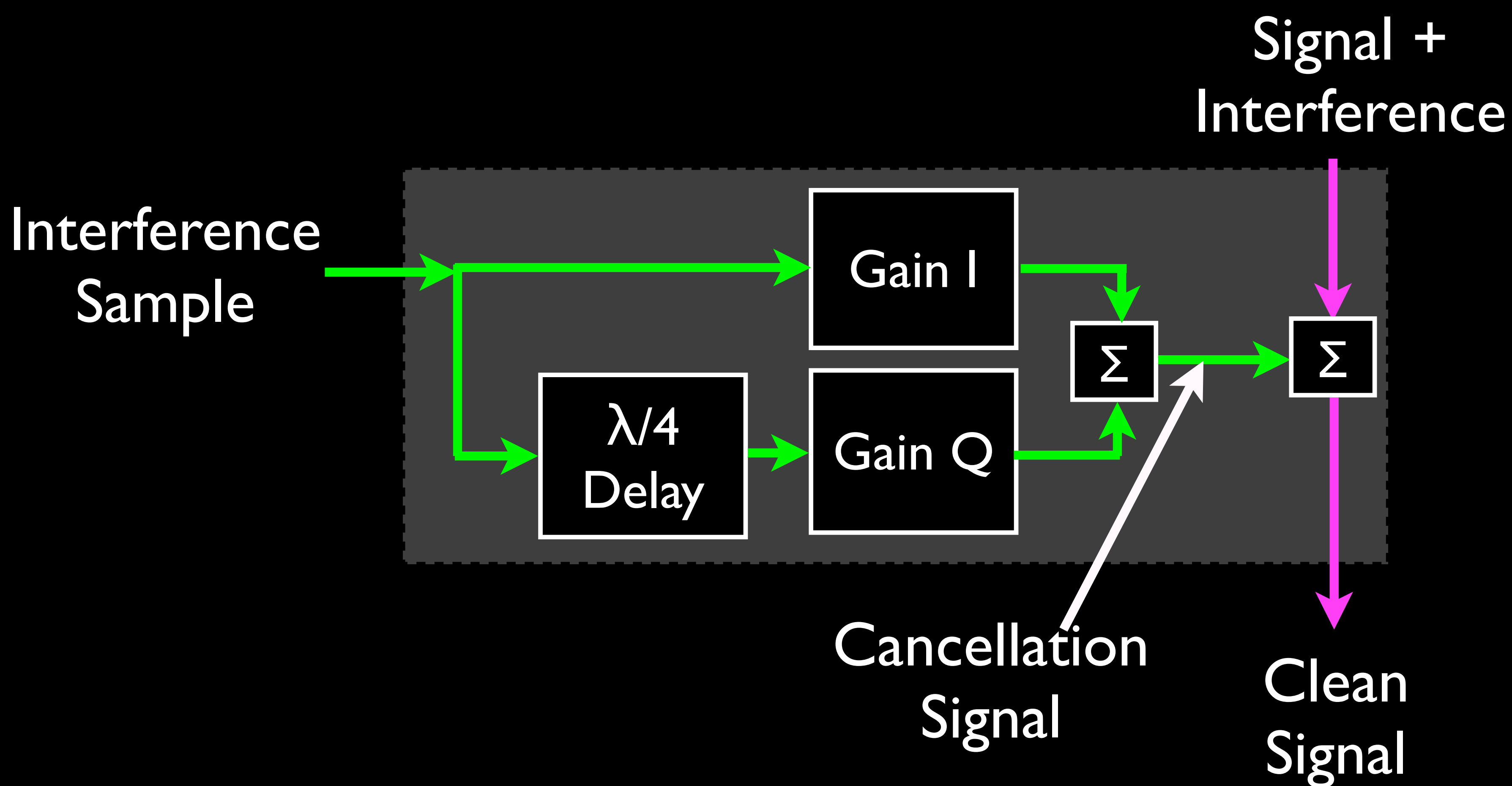


Objective: Minimize received power

Control variables: Delay and Attenuation

→ Simple gradient descent approach to optimize

Off-the-shelf electronically tunable hardware approximation: QHx220 noise canceler



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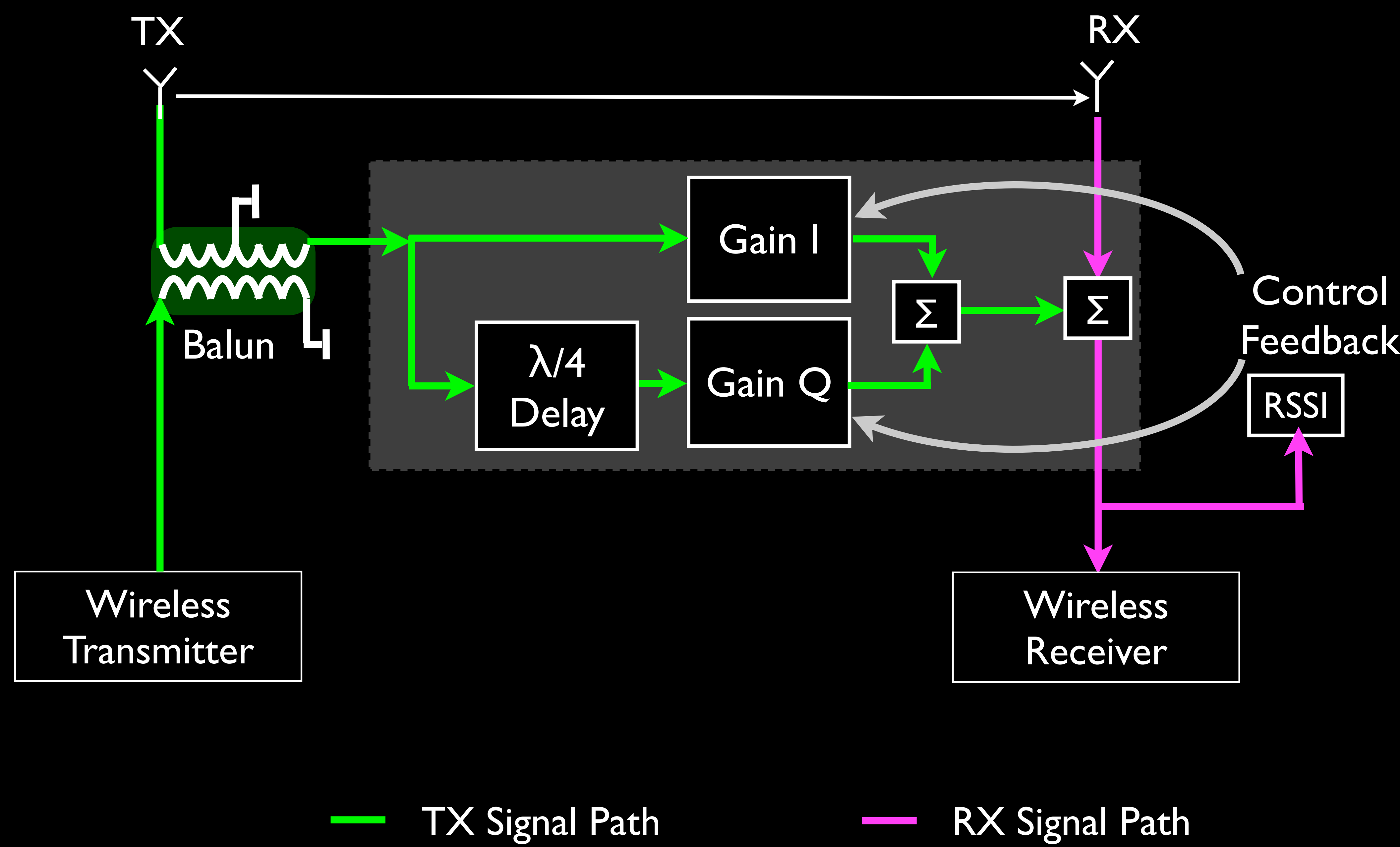

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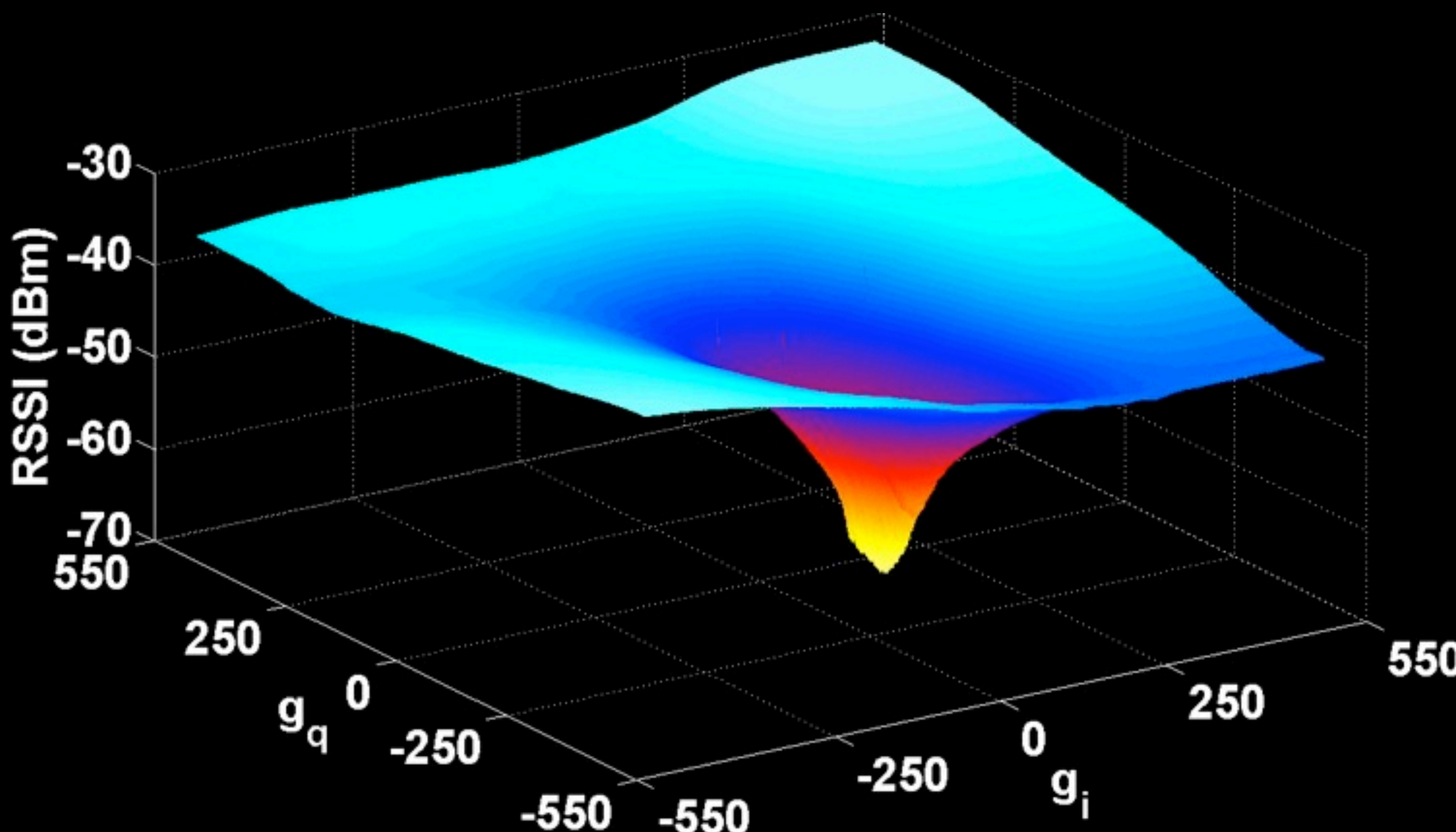
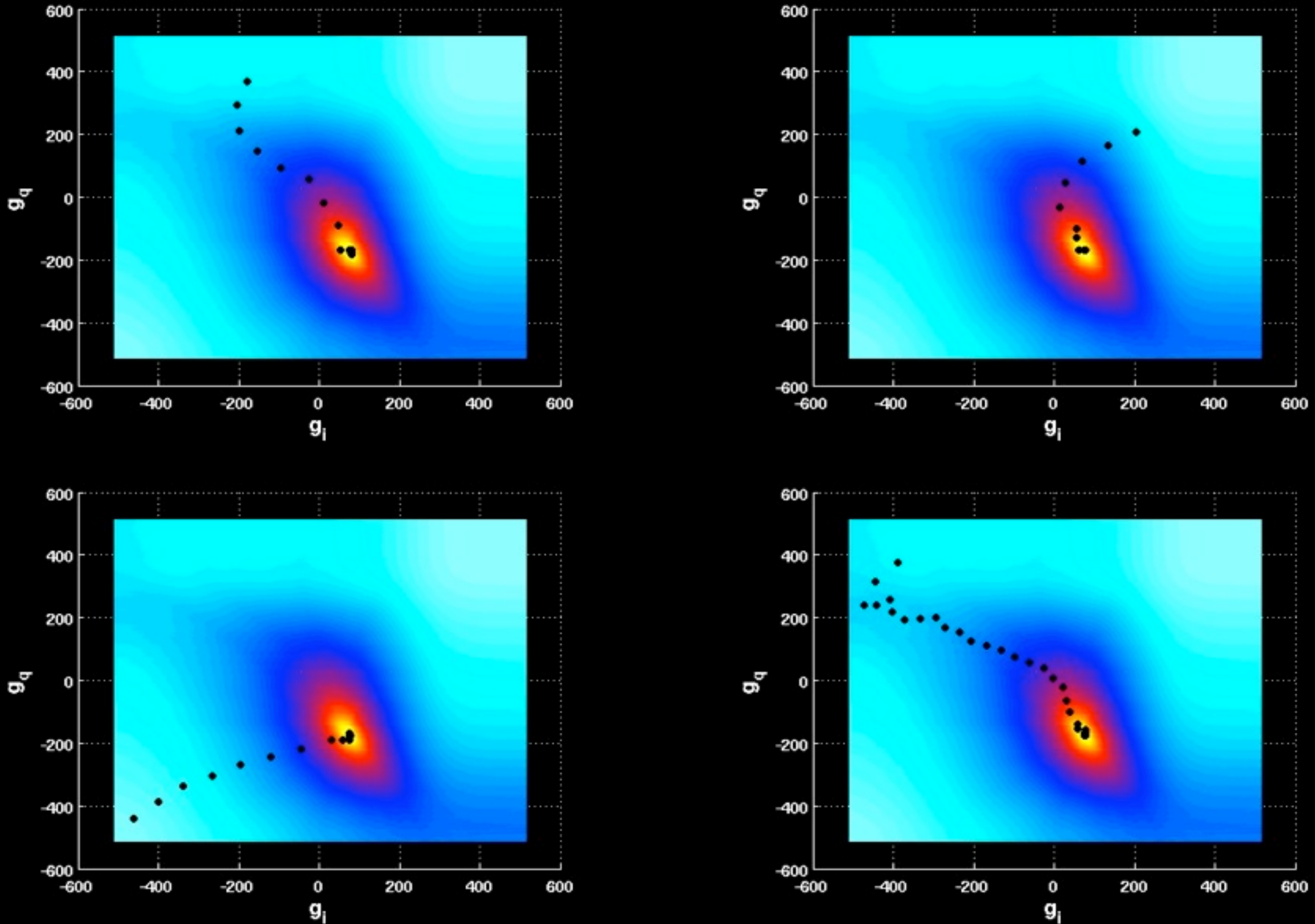




Typical convergence within 8-15 iterations (~1ms total)

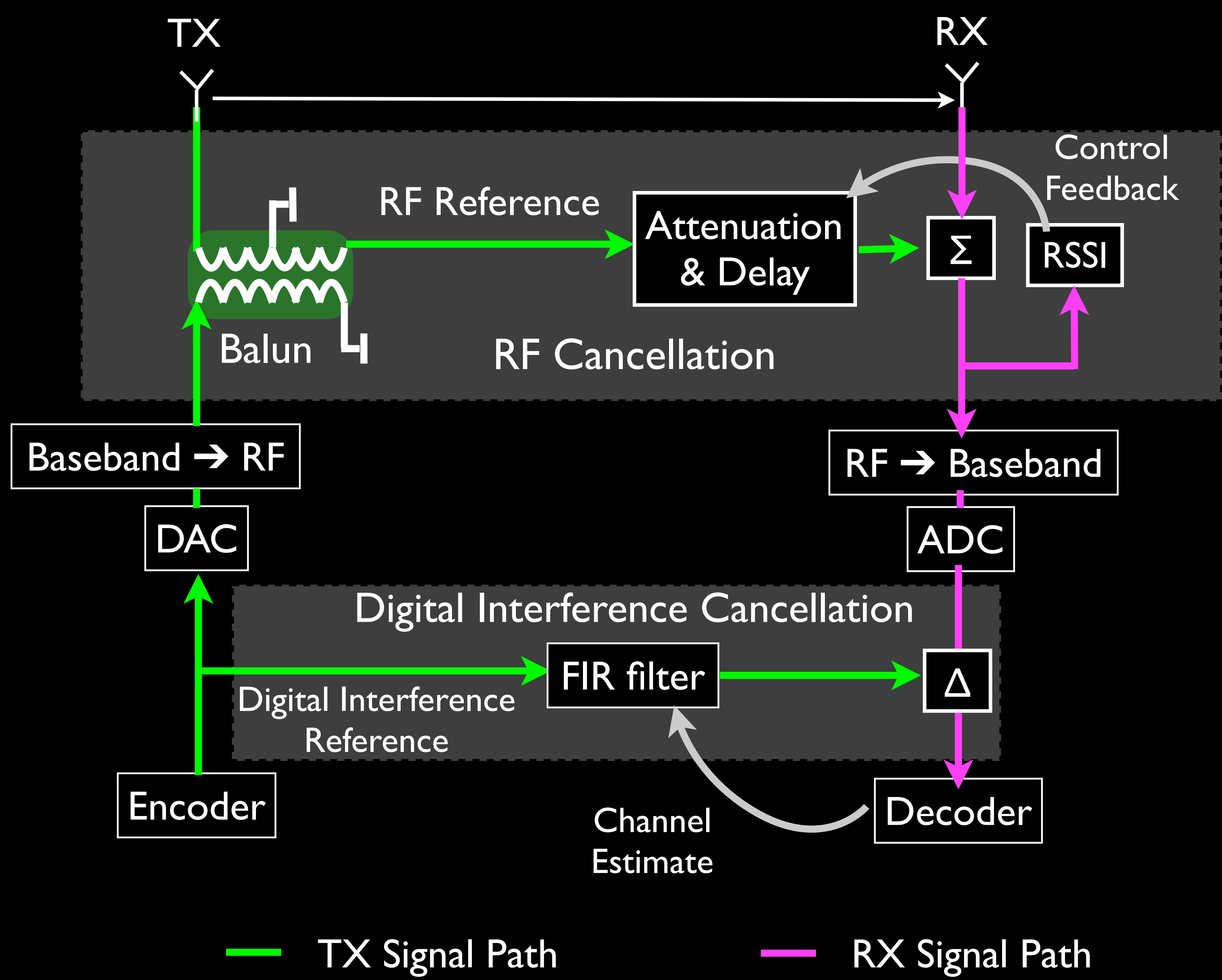
Talk Outline

- RF Design using Signal Inversion: ~50dB for 20Mhz
- Adaptive RF Cancellation: ~1ms convergence
- System Performance
- Implications to Wireless Networks
- Open Questions

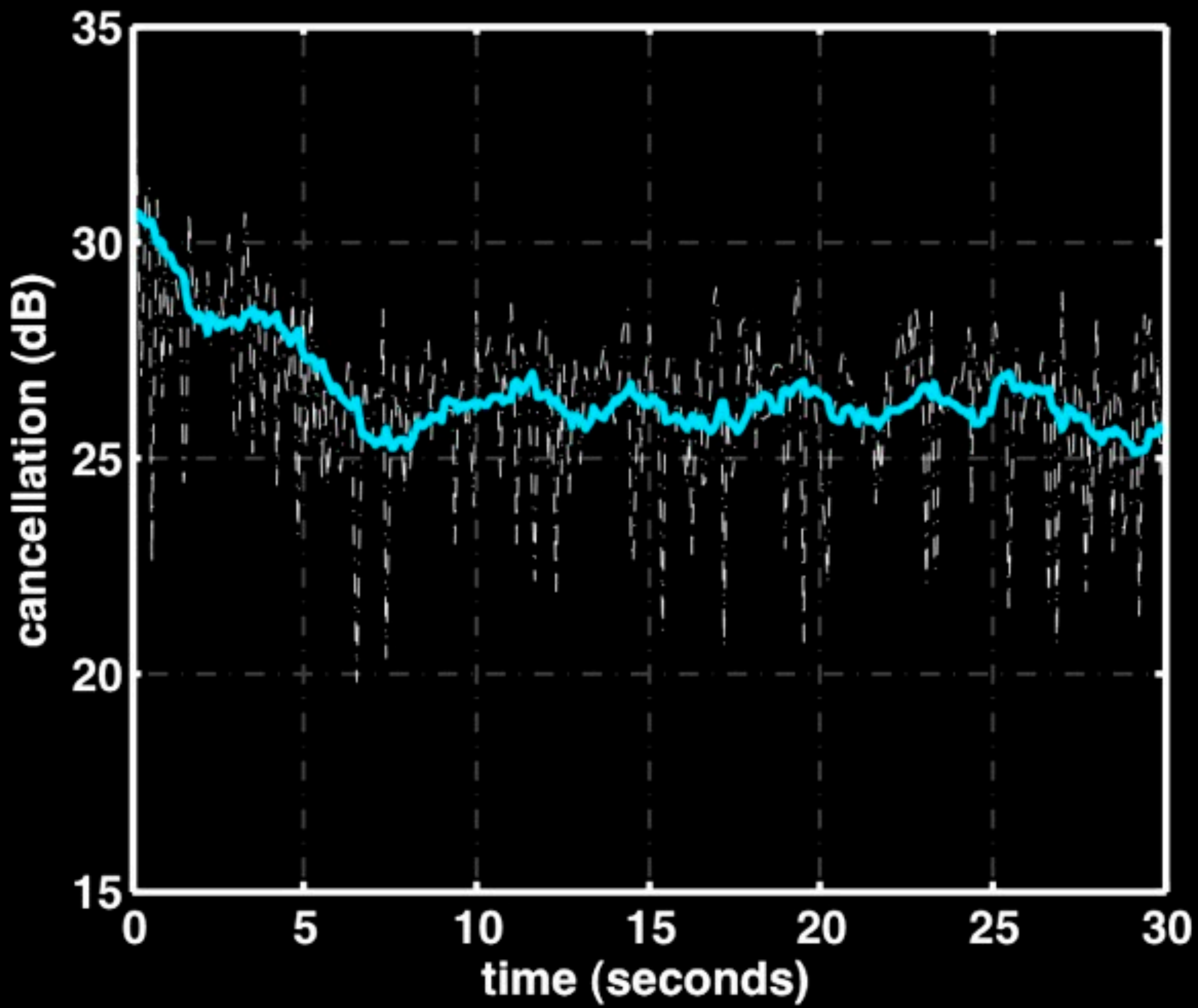
Digital Cancellation

- Measure residual self-interference after RF cancellation
- Subtract self-interference from received digital signal

Bringing It All Together



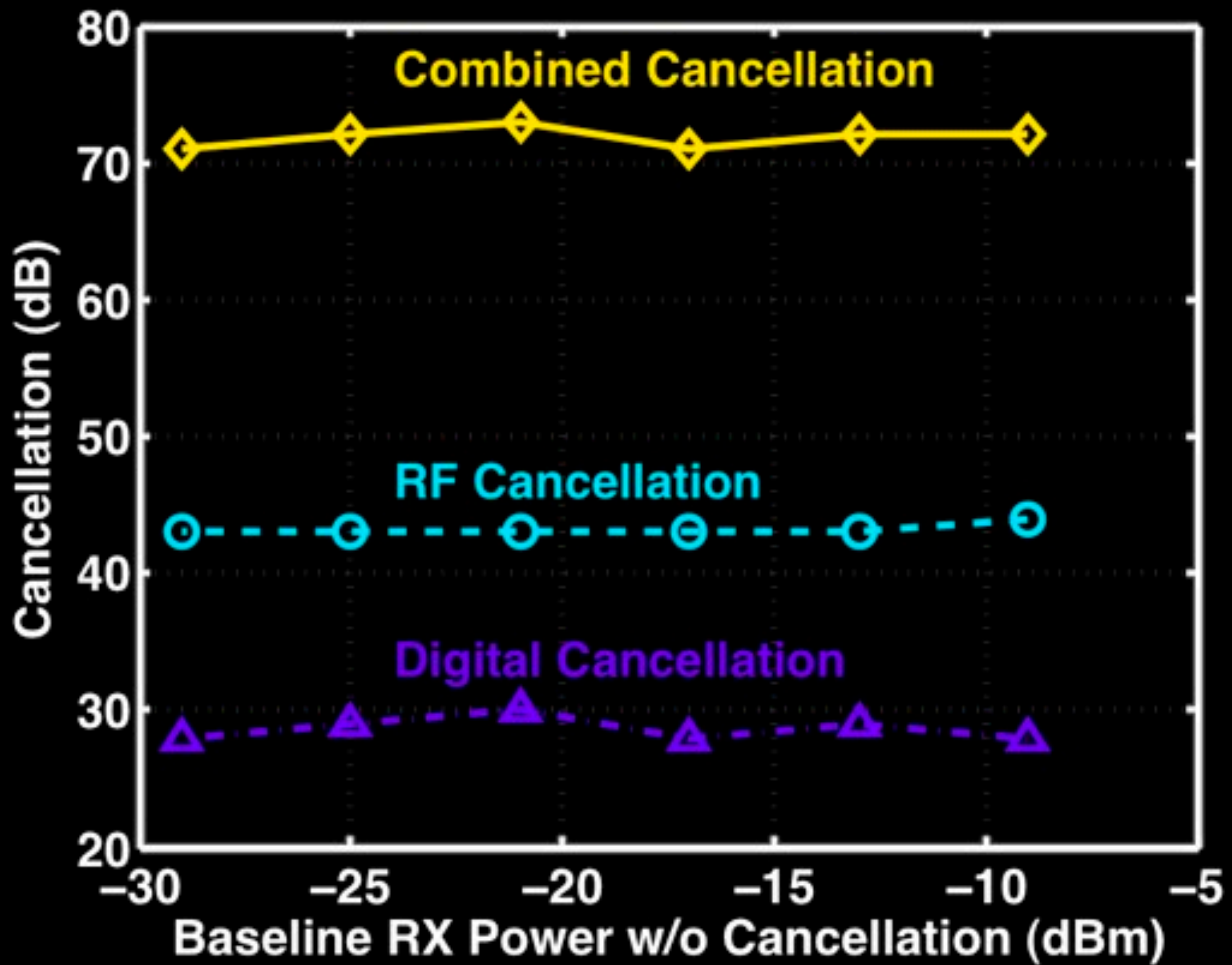
Channel Coherence



~3dB reduction in cancellation in 1-2 seconds

~6dB reduction in <10 seconds

Performance



- WiFi full-duplex: with reasonable antenna separation
- Not enough for cellular full-duplex: need 20dB more

Talk Outline

- RF Design using Signal Inversion: ~50dB for 20Mhz
- Adaptive RF Cancellation: ~1ms convergence
- System Performance: ~73dB cancellation
- Implications to Wireless Networks
- Open Questions

Implications to Wireless Networks

- Breaks a basic assumption in wireless
- Can solve some fundamental problems with wireless networks today[1,2]
  - Hidden terminals
  - Network congestion and WLAN fairness

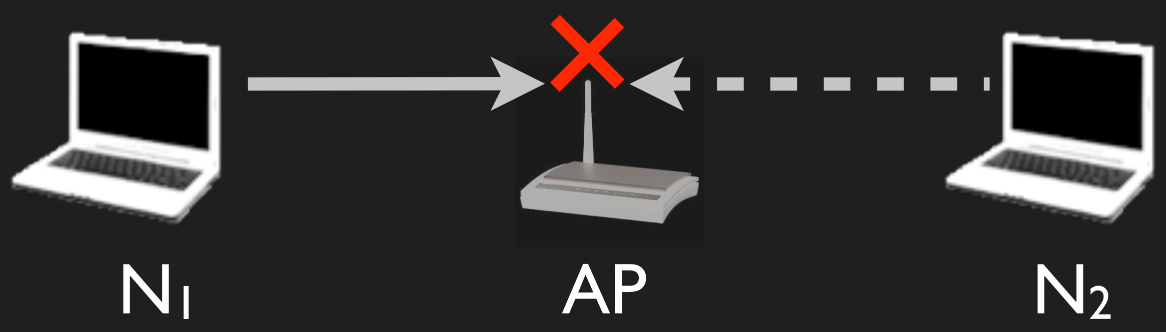
[1] Choi et al. "Achieving single channel, full duplex wireless communication", in Mobicom 2010
[2] Singh et al. "Efficient and Fair MAC for Wireless Networks with Self-interference Cancellation", in WiOpt 2011

Implementation

- WARPv2 boards with 2 radios
- OFDM reference code from Rice University
  - 10MHz bandwidth OFDM signaling
  - CSMA MAC on embedded processor
- Modified for full-duplex

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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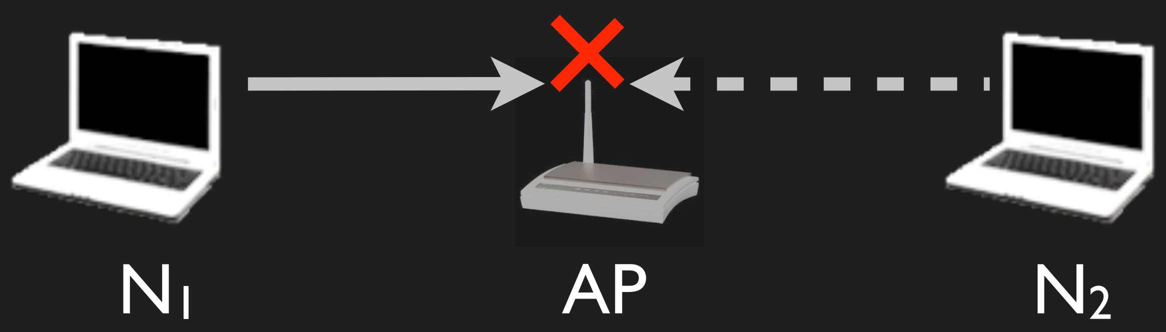

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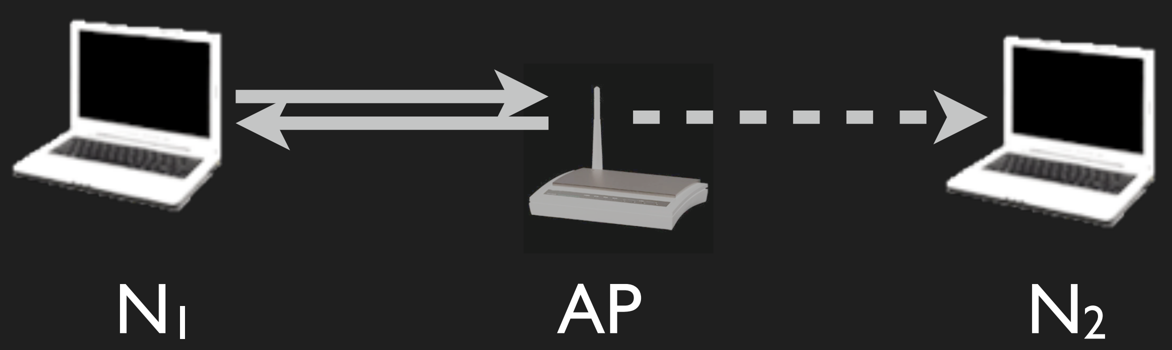
Full Duplex solves hidden terminals



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

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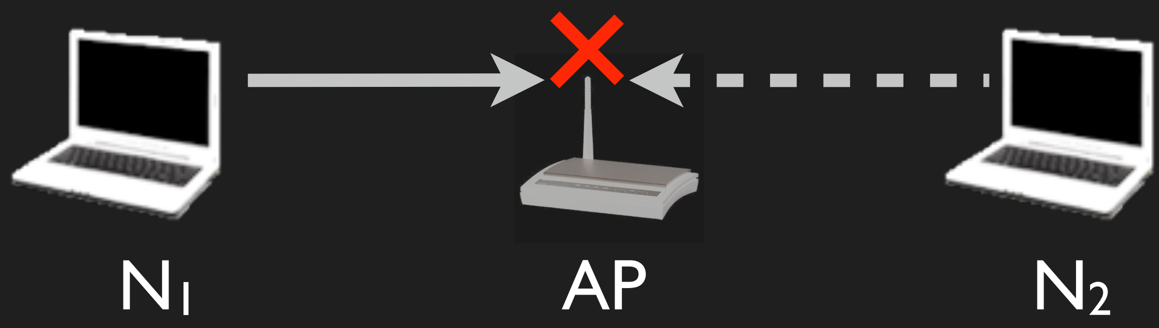

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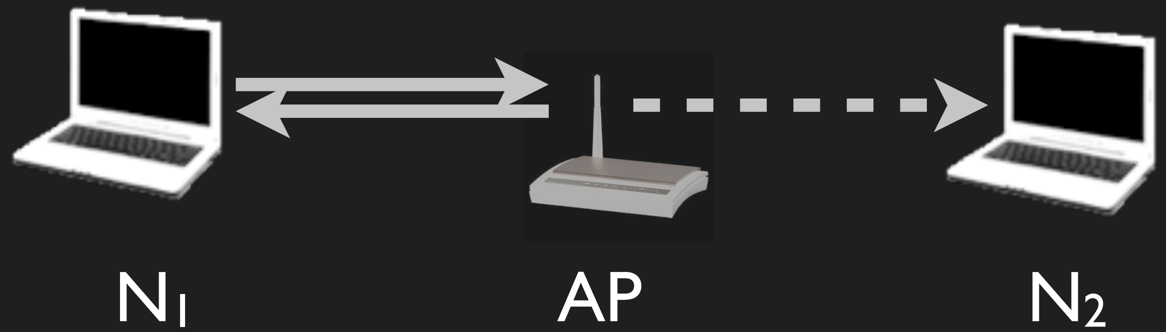

Since both sides transmit at the same time, no hidden terminals exist

Reduces hidden terminal losses by up to 88%

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

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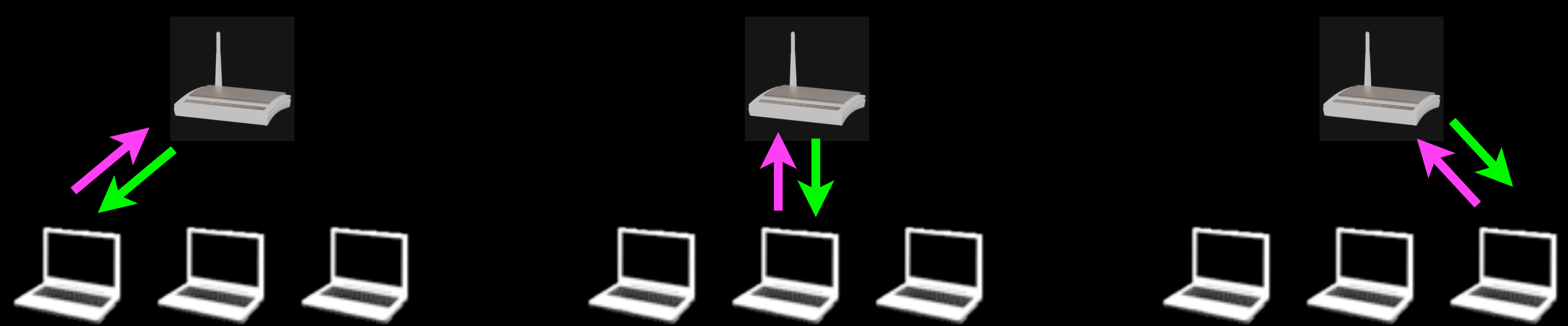


With full-duplex:

- AP sends and receives at the same time

Downlink Throughput = 1   Uplink Throughput = 1

Network Congestion and WLAN Fairness

1 AP with 4 stations without any hidden terminals

	Throughput (Mbps)		Fairness (JFI)
	Upstream	Downstream	
Half-Duplex	5.18	2.36	0.845
Full-Duplex	5.97	4.99	0.977

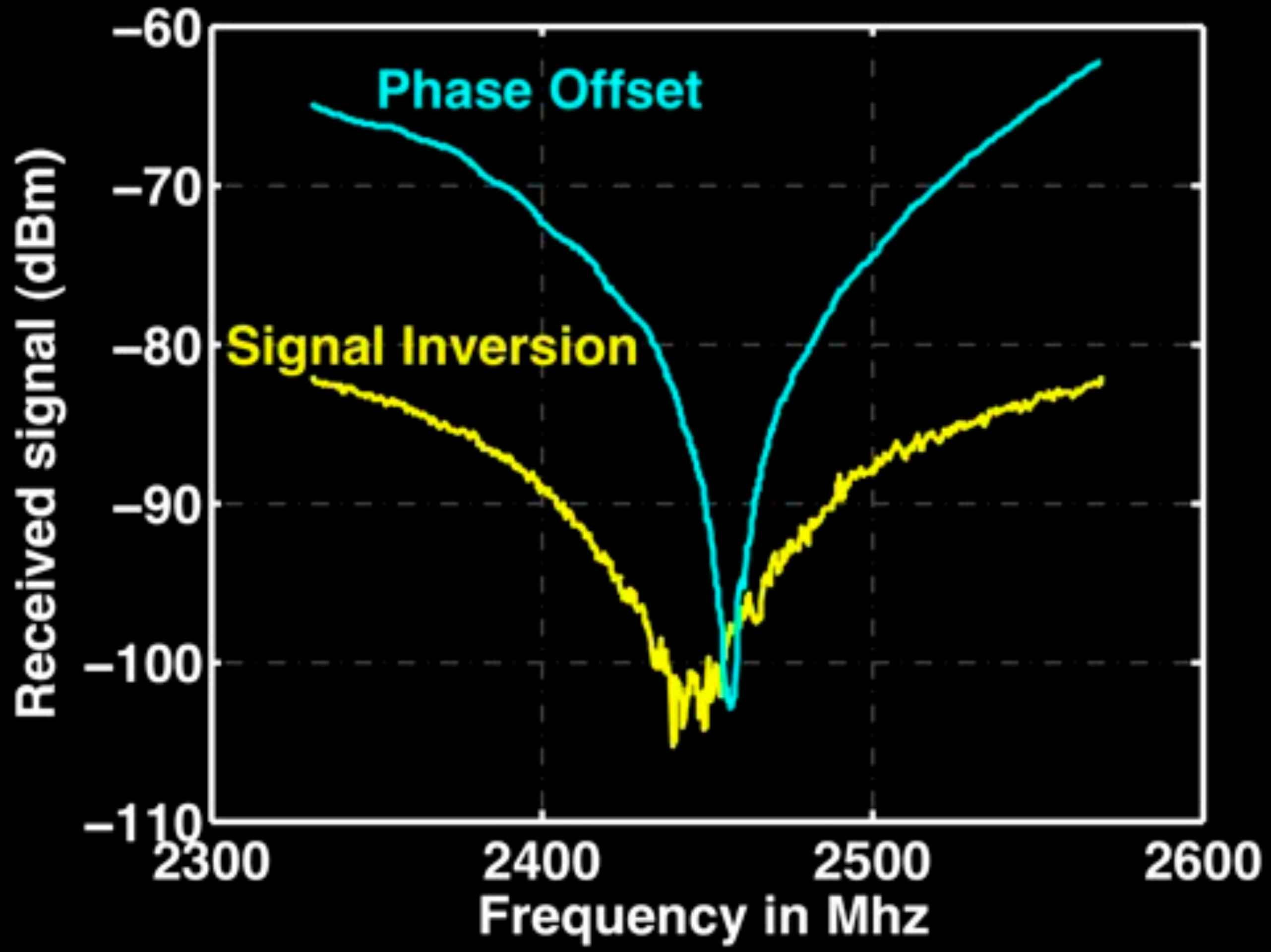
Full-duplex distributes its performance gain to improve fairness

Talk Outline

- RF Design using Signal Inversion: ~50dB for 20Mhz
- Adaptive RF Cancellation: ~1ms convergence
- System Performance: ~73dB cancellation
- Implications to Wireless Networks: Collisions, Fairness
- Open Questions

Improving Full-duplex

- Non-linear channel response



Improving Full-duplex

- Non-linear channel response
  Reduce distortion: feedforward amplifiers

Improving Full-duplex

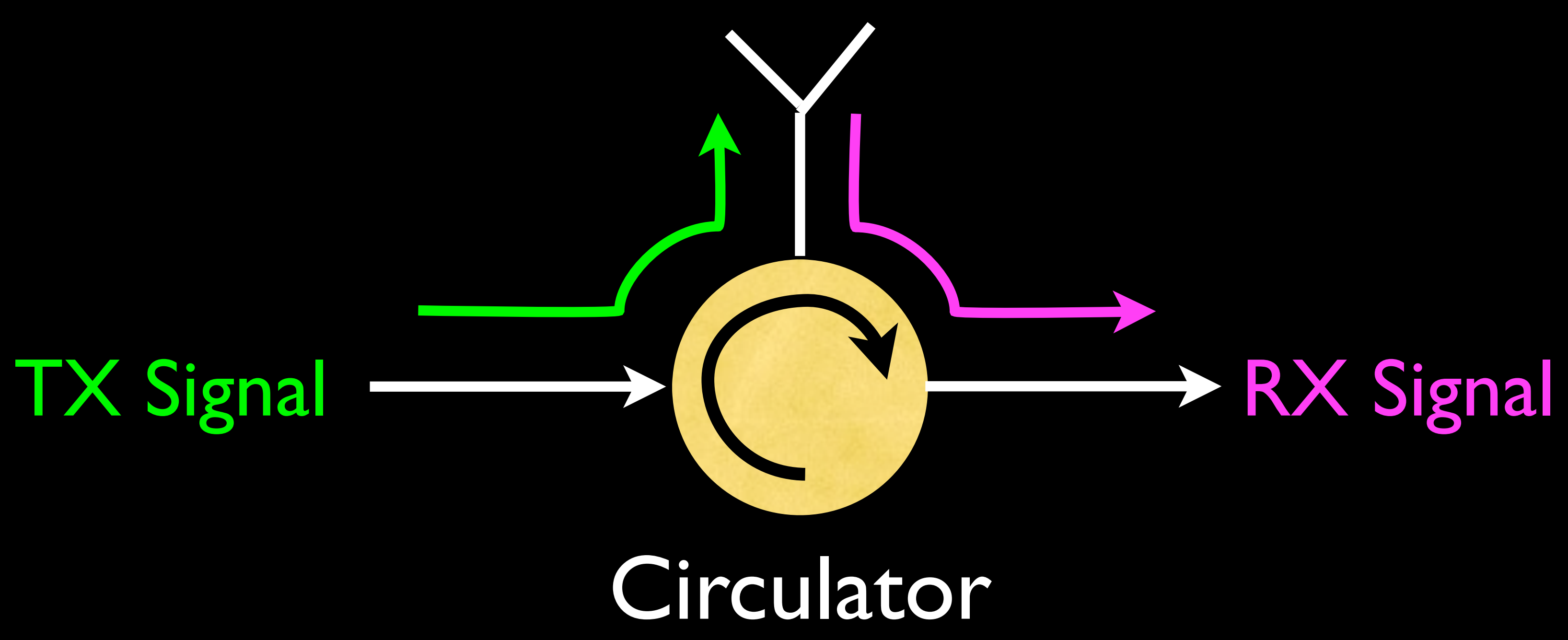
- Non-linear channel response

  Reduce distortion: feedforward amplifiers

  Compensate: non-linear digital cancellation

Improving Full-duplex

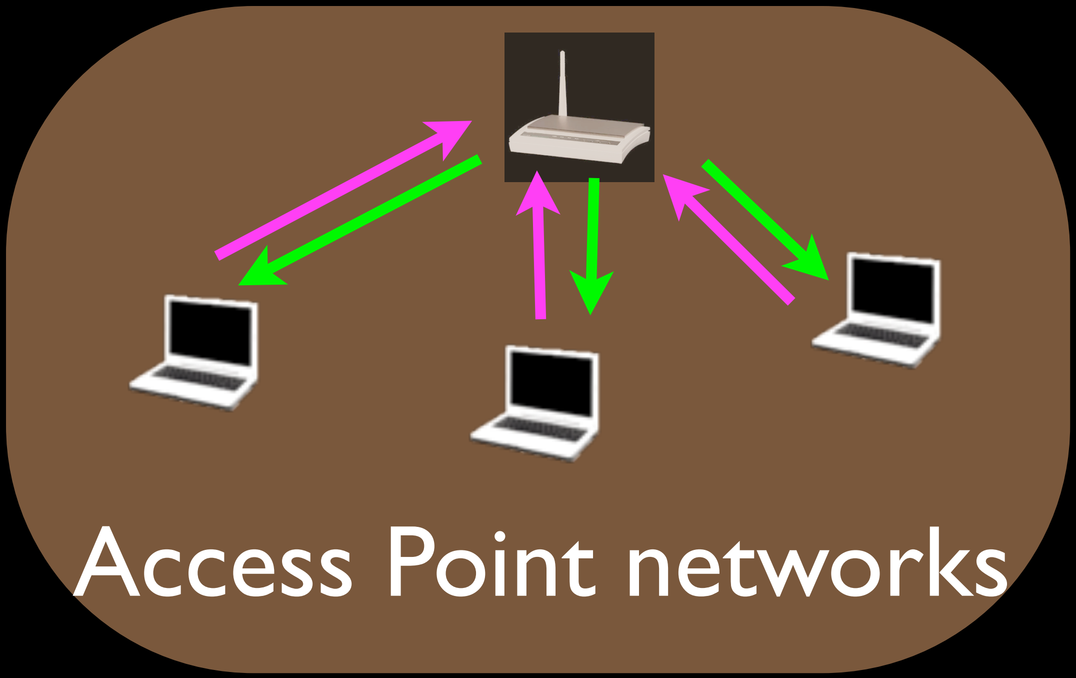
- Non-linear channel response
  Reduce distortion: feedforward amplifiers
  Compensate: non-linear digital cancellation
- Single antenna solution: circulators



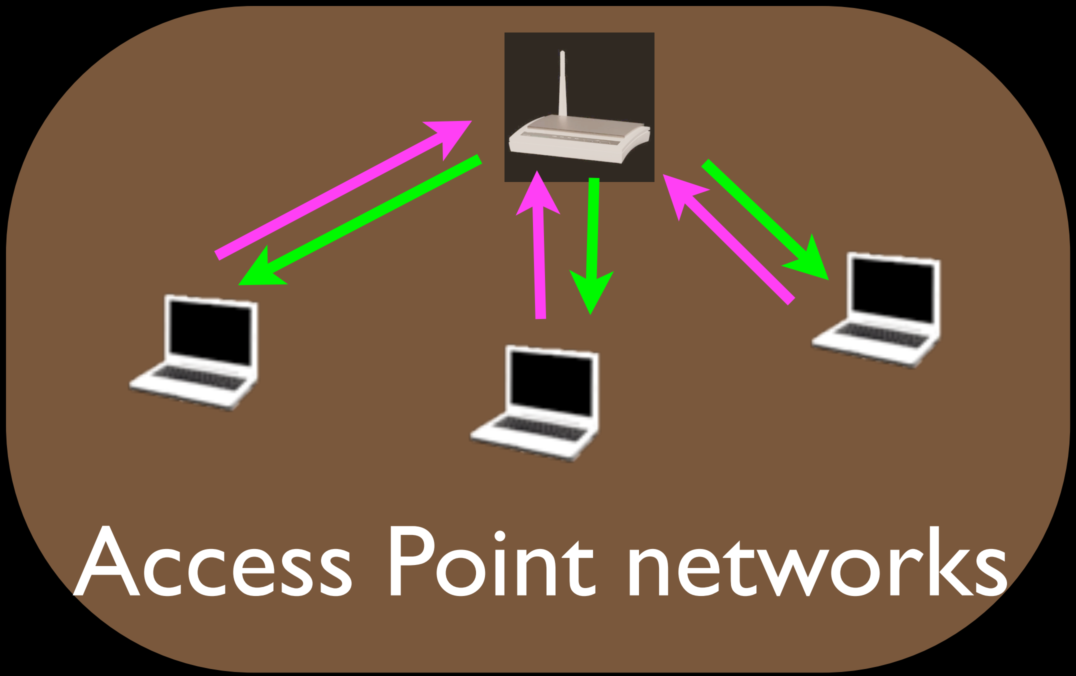
Improving Full-duplex

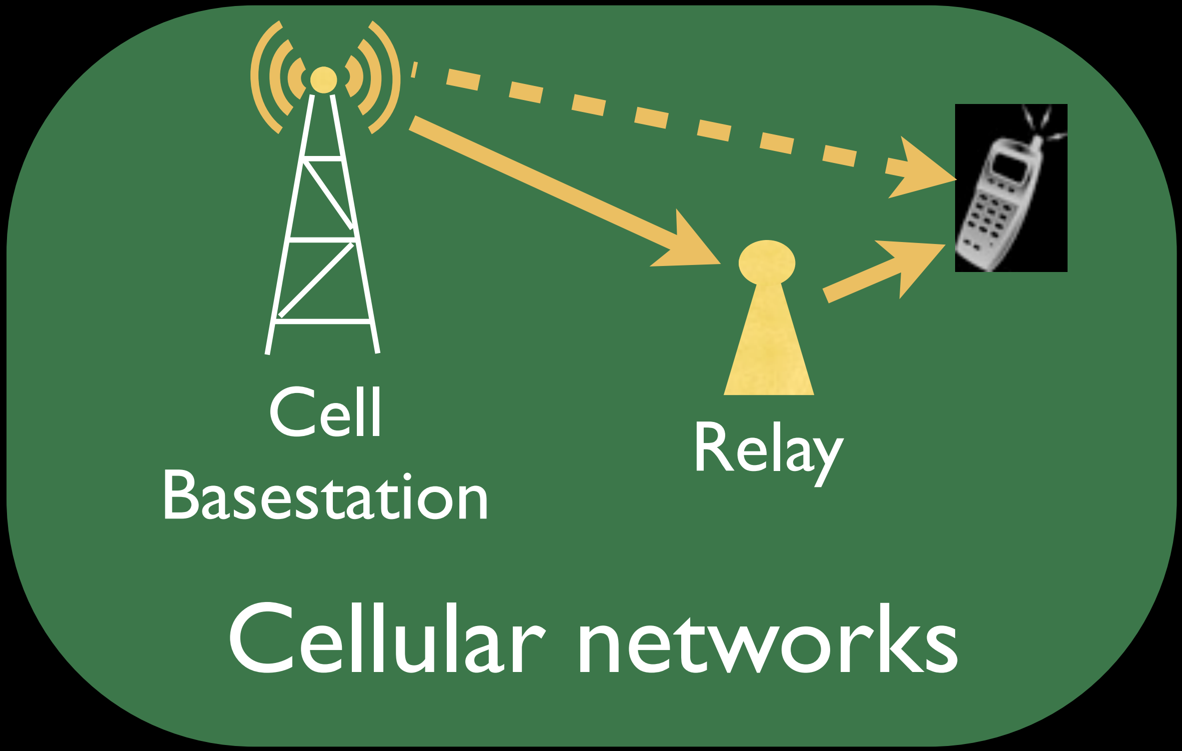
- Non-linear channel response
  Reduce distortion: feedforward amplifiers
  Compensate: non-linear digital cancellation
- Single antenna solution: circulators
- MIMO full-duplex

Full-duplex Networking



Full-duplex Networking





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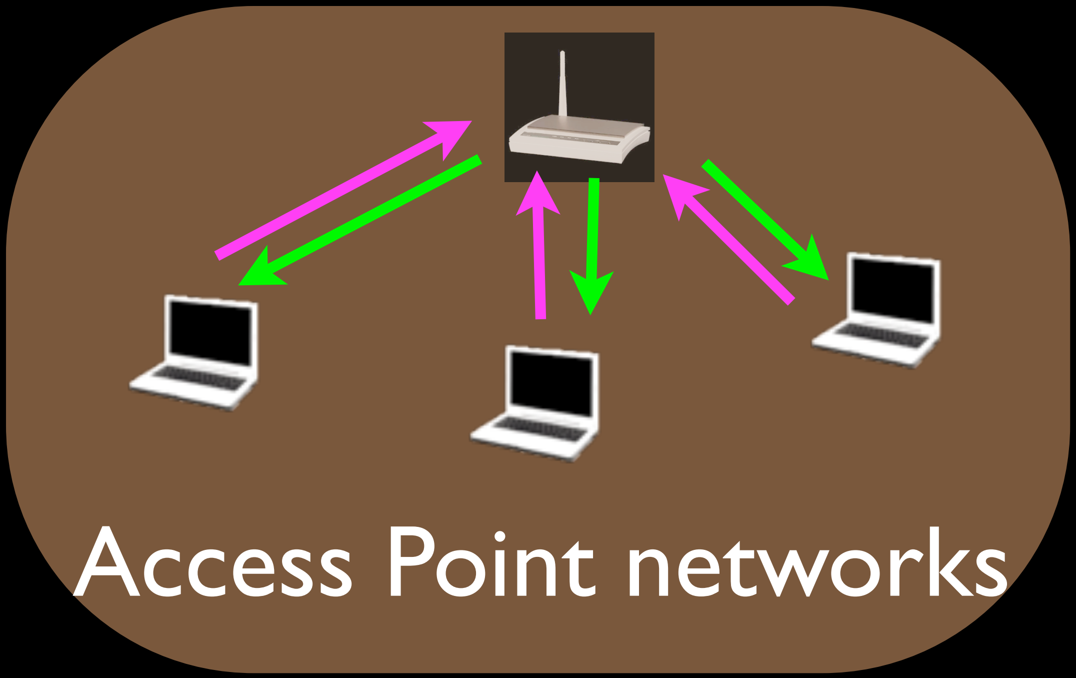

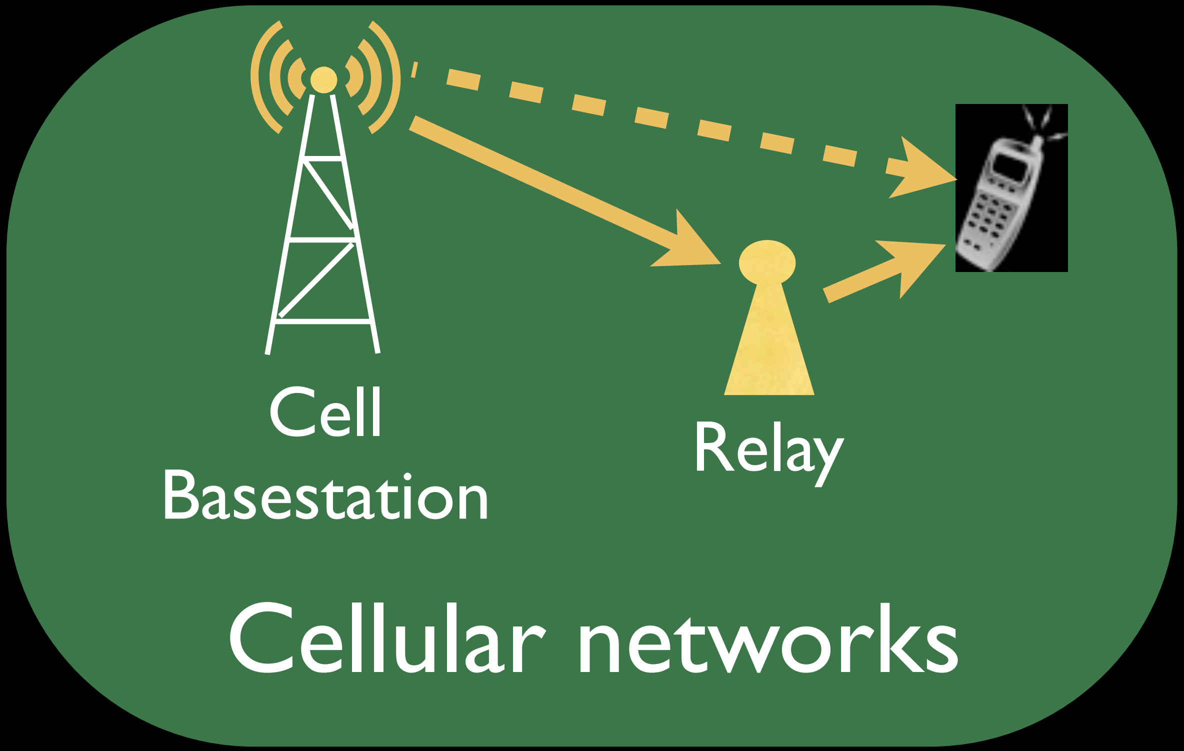

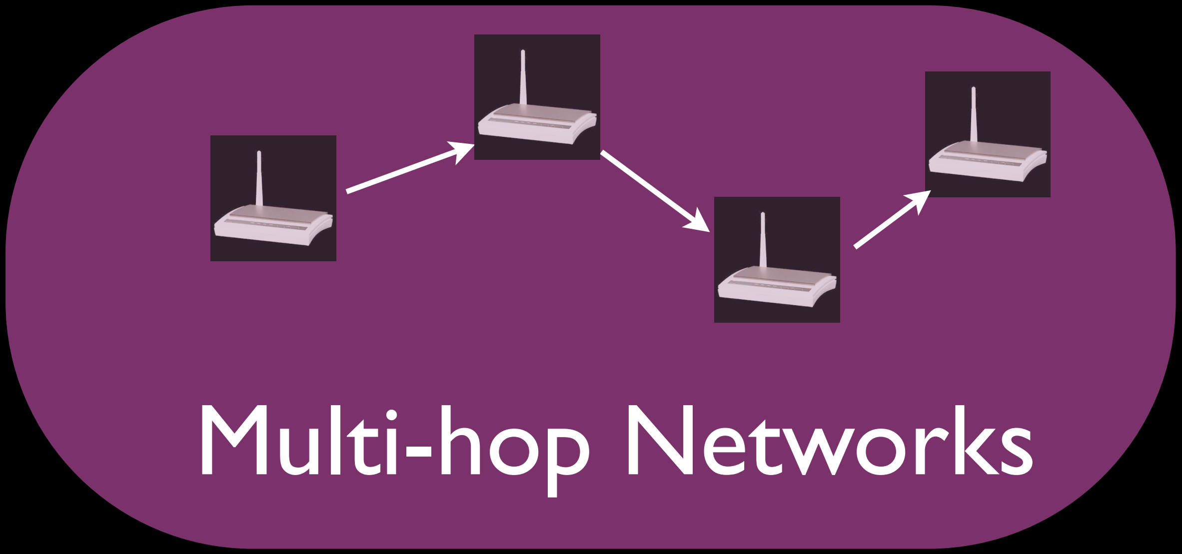

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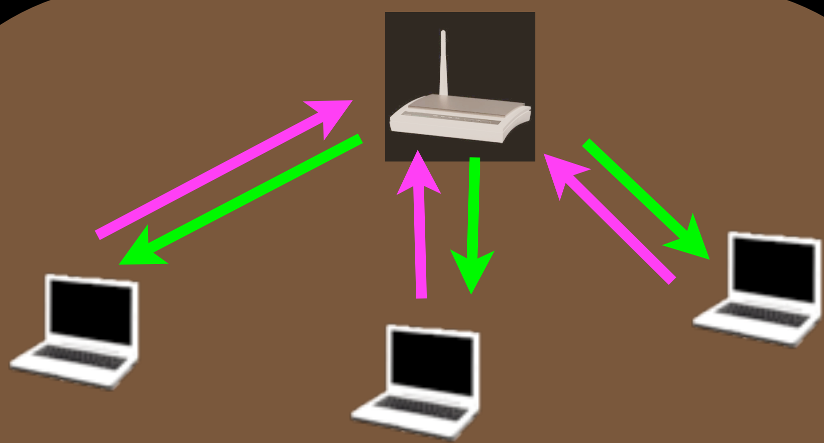
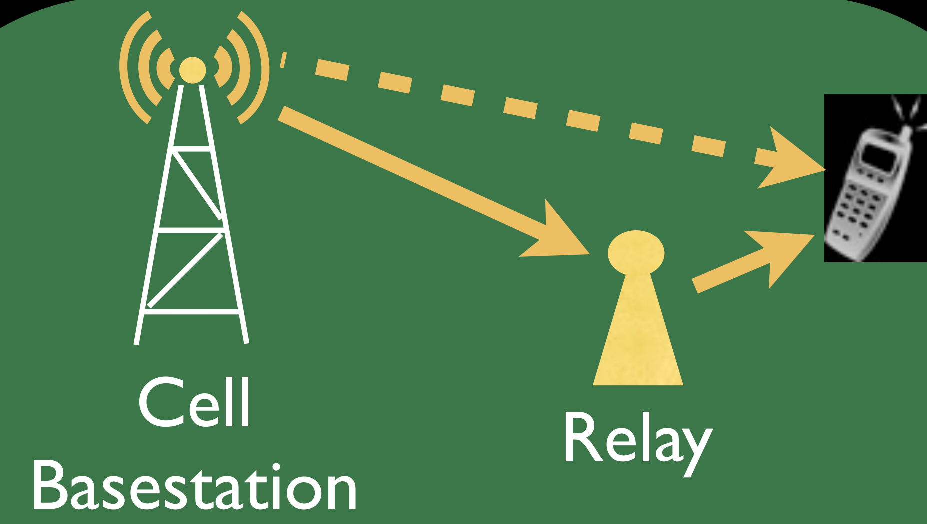
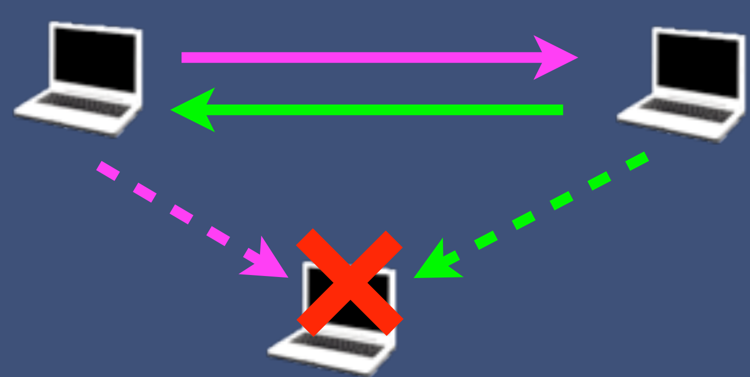


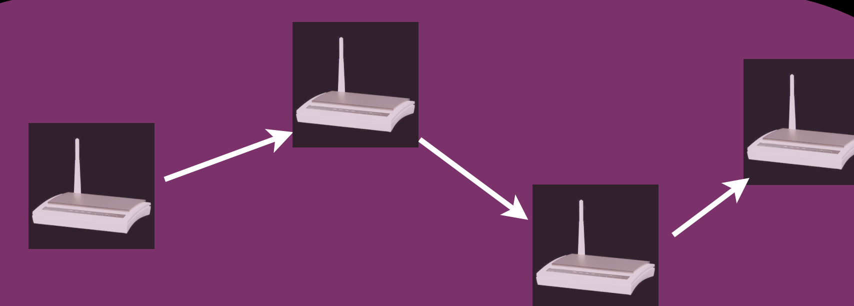
Access Point networks



Cellular networks



Secure Networks[1,2]

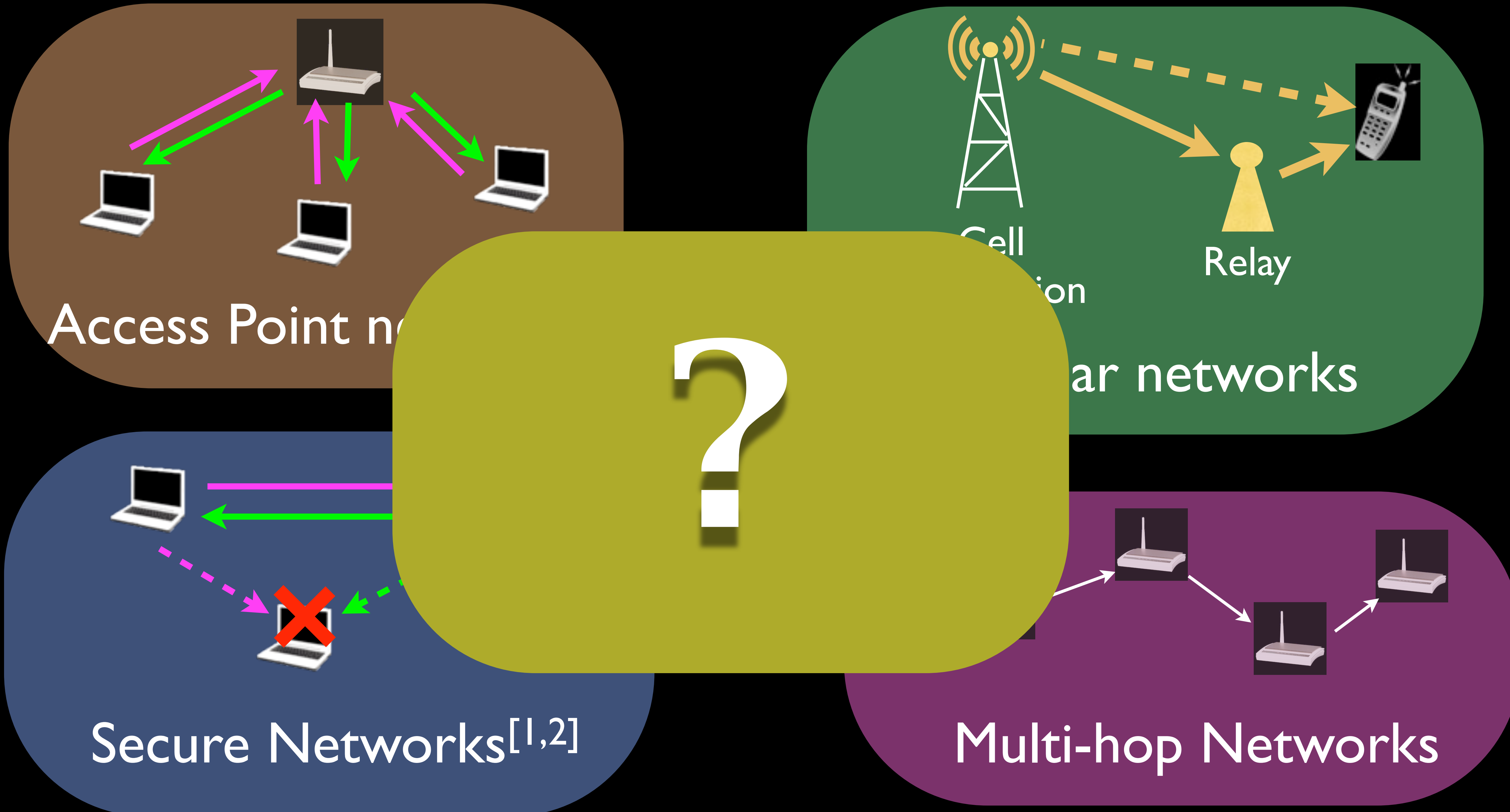


Multi-hop Networks

[1] Gollakota et al. "They Can Hear Your Heartbeats: Non-Invasive Security for Implantable Medical Devices.", in Sigcomm 2011.

[2] Lee et al. "Secured Bilateral Rendezvous using Self-interference Cancellation in Wireless Networks", in IFIP 2011.

Full-duplex Networking



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Summary

- Design for real-time full-duplex wireless
  - Makes full-duplex WiFi possible
  - Still some way to go for full-duplex cellular
- Made practical using adaptive techniques
- Rethinking of wireless networks
  - WiFi: hidden terminals and fairness
  - Many more possibilities

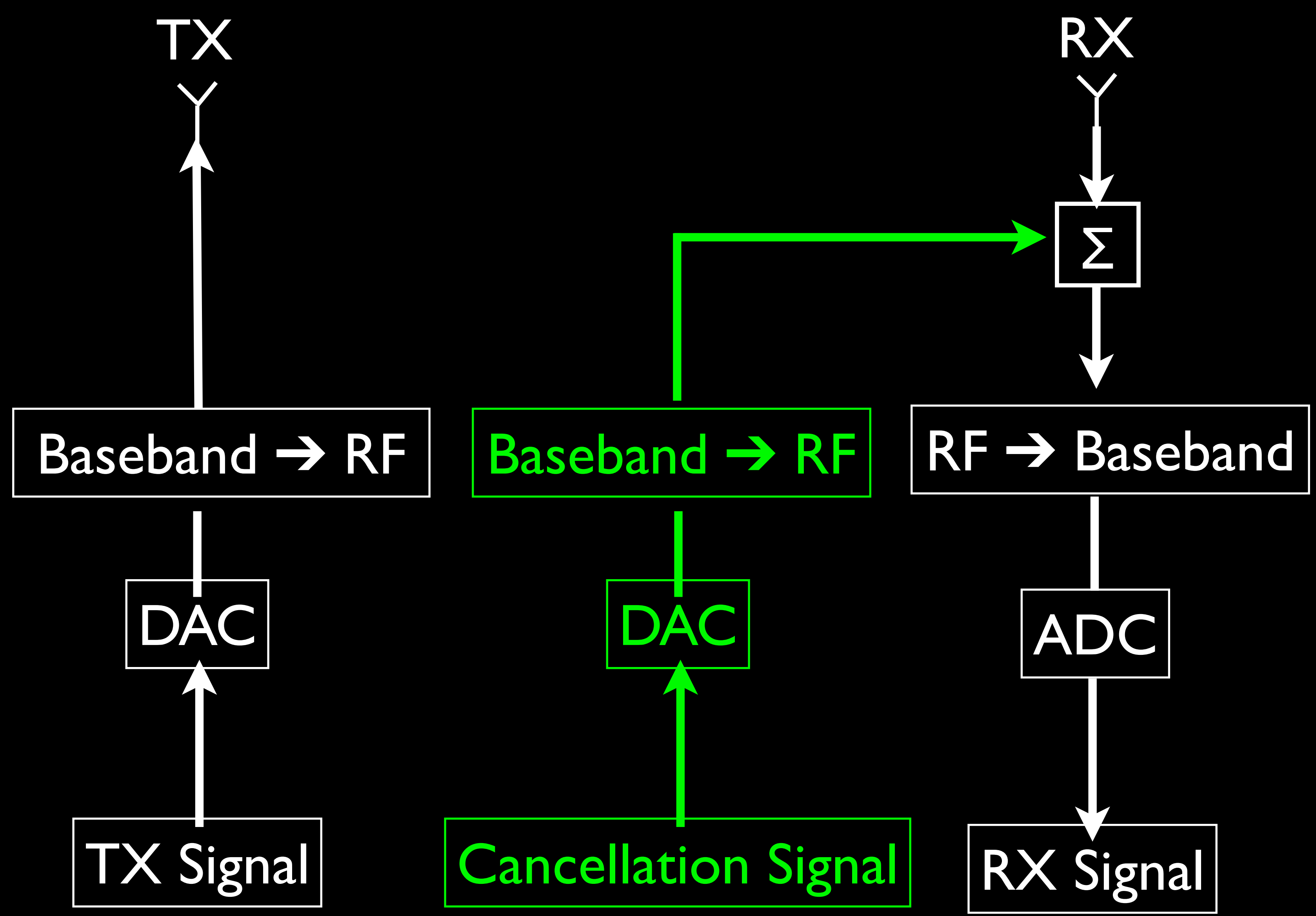
Thank You

Questions?

Backup

- Other cancellation techniques

  Digital estimation for RF cancellation[1]



[1] Duarte et al. "Full-Duplex Wireless Communications Using Off-The-Shelf Radios: Feasibility and First Results.", in Asilomar 2010.

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- Adaptive RF Cancellation: ~1ms convergence
- Adaptive Digital Cancellation
- System Performance
- Implications to Wireless Networks
- Looking Forward

Digital Cancellation

- Create a precise "digital replica" of the self-interference signal using TX digital samples
- Subtract self-interference replica from received digital signal

Requires ADC not saturated: RF cancellation

OFDM processing

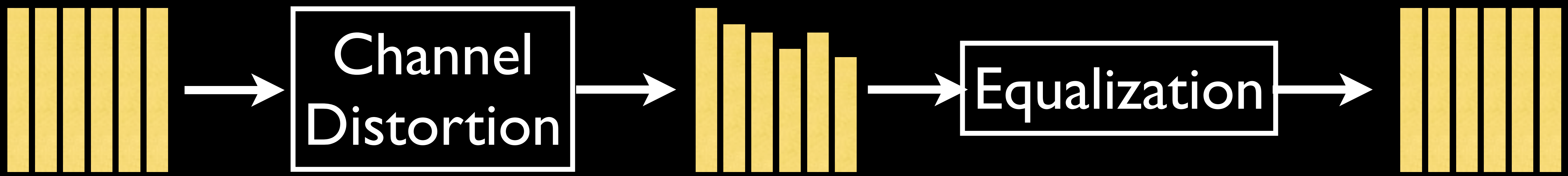
Signal Band

OFDM processing

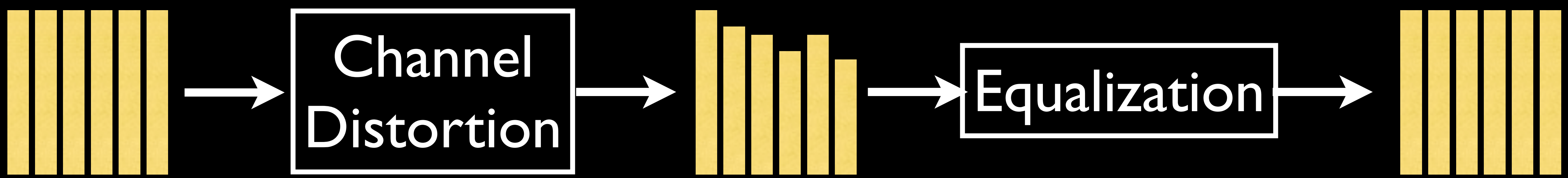
Sub-bands

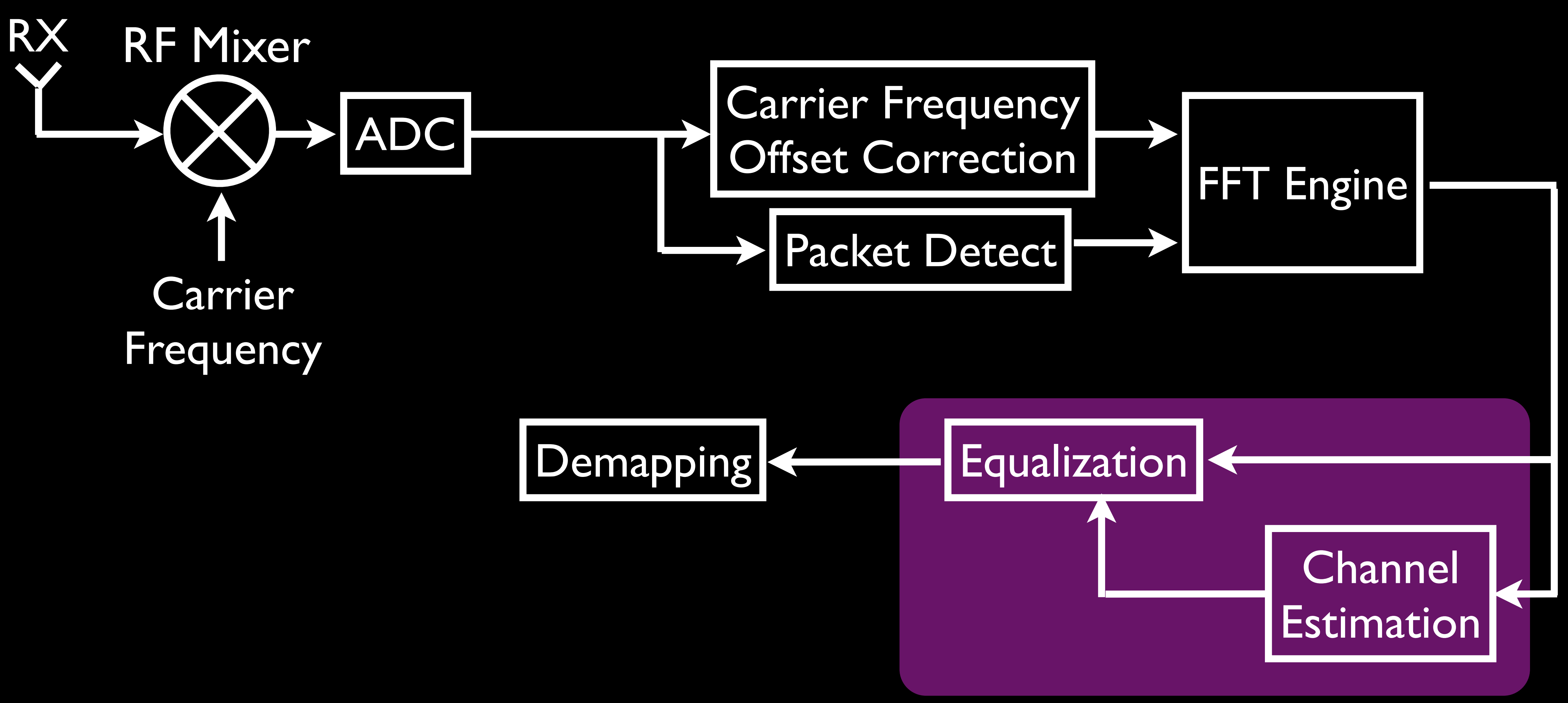
OFDM processing

OFDM processing

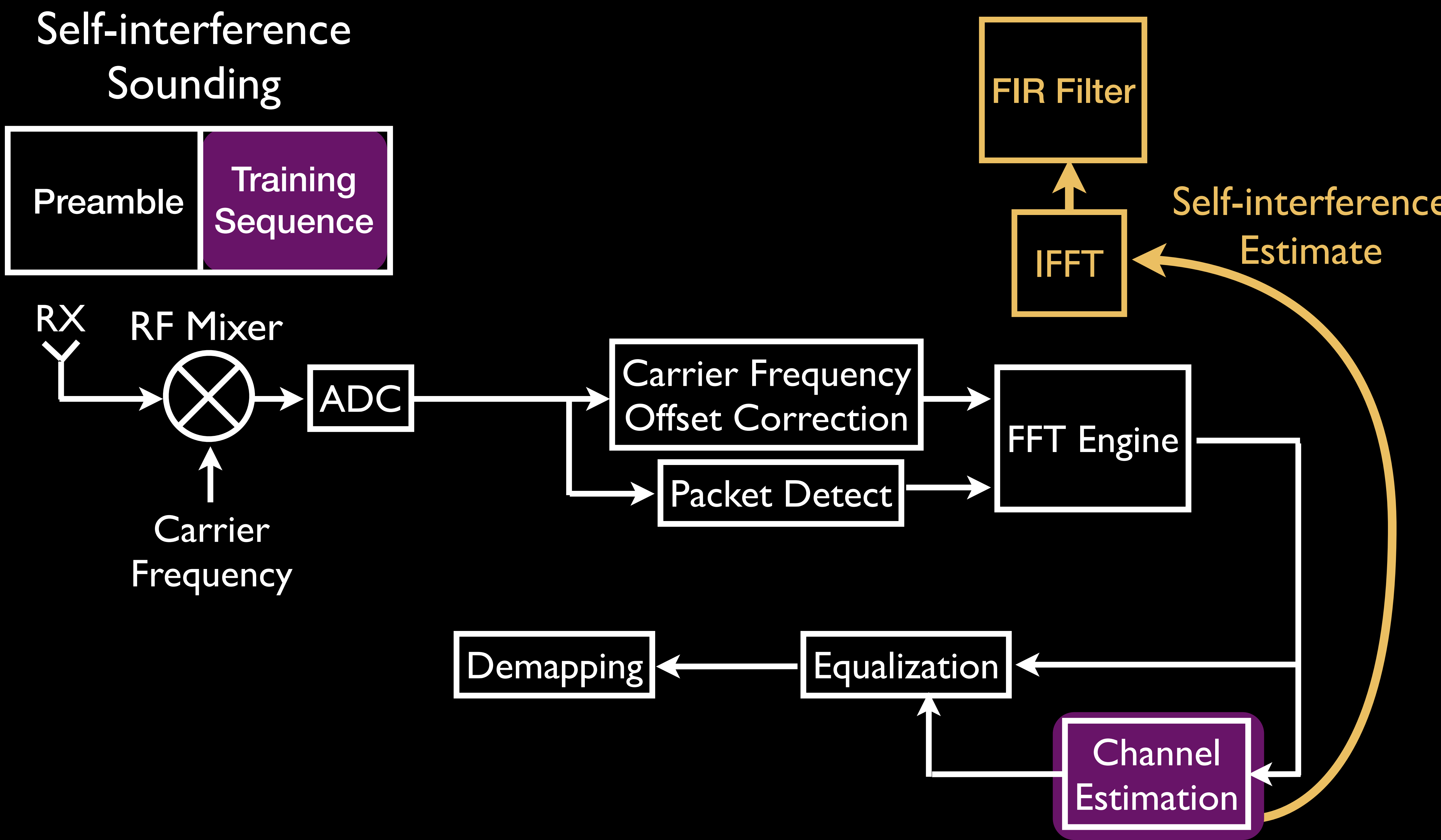


OFDM processing



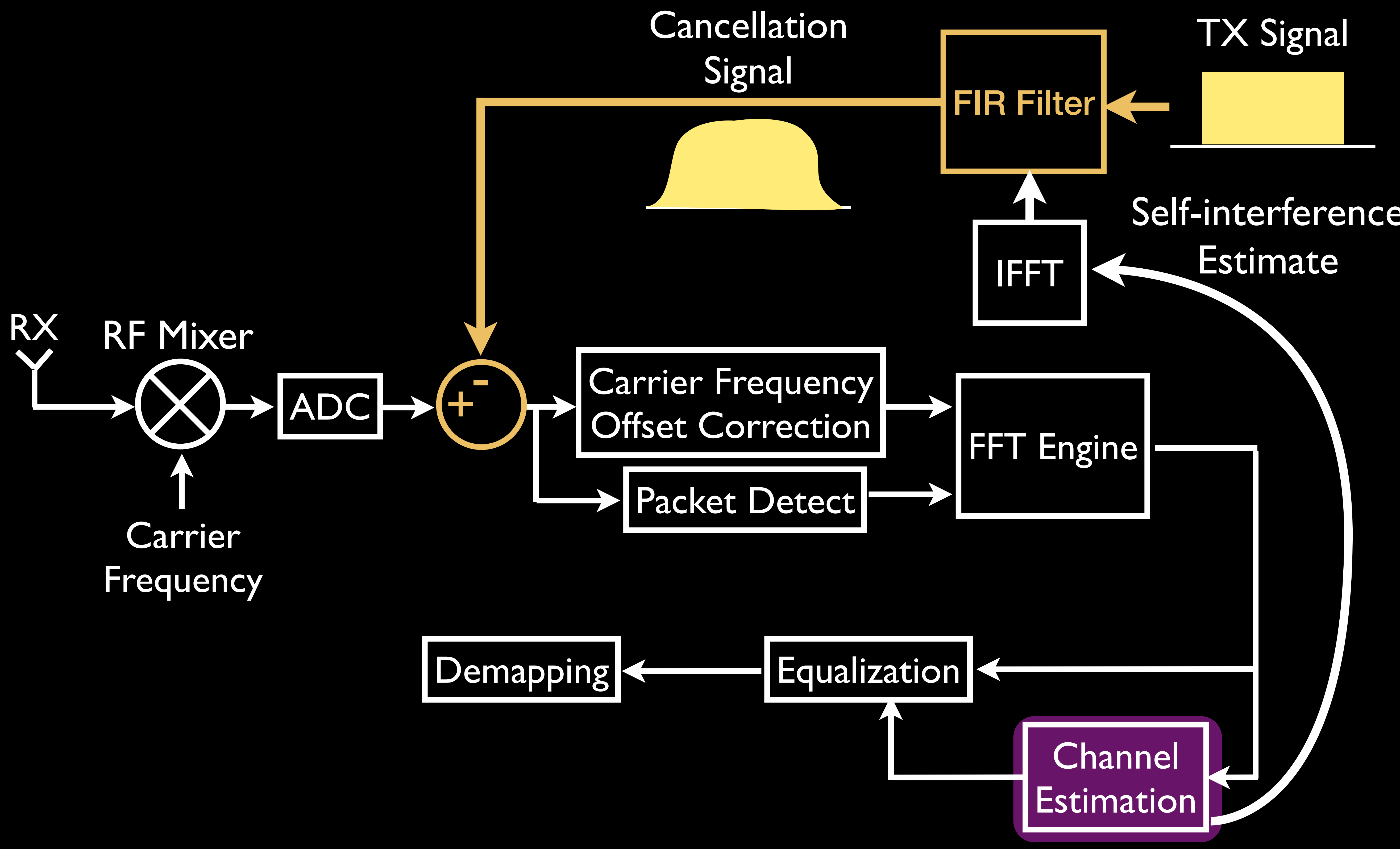


Step 1: Estimation

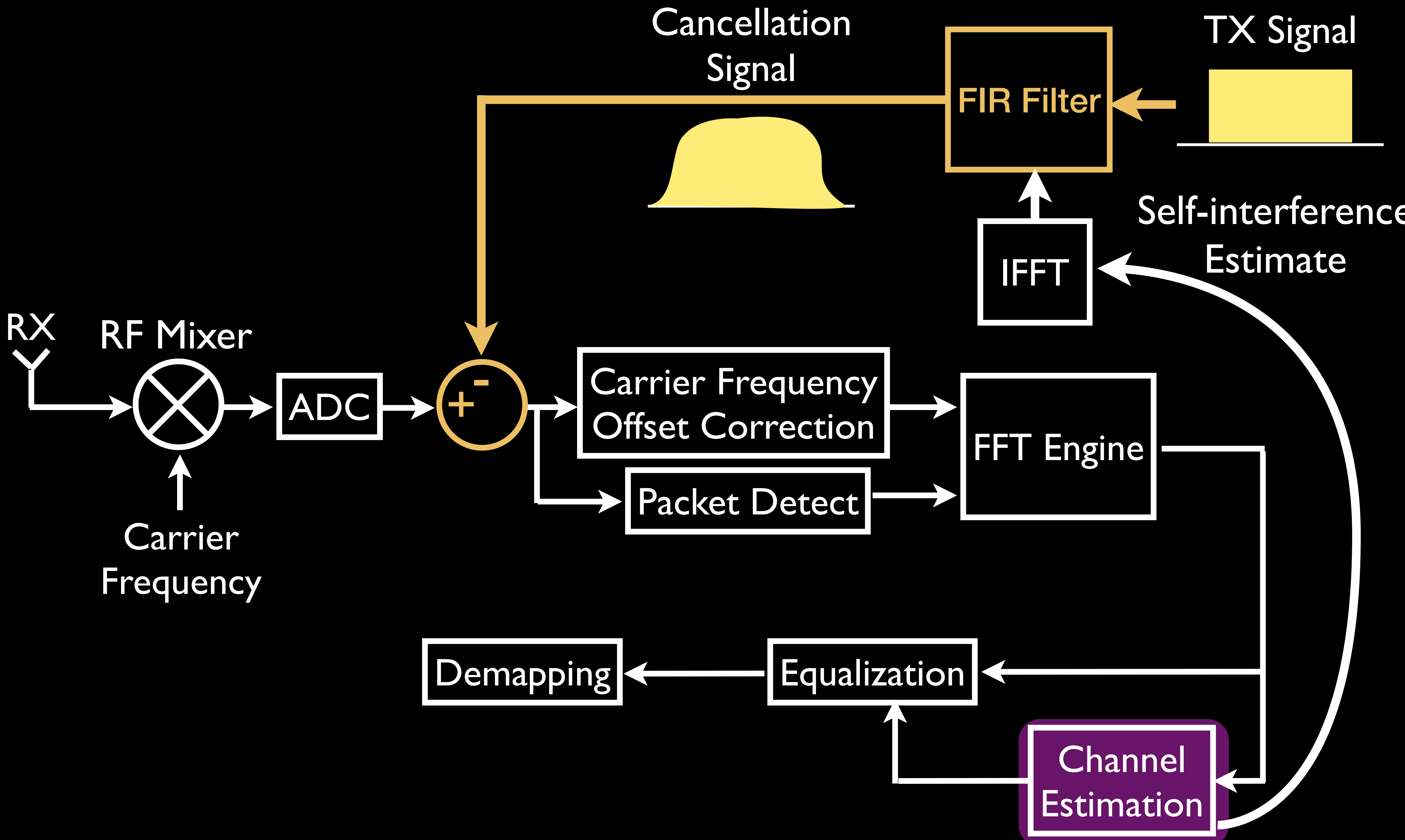


Estimation includes effect of RF cancellation

Step 2: Cancellation



Step 2: Cancellation

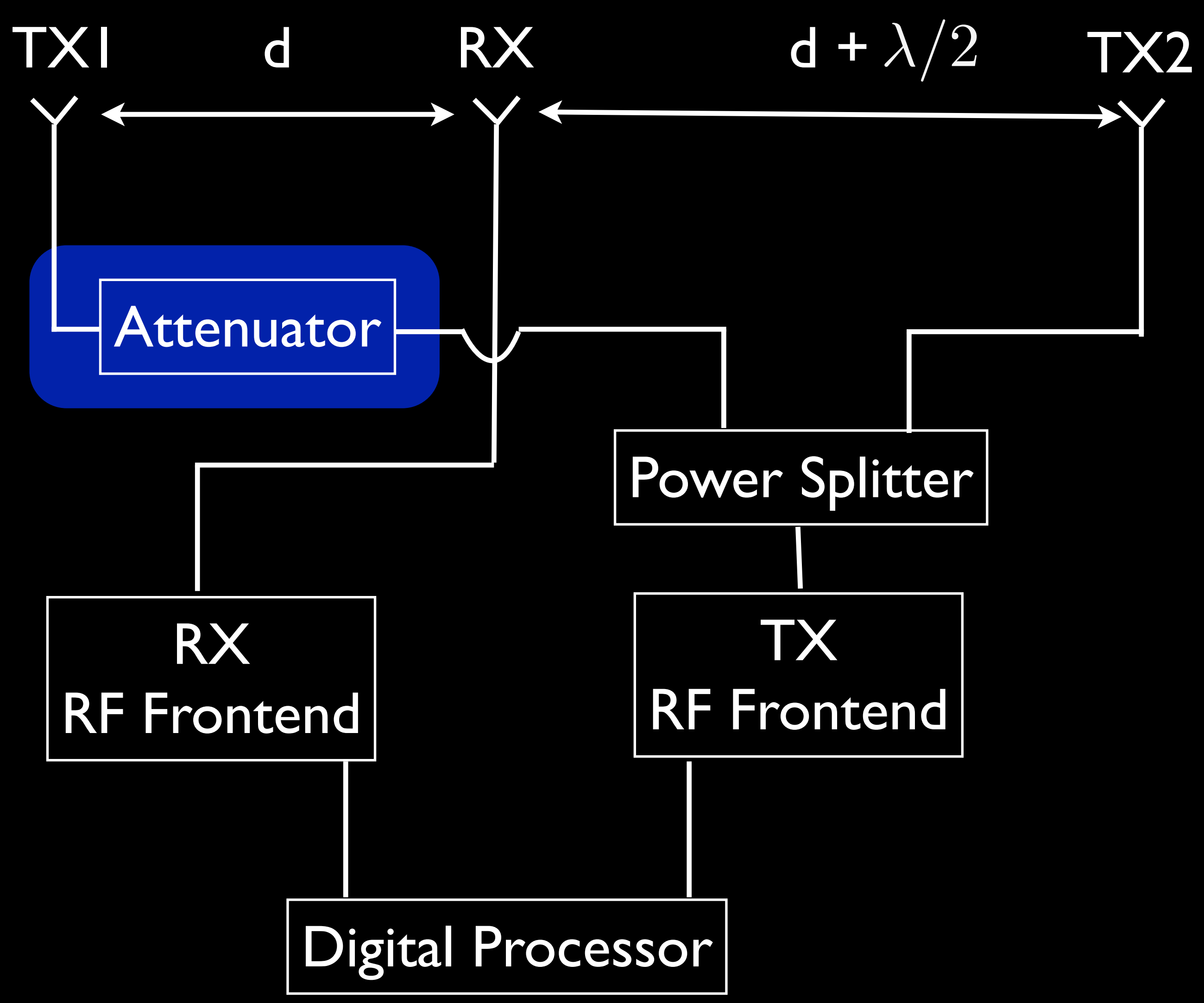


30dB Cancellation

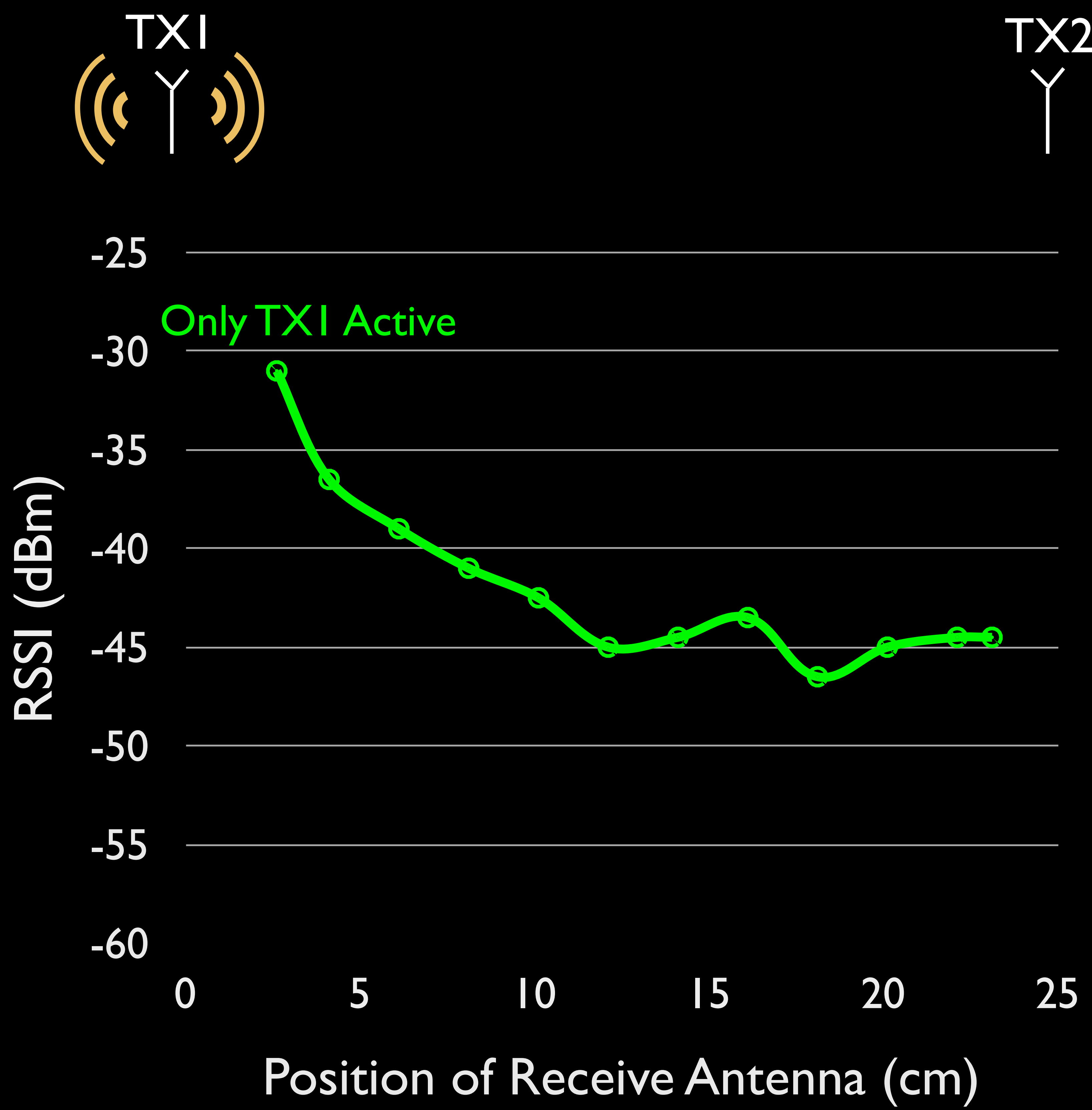
Talk Outline

- RF Cancellation using Signal Inversion: ~50dB for 20Mhz
- Adaptive RF Cancellation: ~1ms convergence
- Adaptive Digital Cancellation: ~30dB cancellation
- System Performance
- Implications to Wireless Networks
- Looking Forward

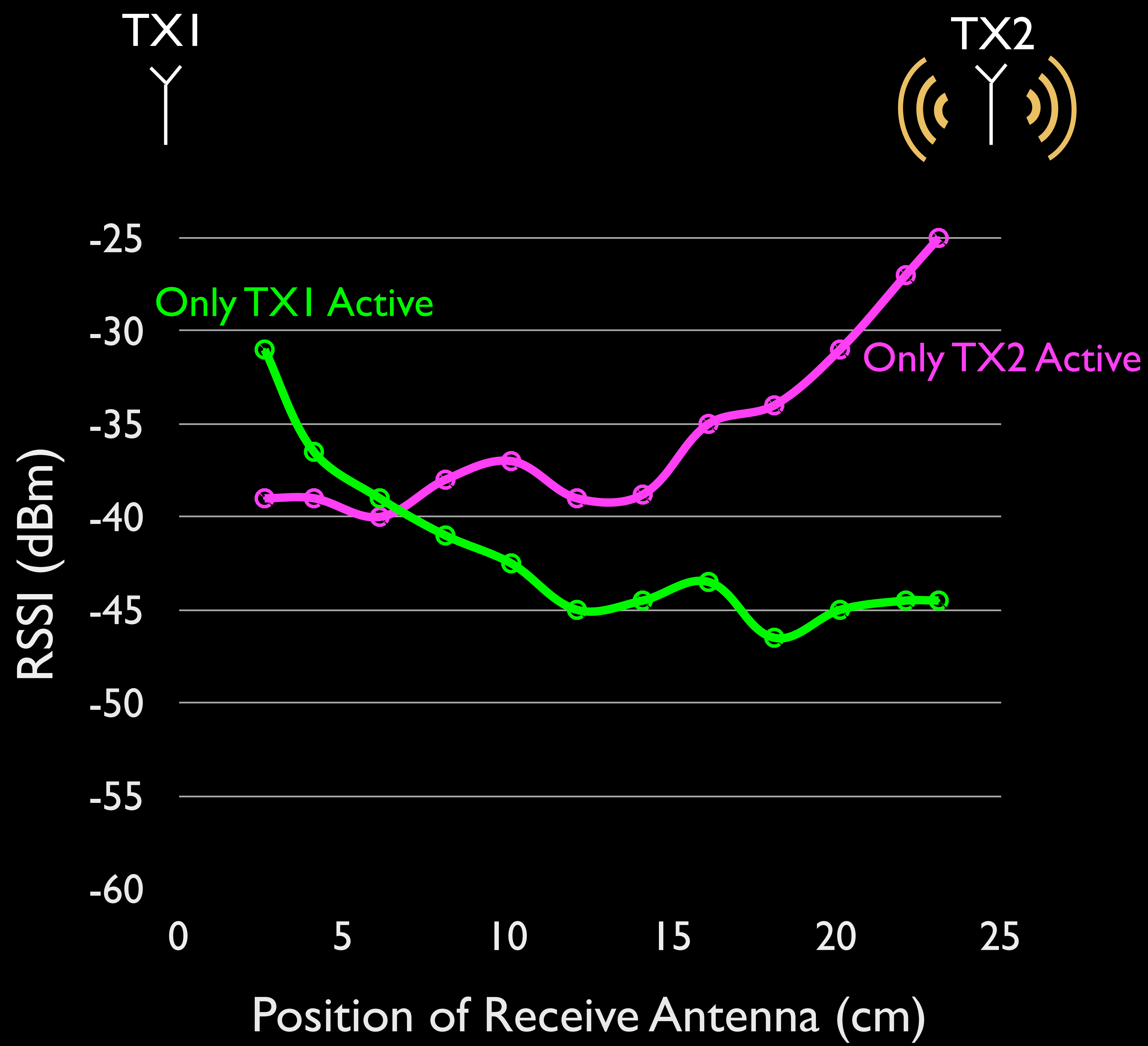
Phase Offset Cancellation: Block Diagram



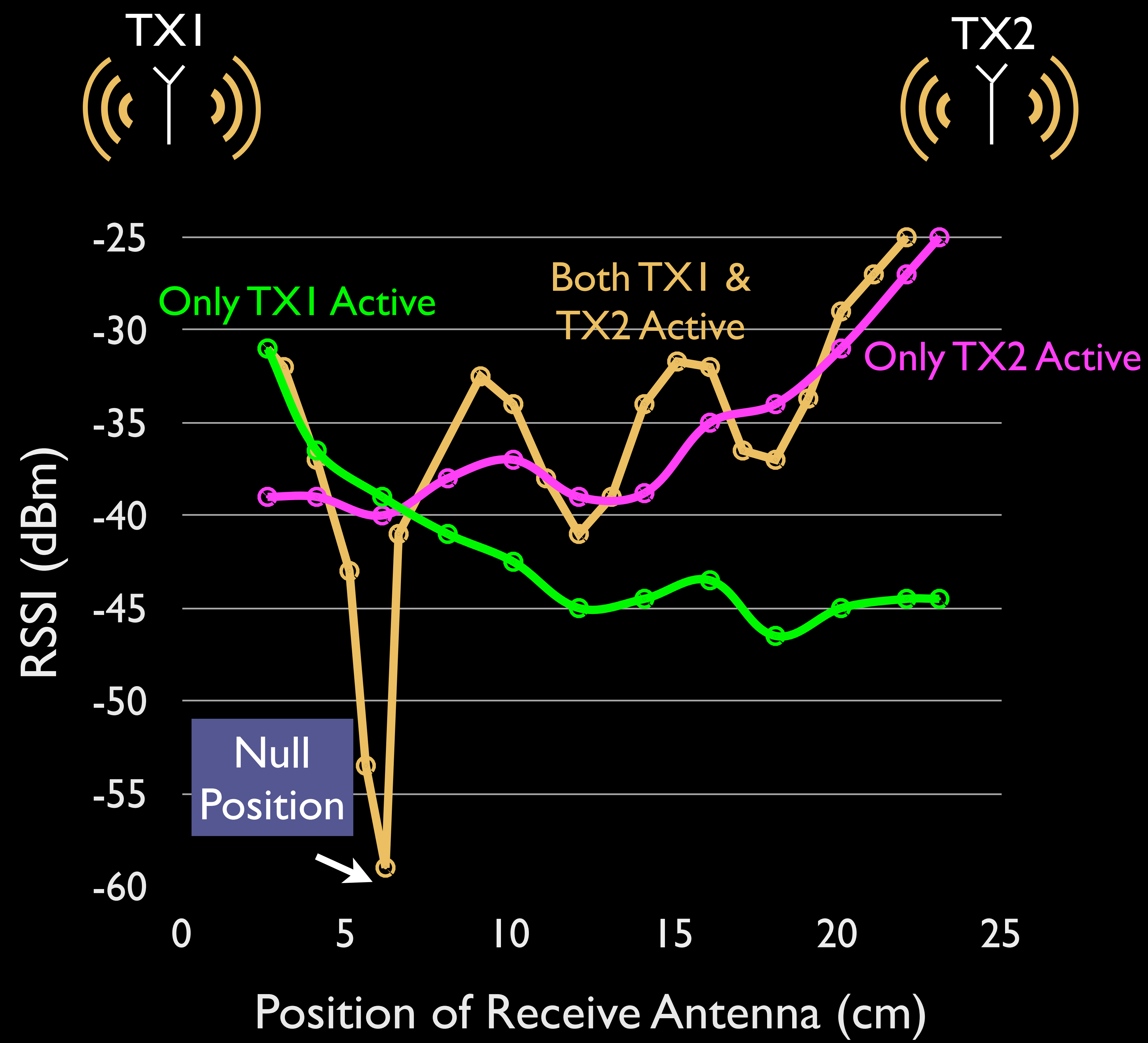
Phase Offset Cancellation: Performance



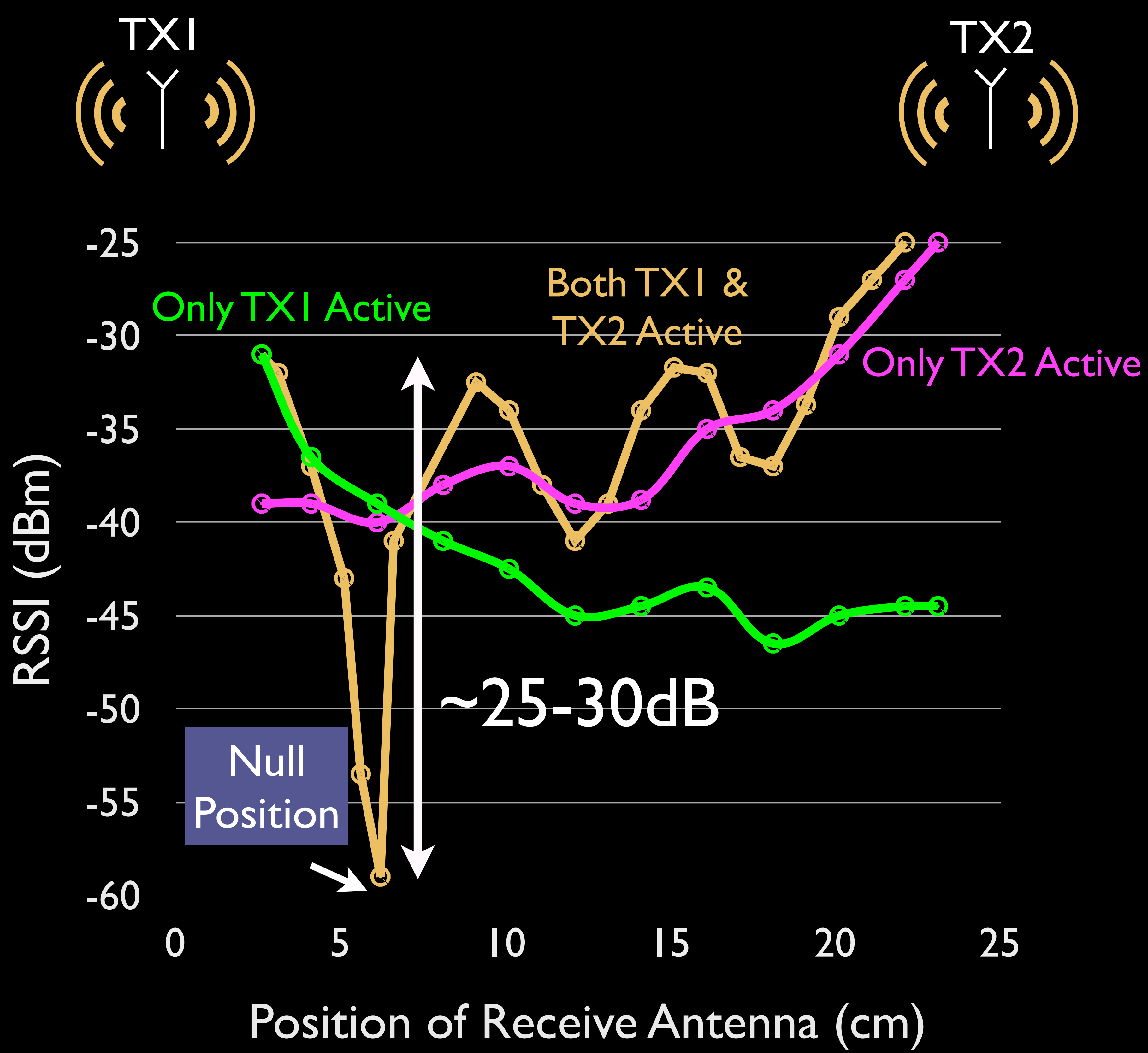
Phase Offset Cancellation: Performance



Phase Offset Cancellation: Performance

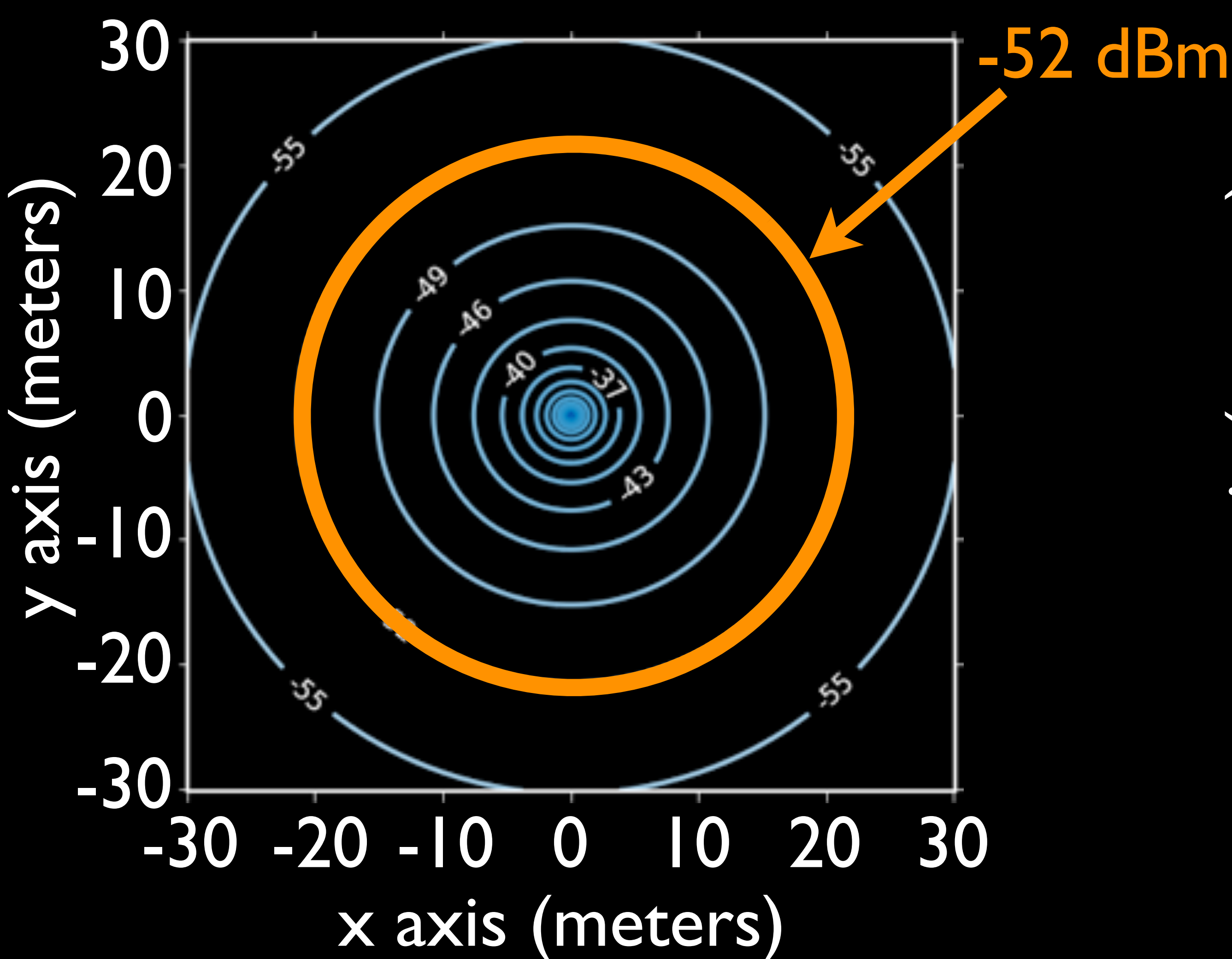


Phase Offset Cancellation: Performance

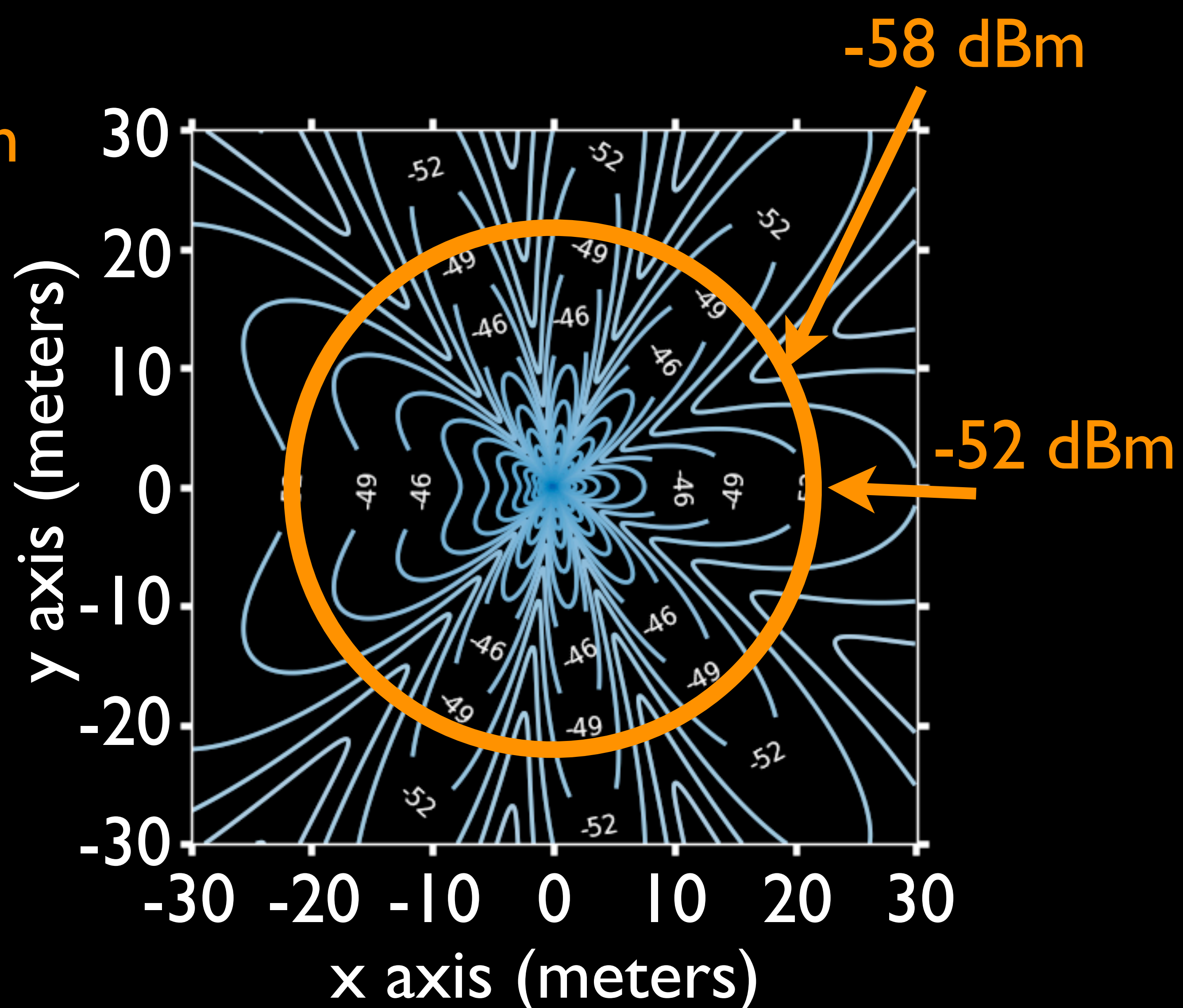


What about attenuation at intended receivers? Destructive interference can affect this signal too!

- Different transmit powers for two TX helps

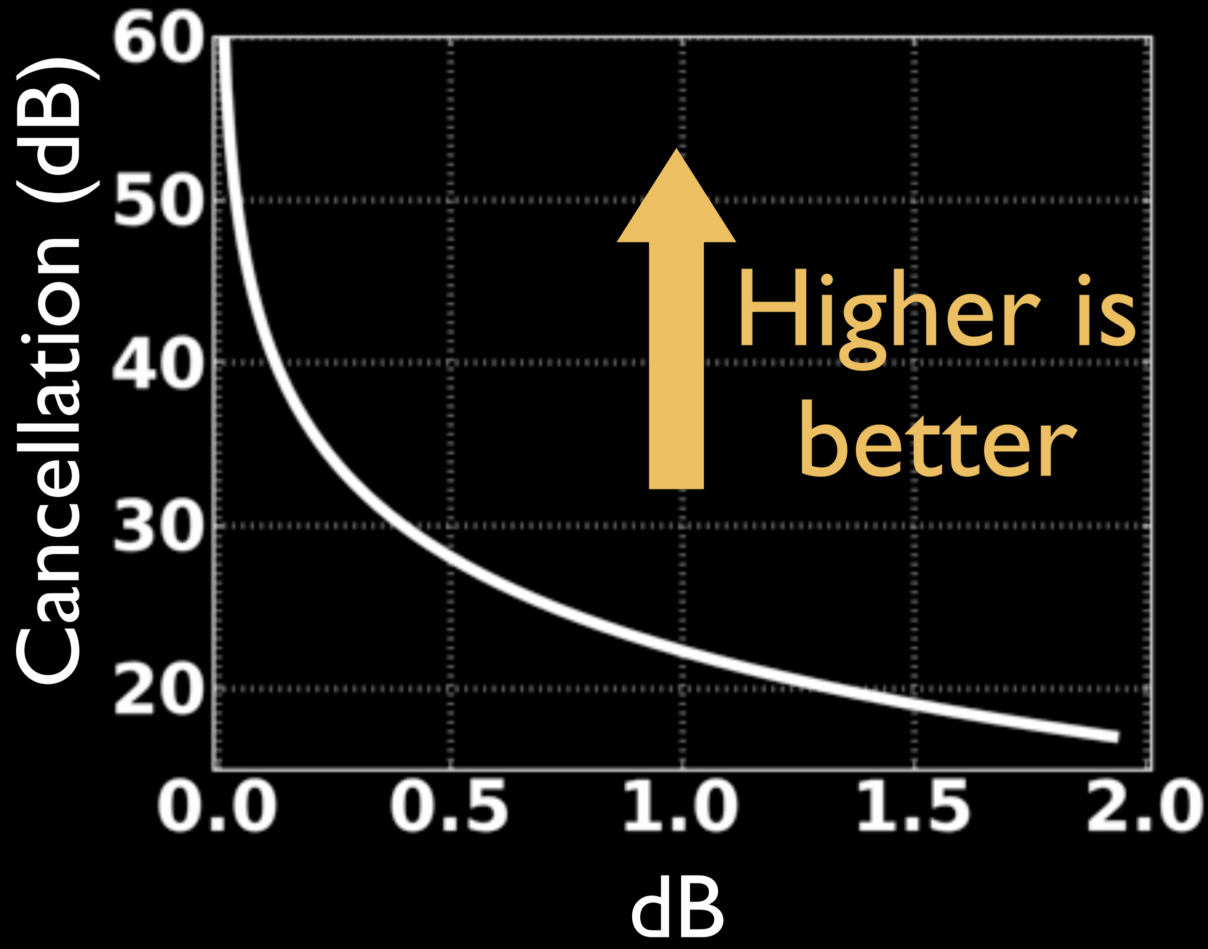


Single Transmit Antenna



Two Transmit Antennas

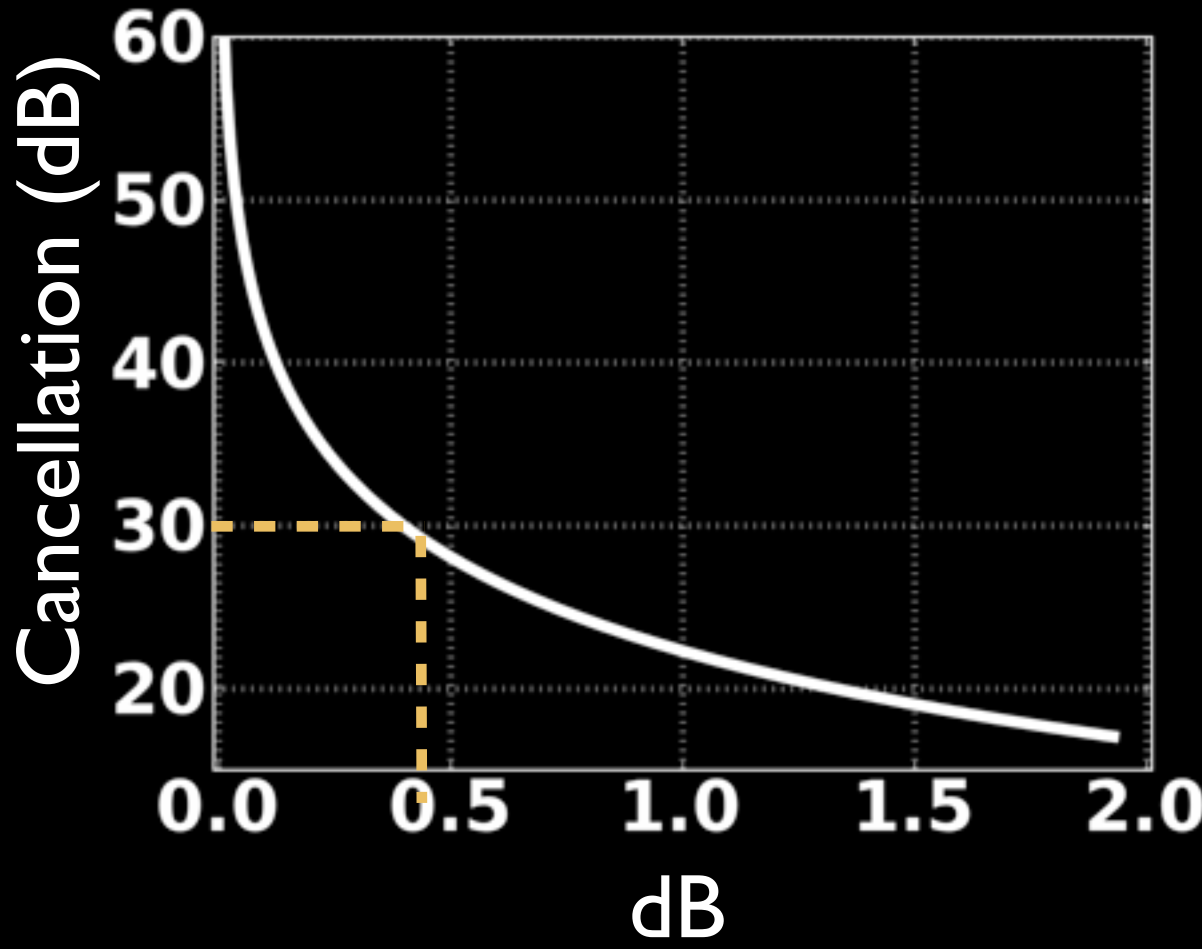
Sensitivity of Phase Offset Cancellation



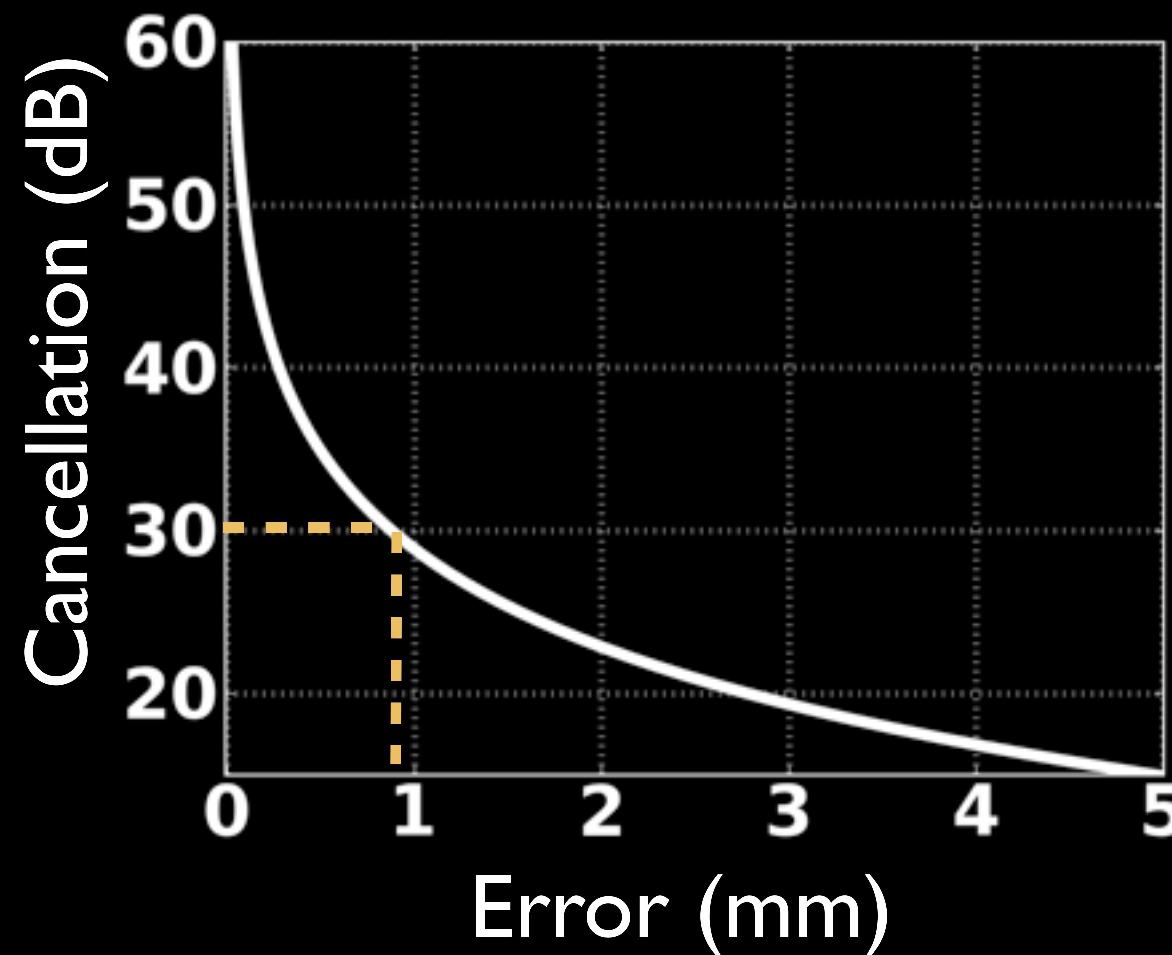
Amplitude Mismatch between TX1 and TX2

Placement Error for RX

Sensitivity of Phase Offset Cancellation



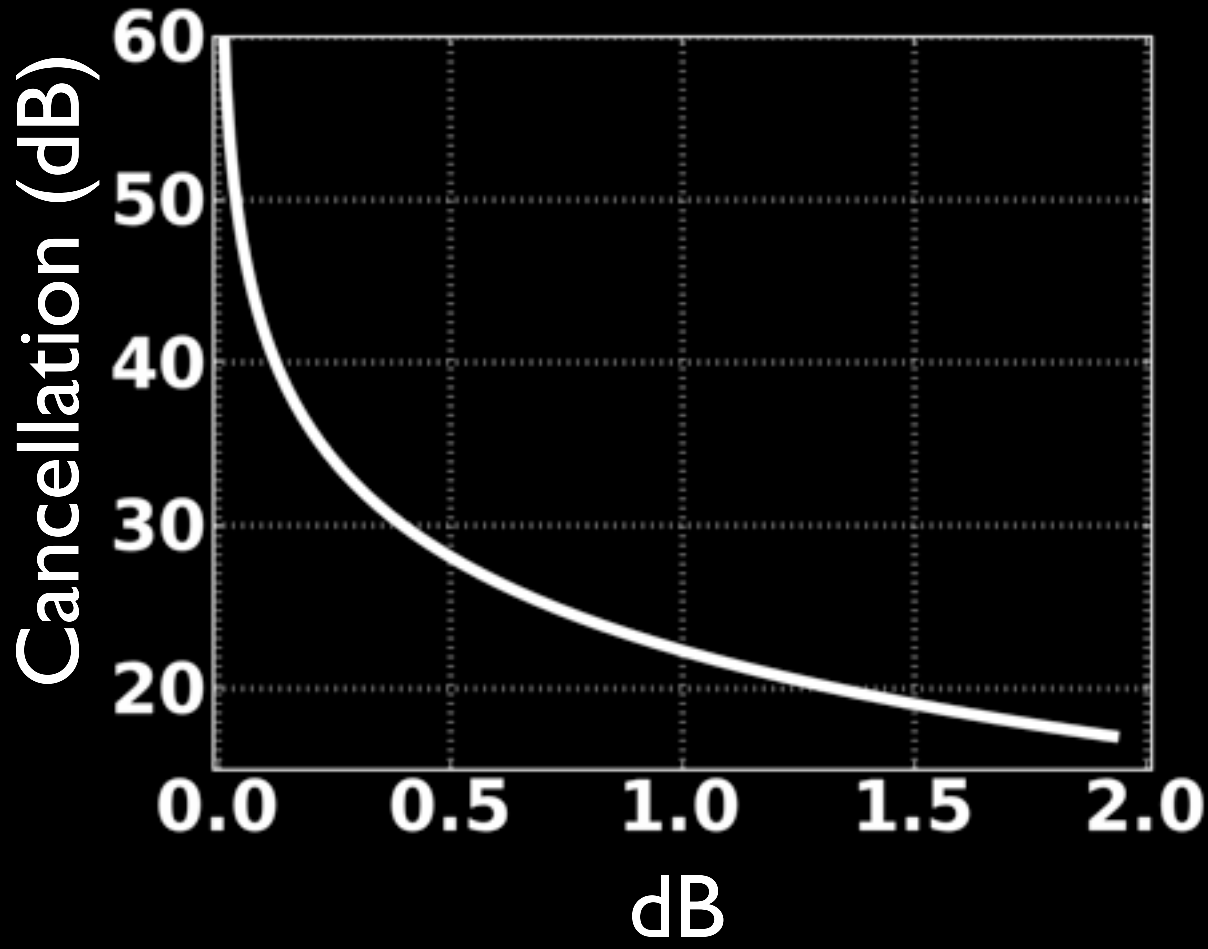
Amplitude Mismatch
between TX1 and TX2



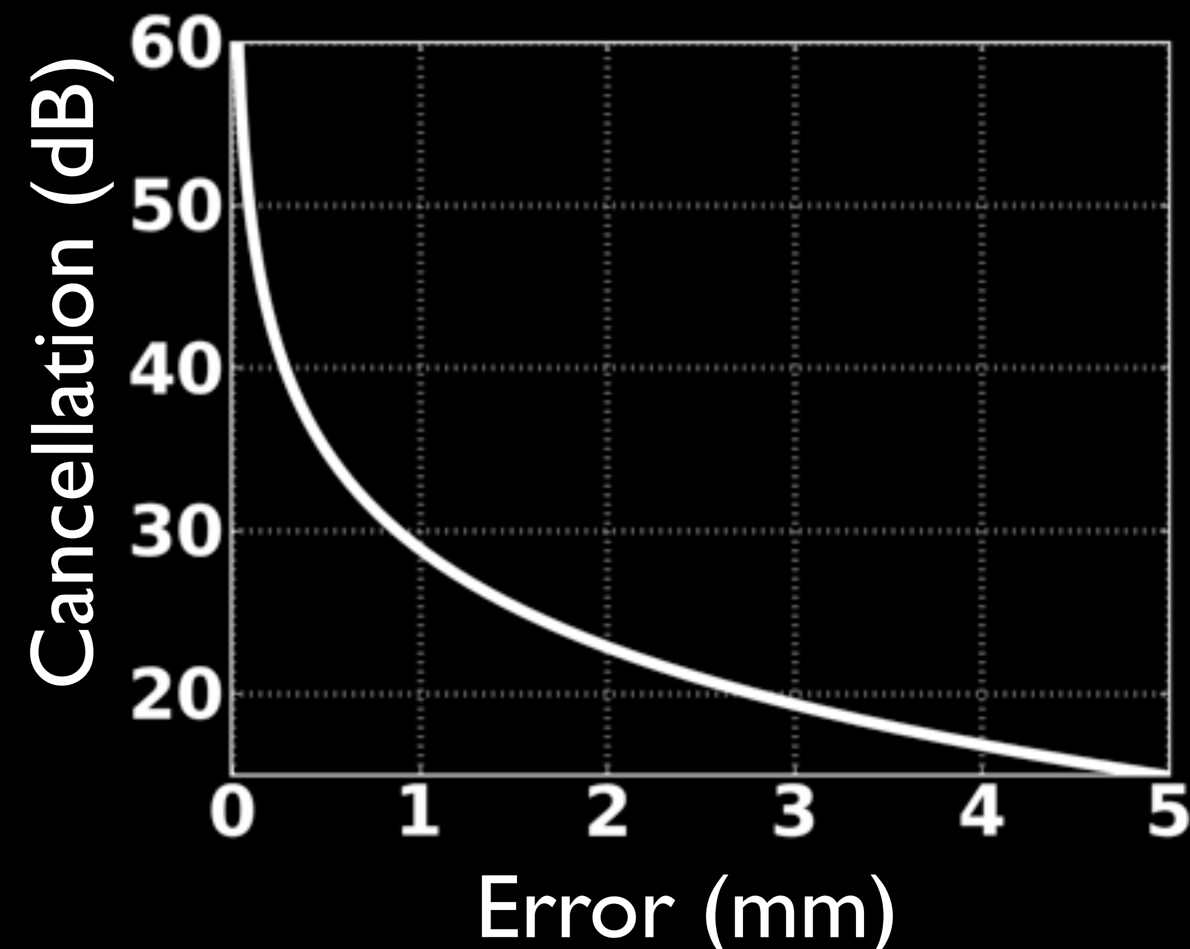
Placement Error
for RX

30dB cancellation < 5% (~0.5dB) amplitude mismatch
< 1mm distance mismatch

Sensitivity of Phase Offset Cancellation



Amplitude Mismatch
between TX1 and TX2

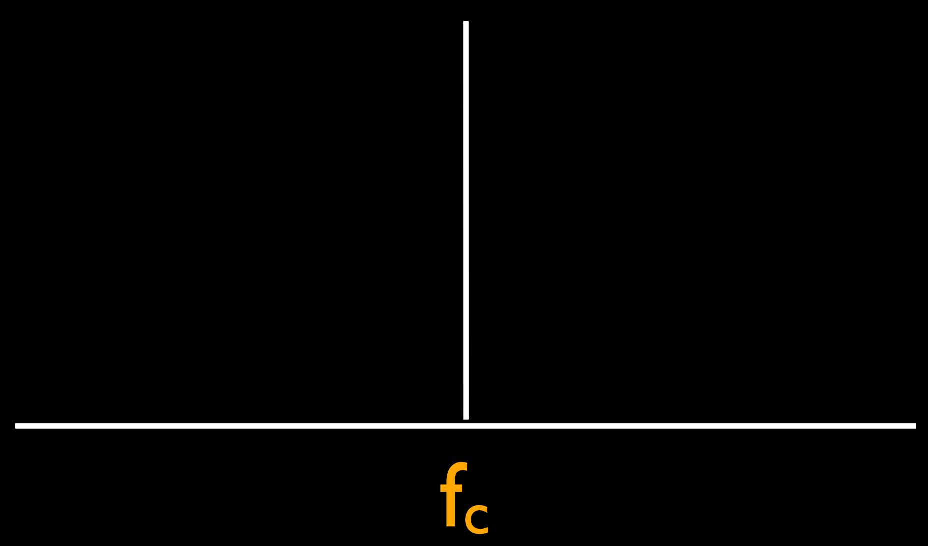


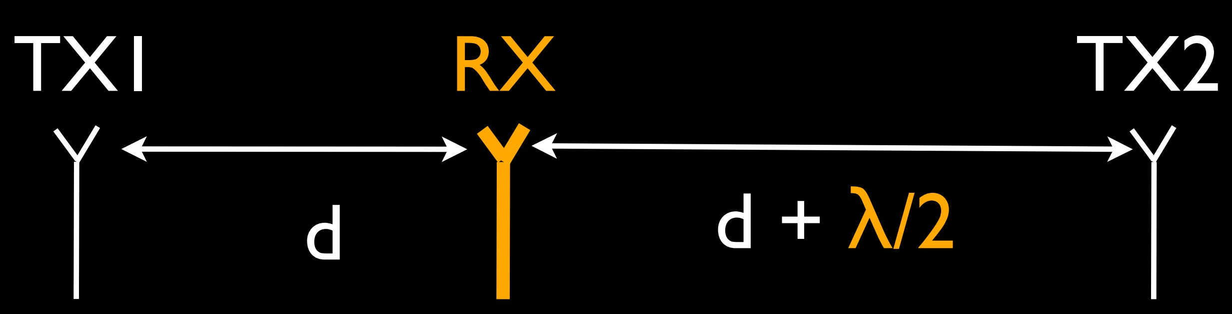
Placement Error
for RX

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

Bandwidth Constraint

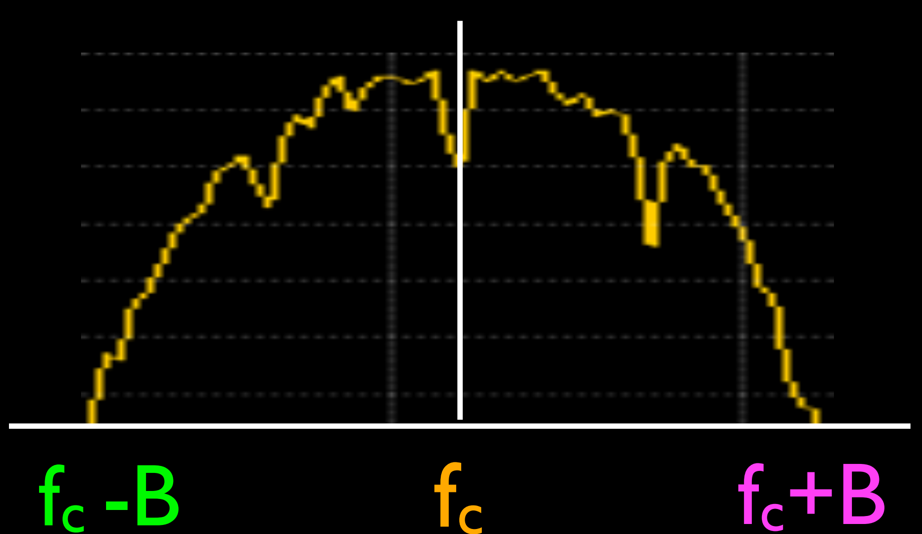
A λ/2 offset is precise for one frequency

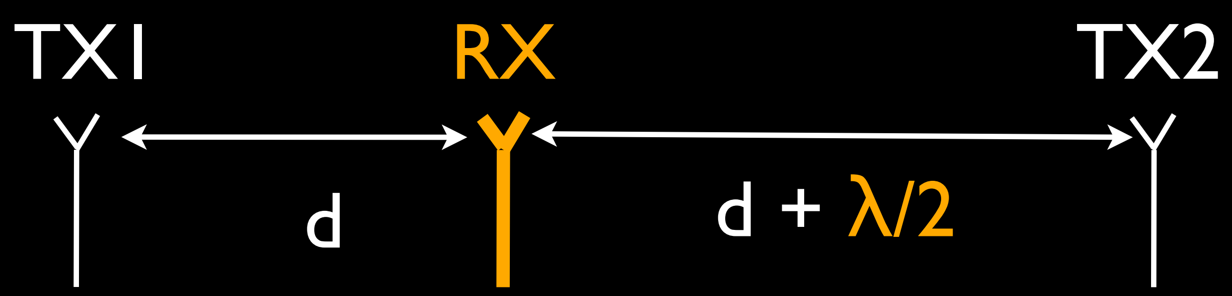




Bandwidth Constraint

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





Bandwidth Constraint

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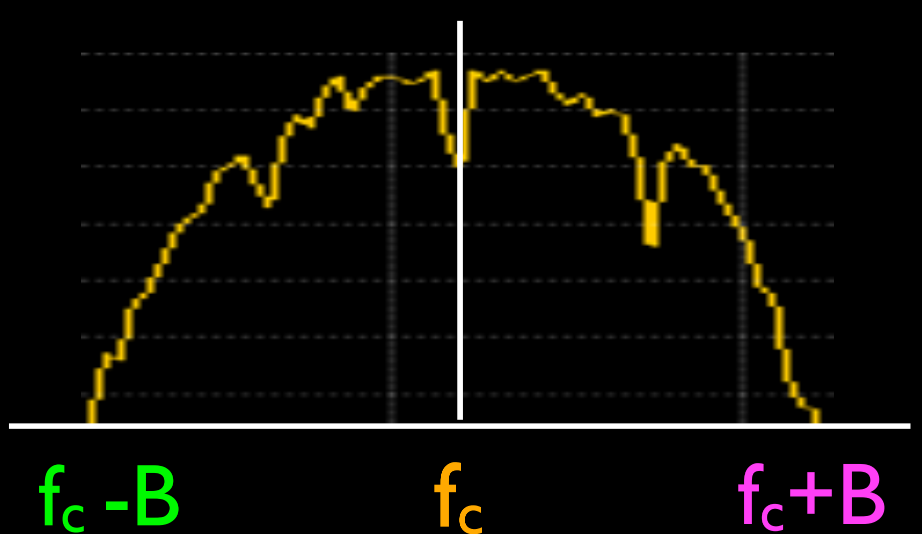

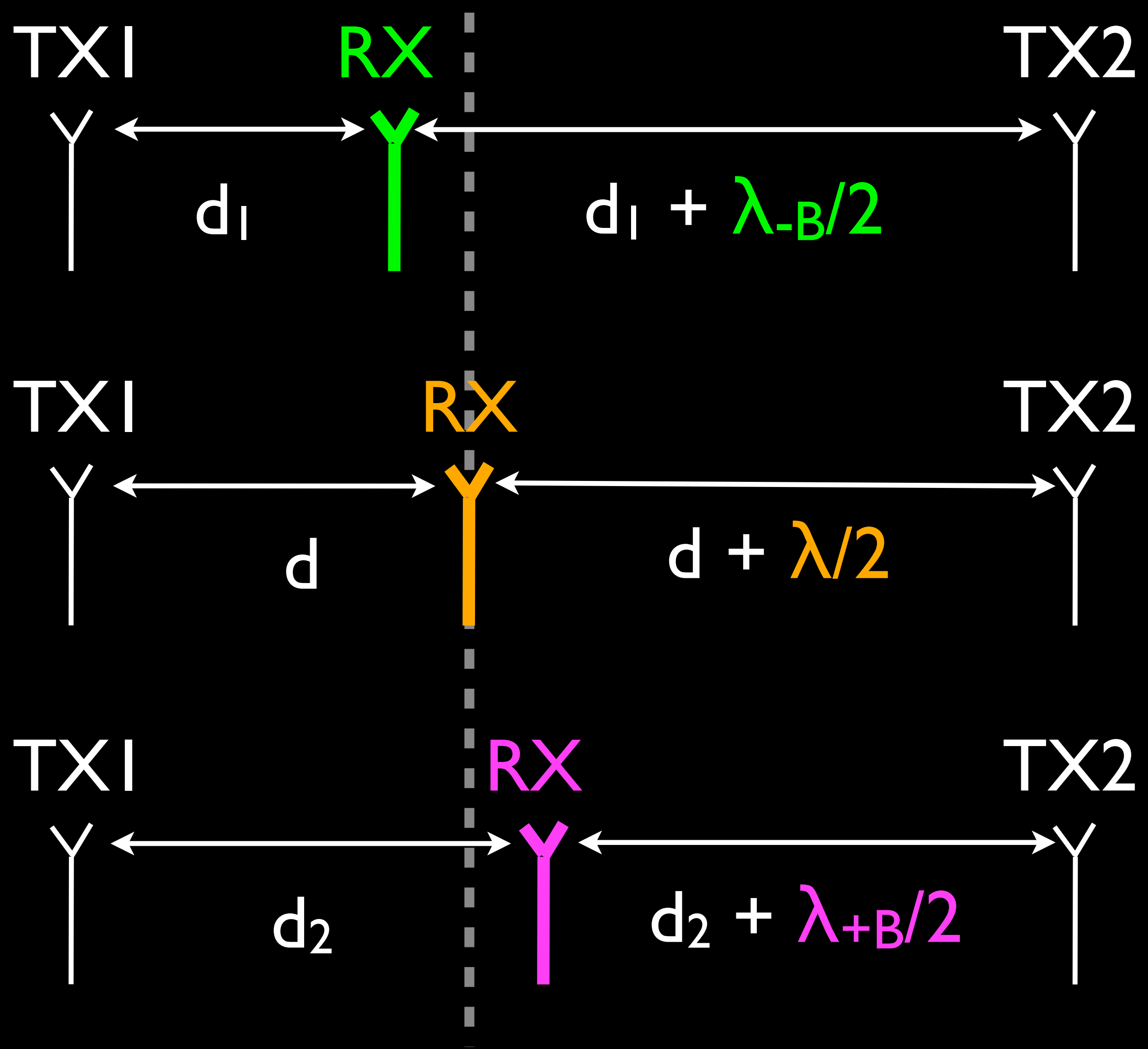

Bandwidth Constraint

A λ/2 offset is precise for one frequency
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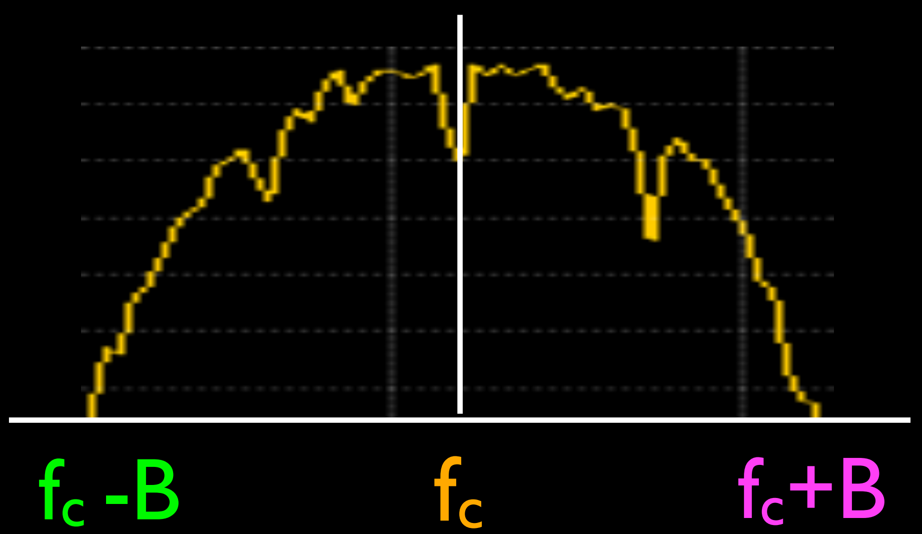
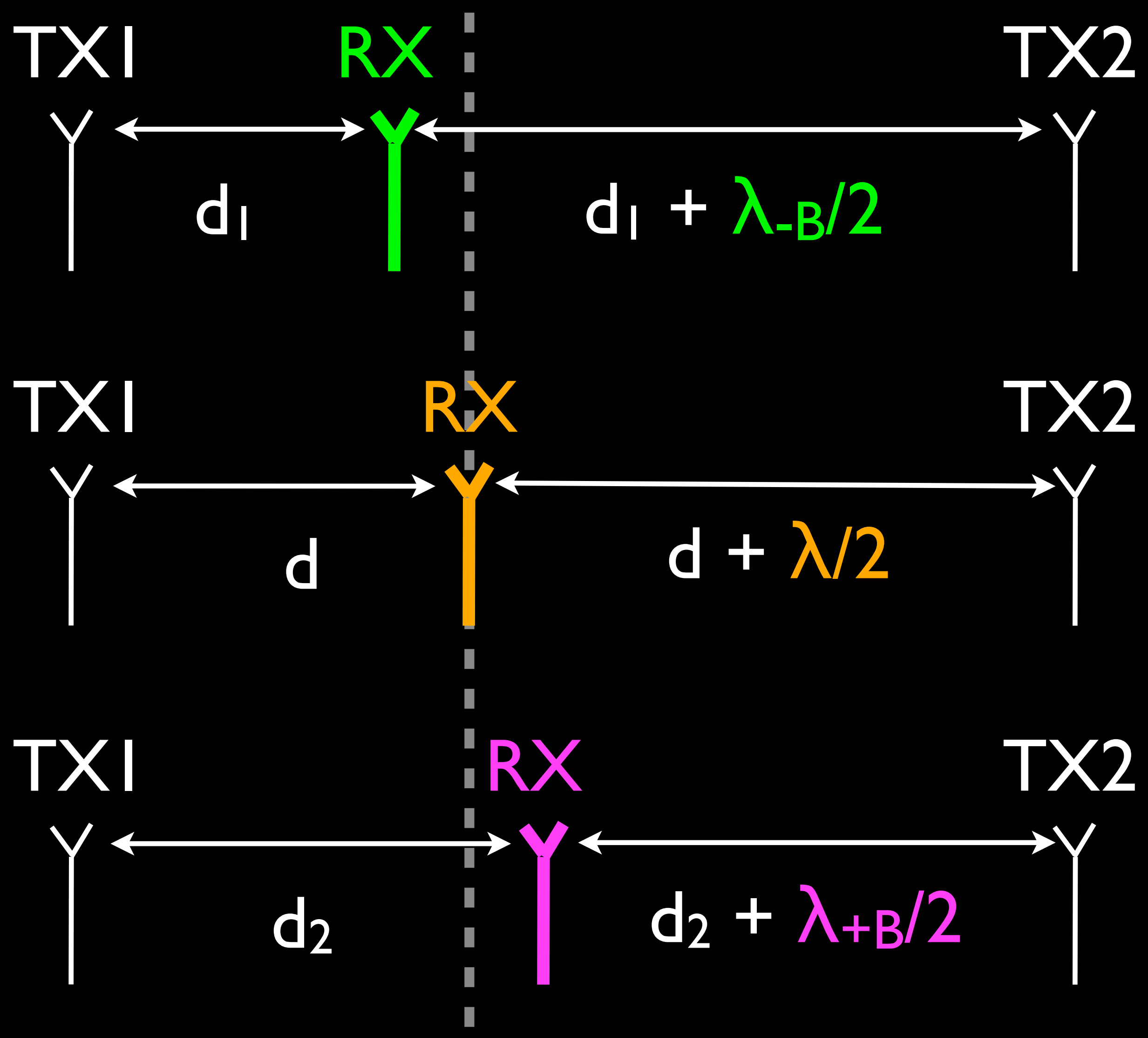
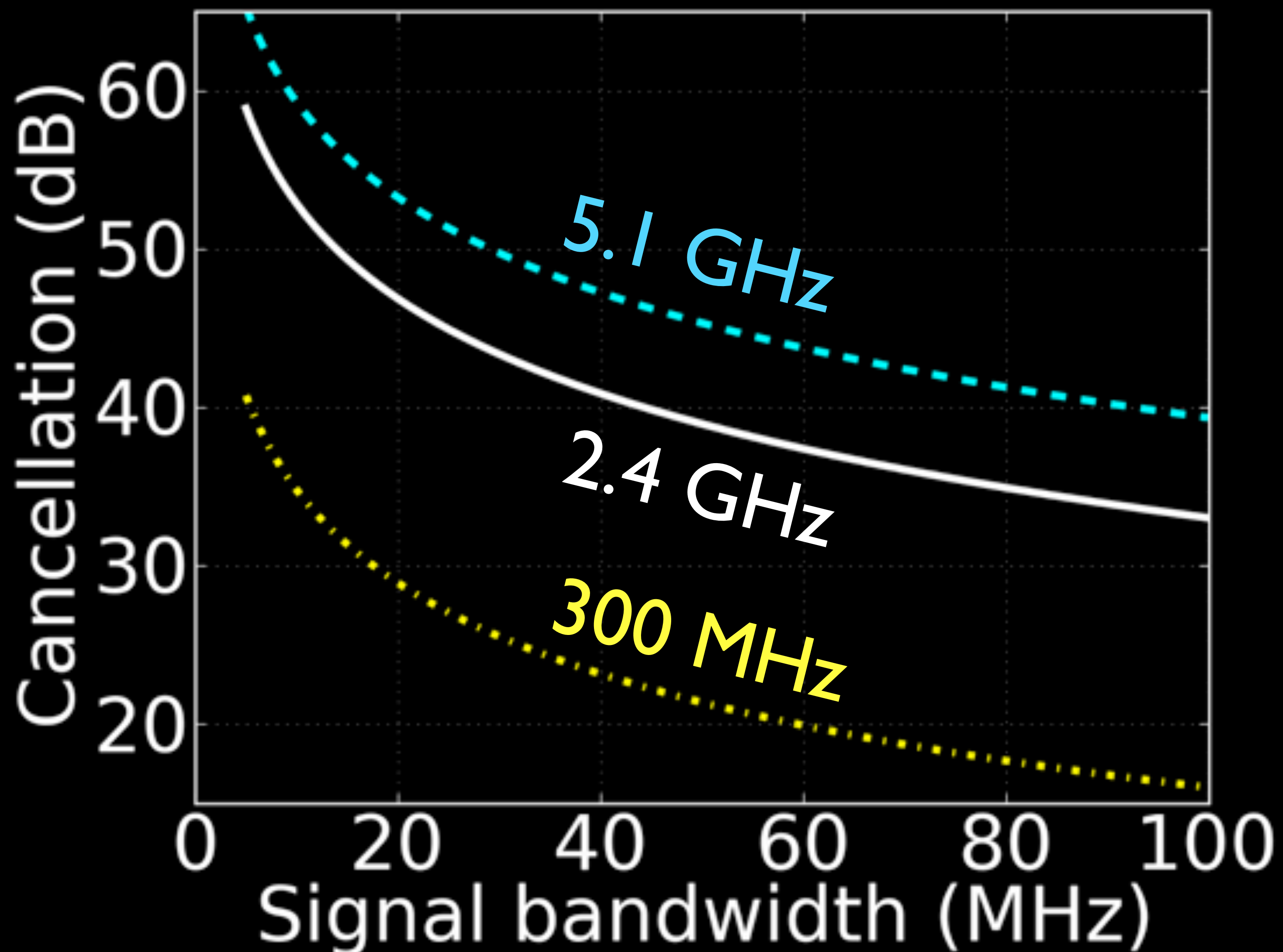
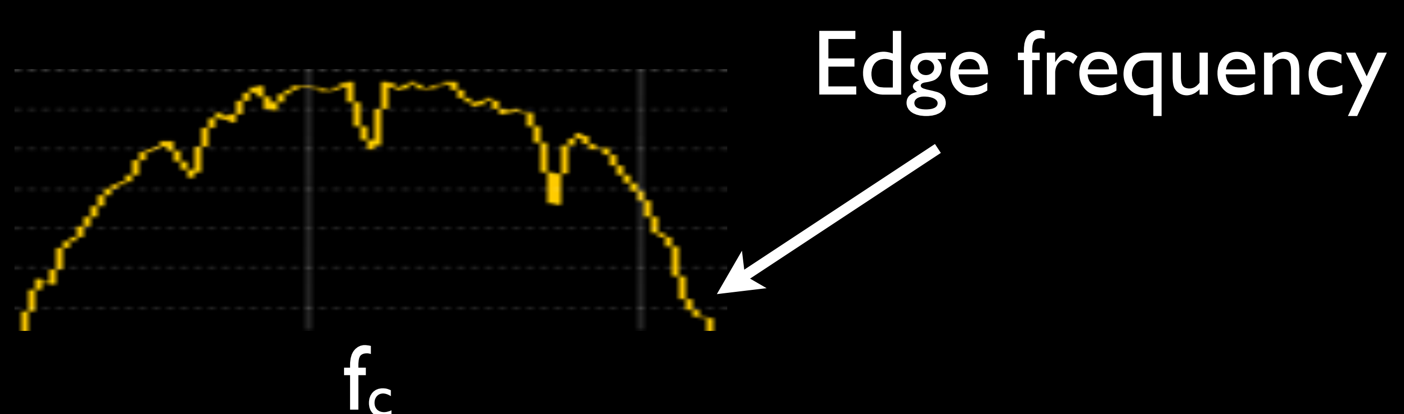




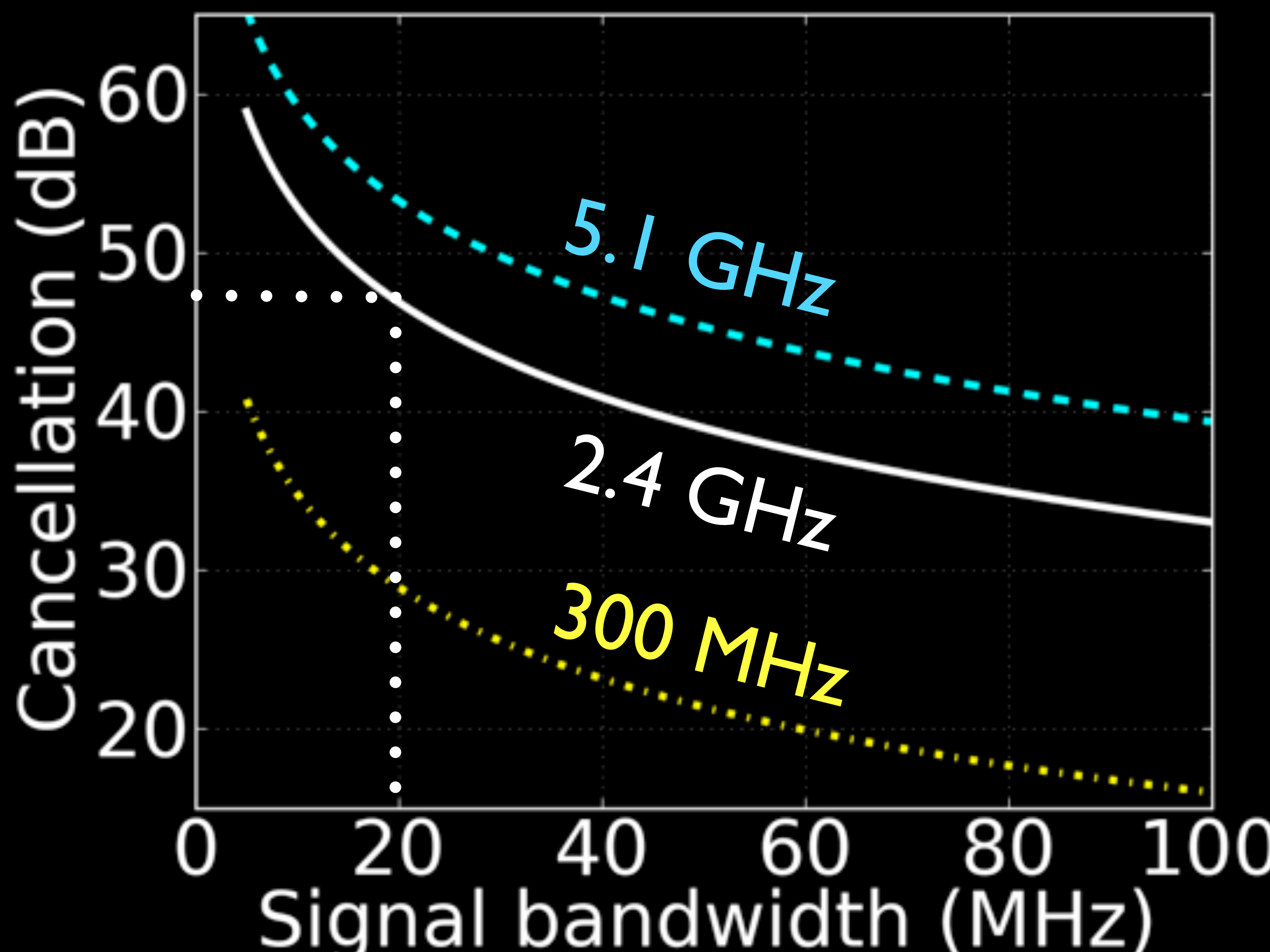
WiFi (2.4G, 20MHz) => ~0.26mm precision error

Bandwidth Constraint





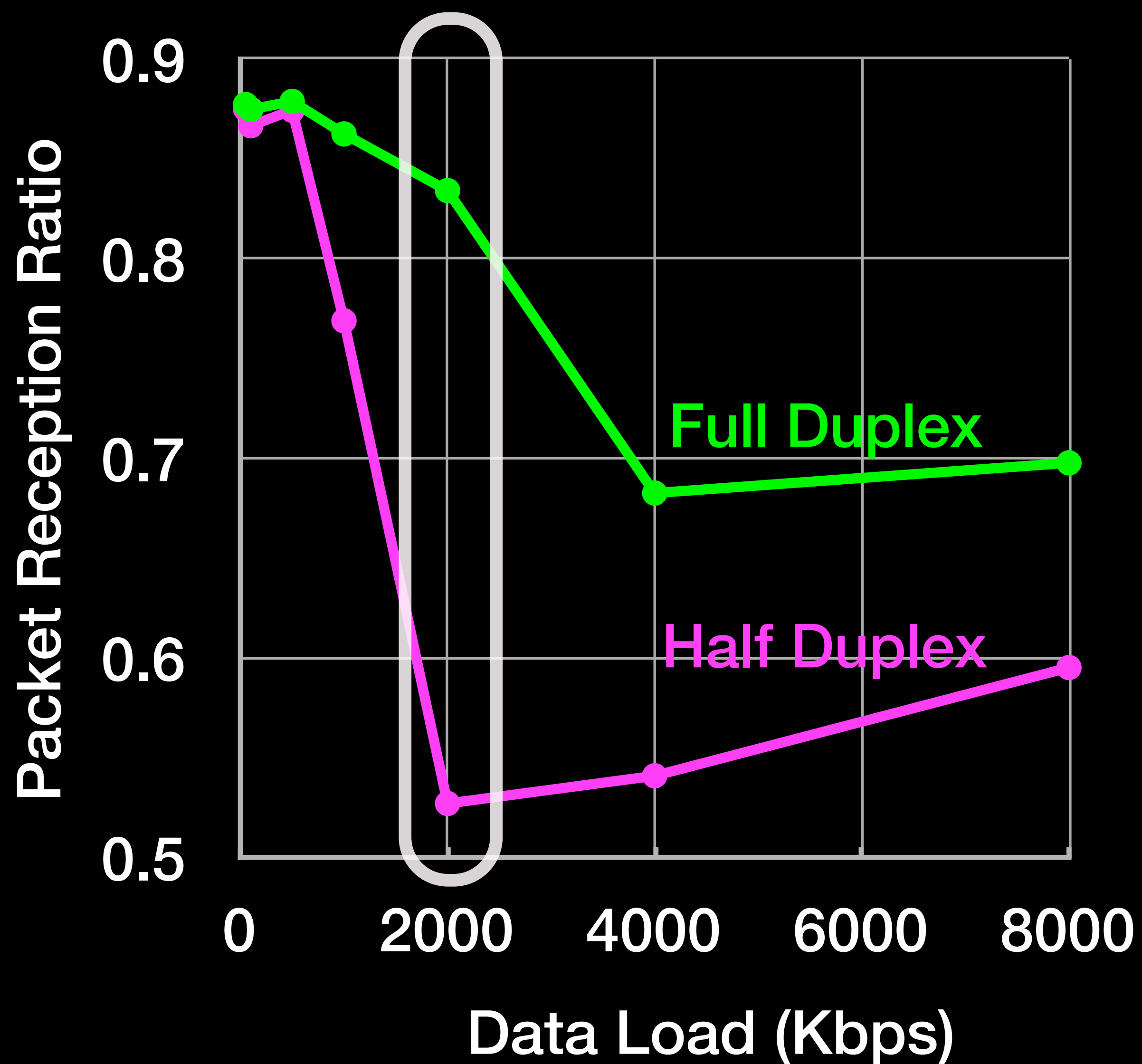
Bandwidth Constraint



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

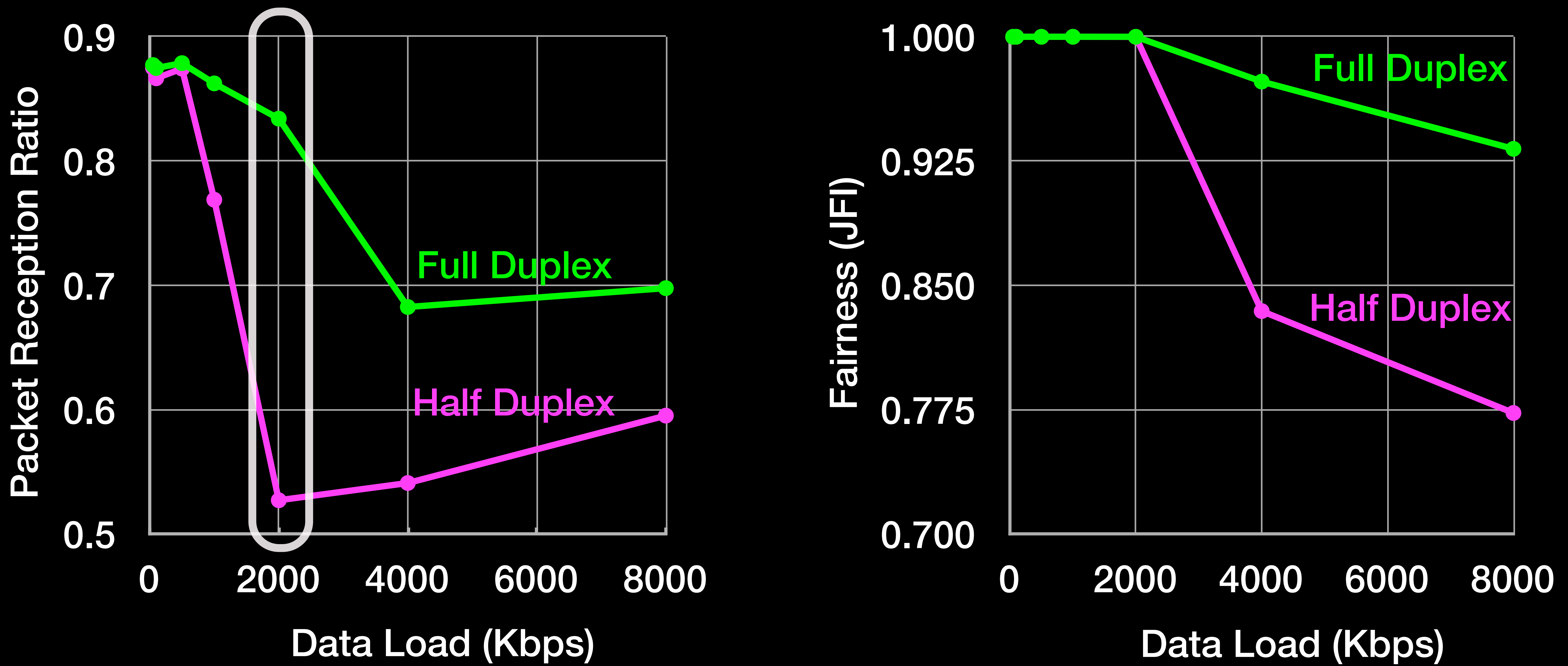
Mitigating Hidden Terminals

Mitigating Hidden Terminals

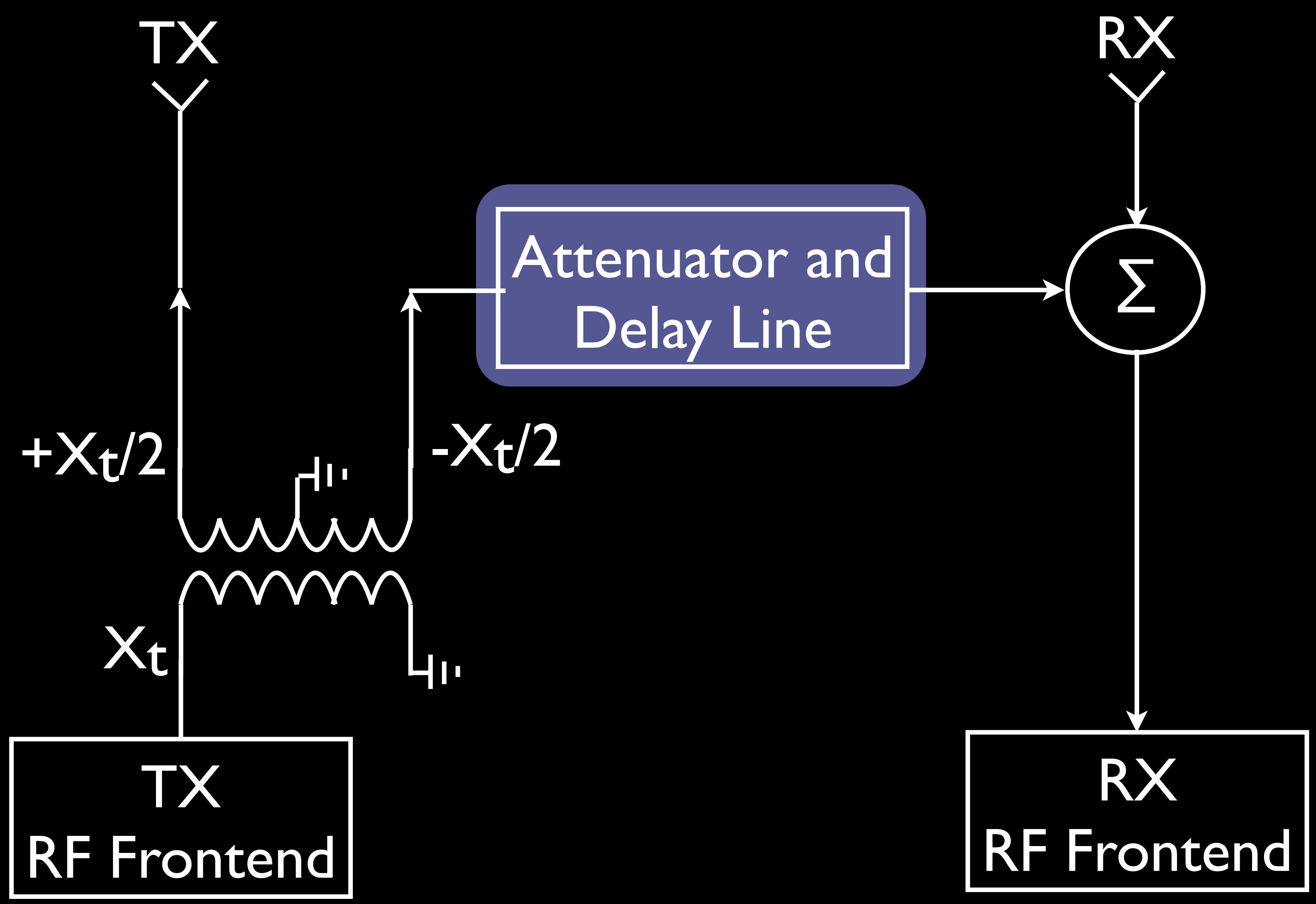


- Full-duplex reduces hidden terminal related losses by 88% at 2 Mbps

Mitigating Hidden Terminals

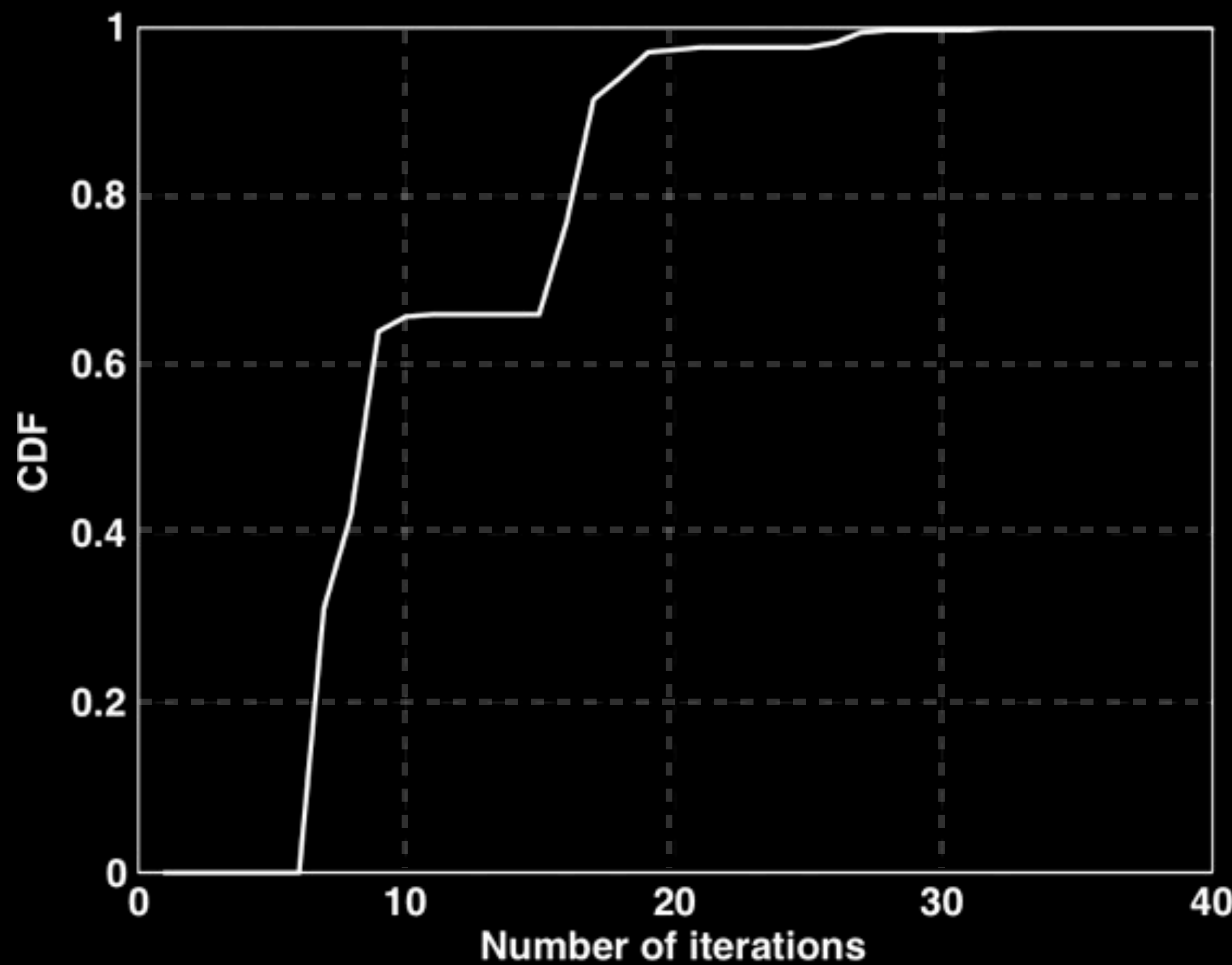


- Full-duplex reduces hidden terminal related losses by 88% at 2 Mbps
- At higher loads, half-duplex improves PRR at the expense of fairness

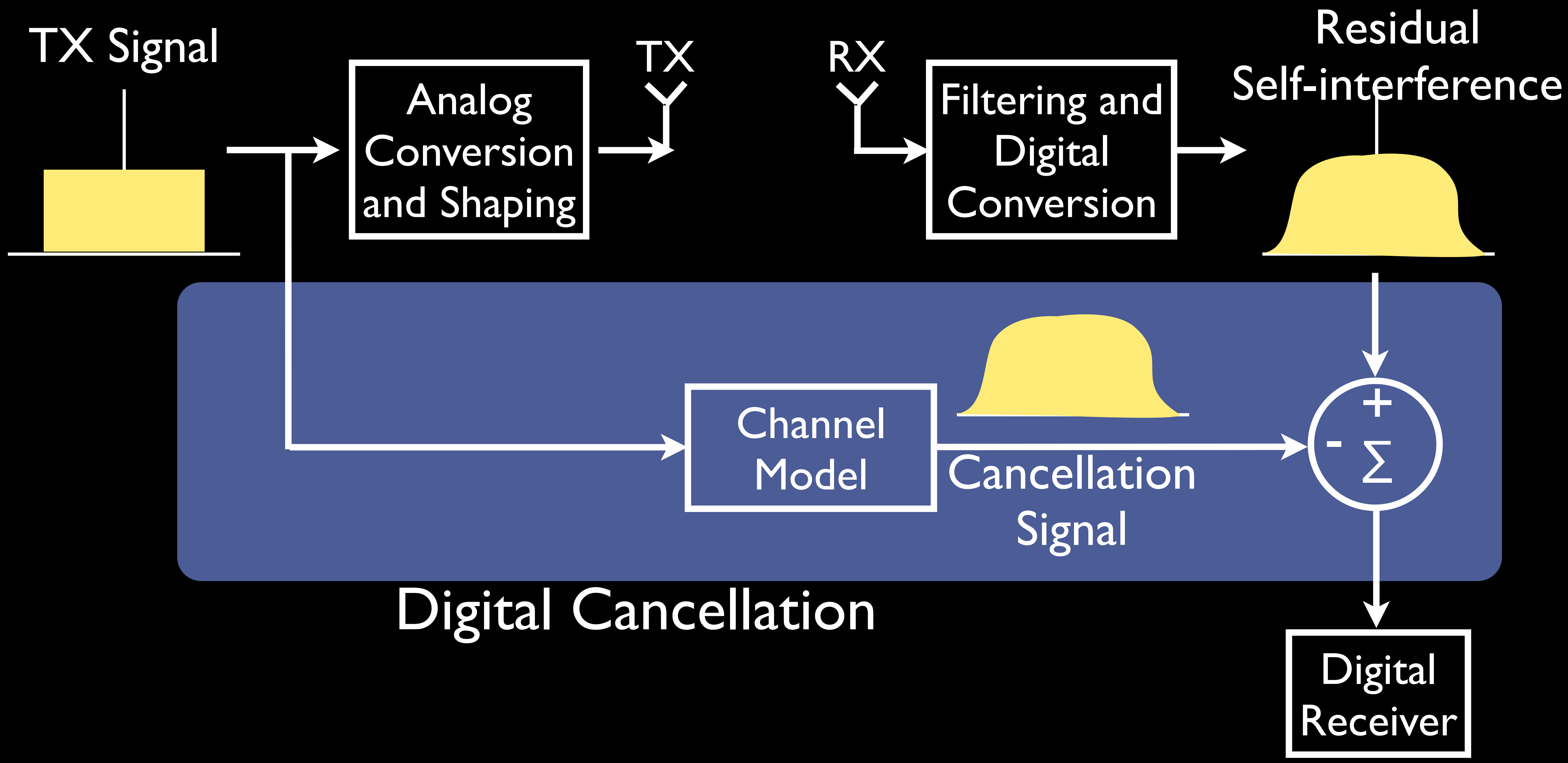


Passive components better than active components

- No gain required
- Saturation can lead to non-linearity
- Passive components are more frequency flat



- ~65% converge without going through a local minima
- 98% converge in <20 iterations


TX Signal
Analog Conversion and Shaping
TX
RX
Filtering and Digital Conversion
Residual Self-interference
Channel Model
Cancellation Signal
+
-
Σ
Digital Cancellation
Digital Receiver

- Other cancellation techniques

  Digital estimation for RF cancellation[1]

- Non-linear channel response

  Reduce distortion: feedforward amplifiers