Practical, Real-time, Full-Duplex Wireless

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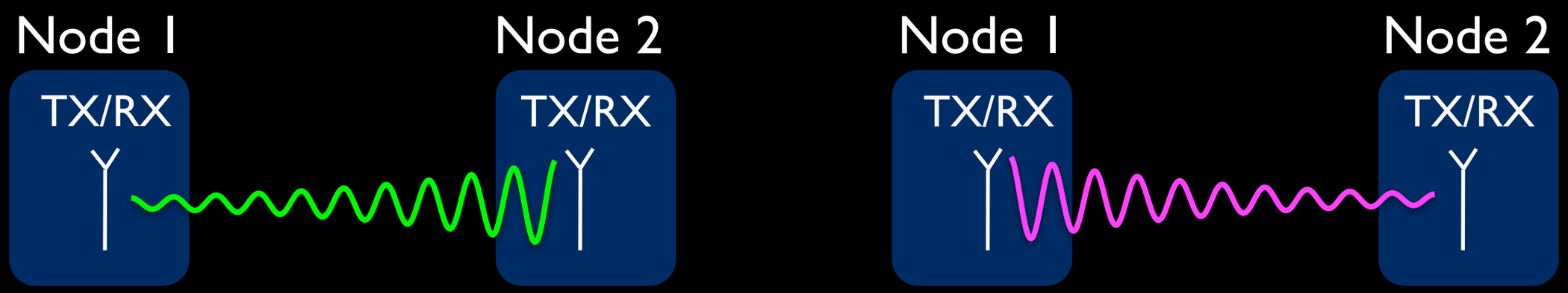
STANFORD
UNIVERSITY

What full-duplex

What full-duplex ... and why?

Current wireless radios

- Time Division Duplexing



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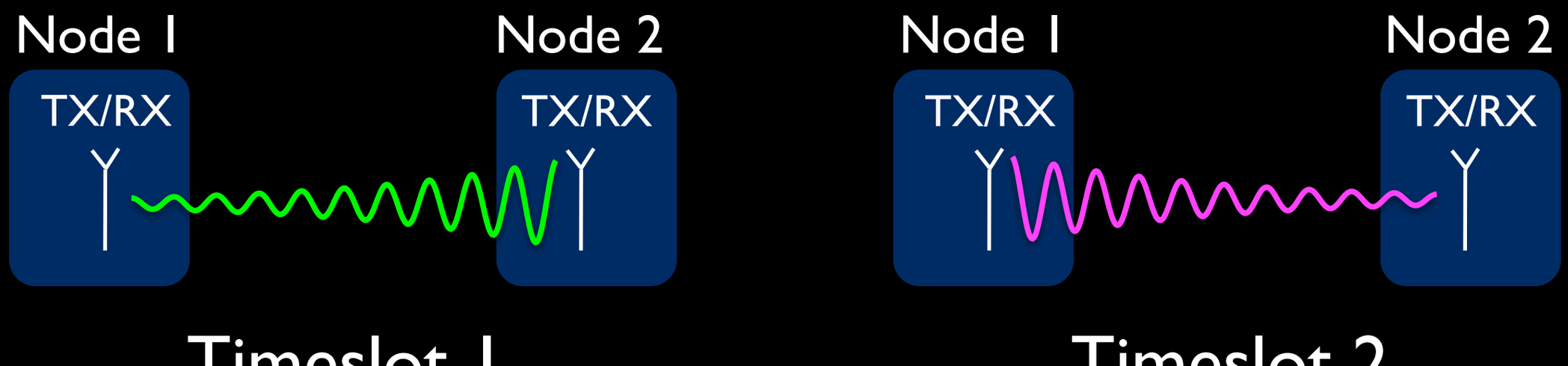
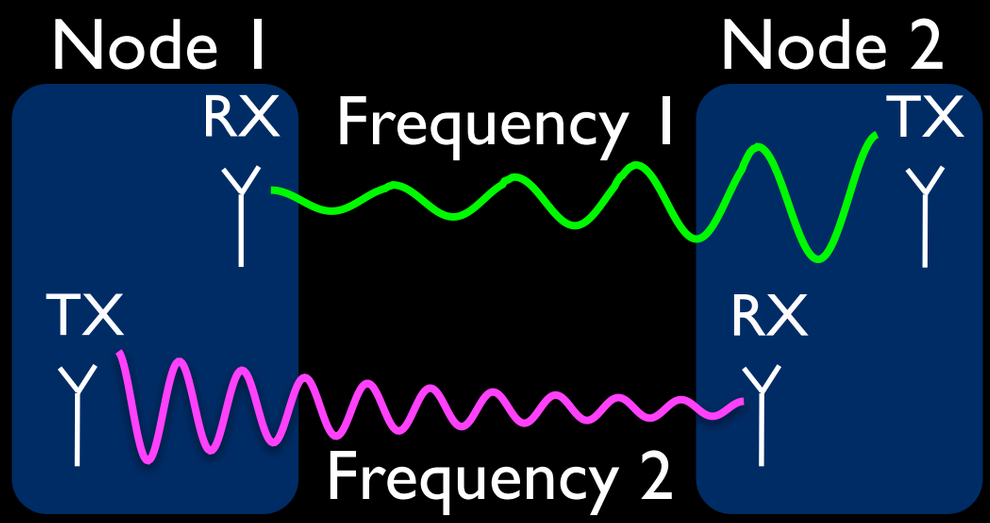
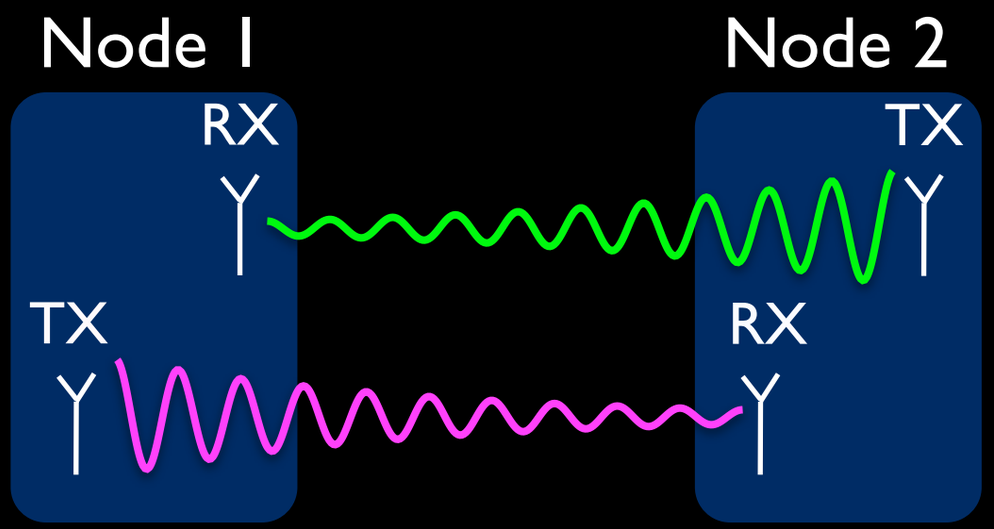


- Frequency Division Duplexing

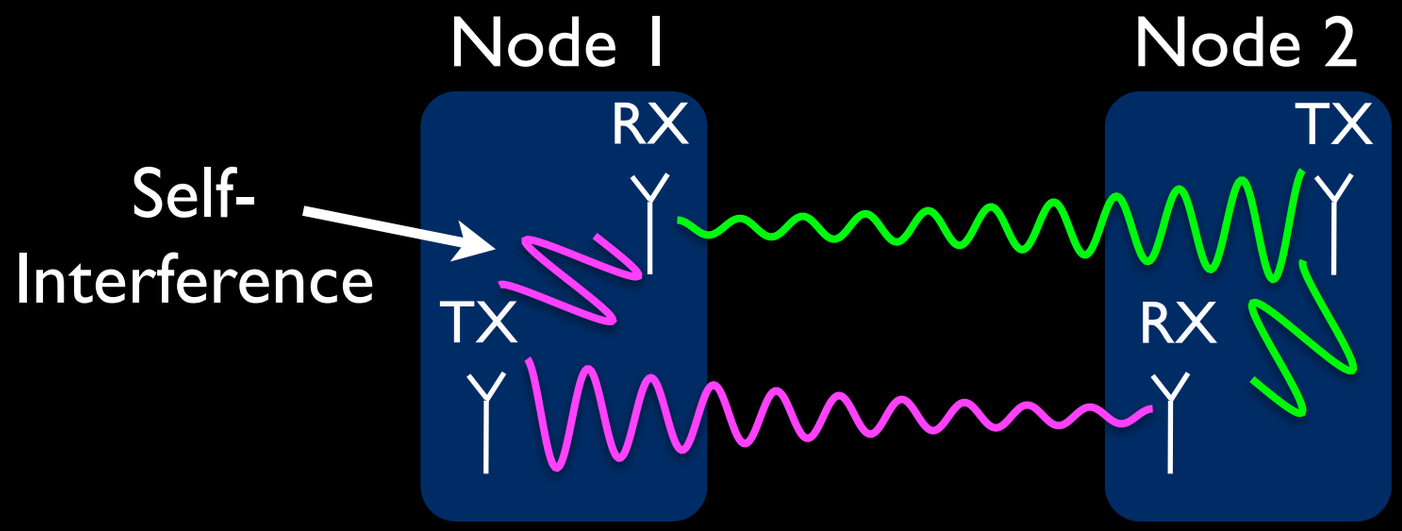


Single channel full-duplex



Single channel full-duplex

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



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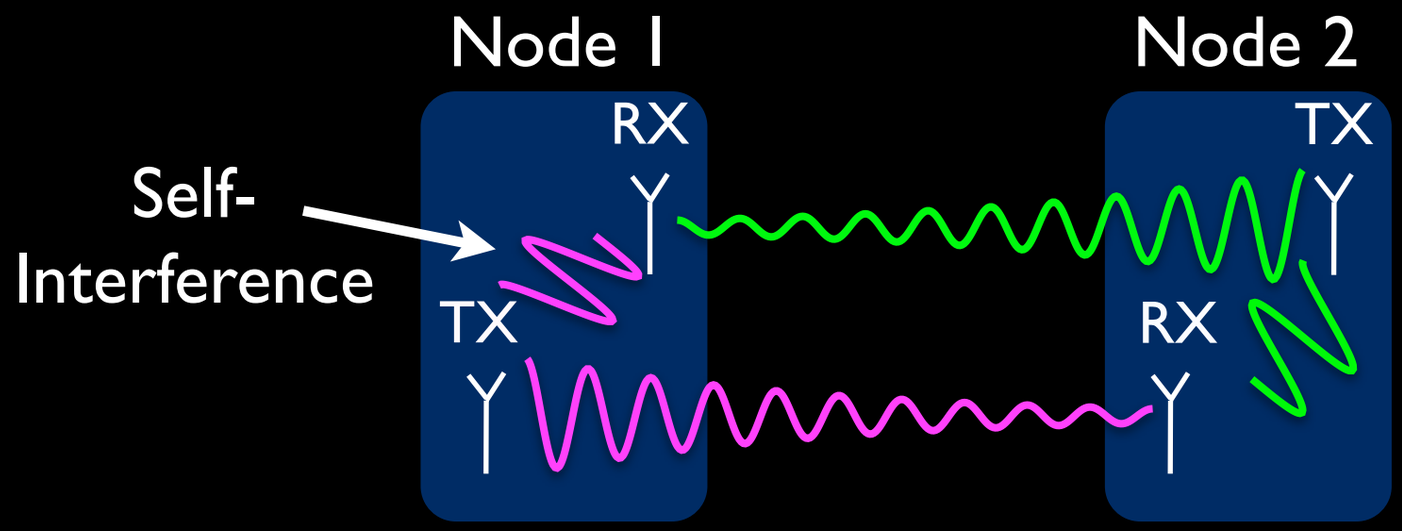


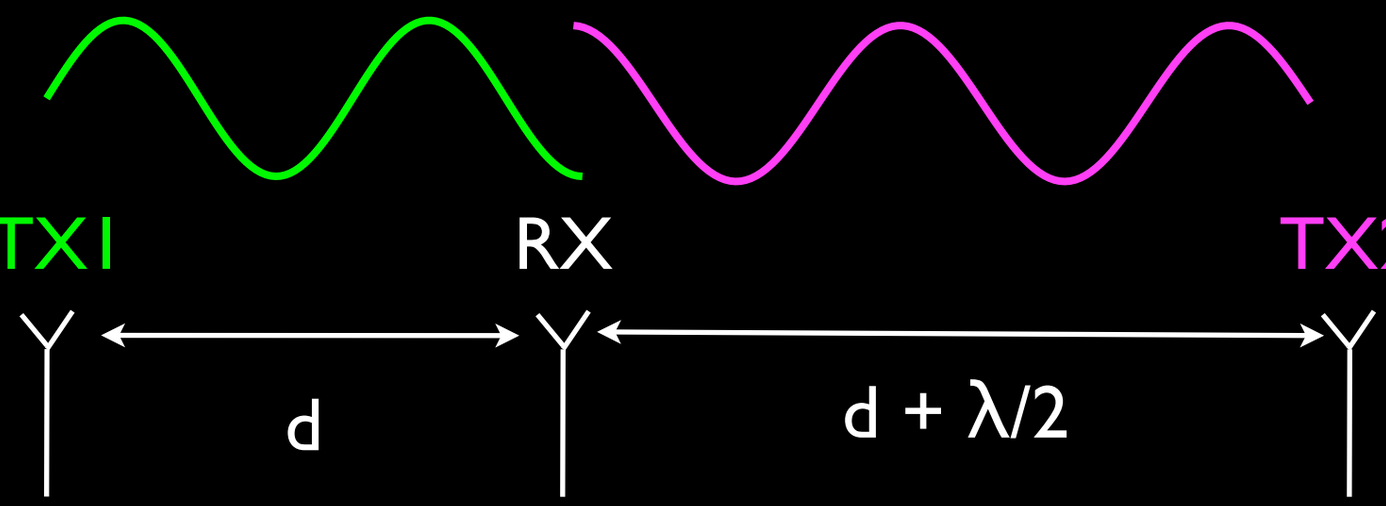
Main idea: cancel self-interference

Combine RF and digital techniques for cancellation

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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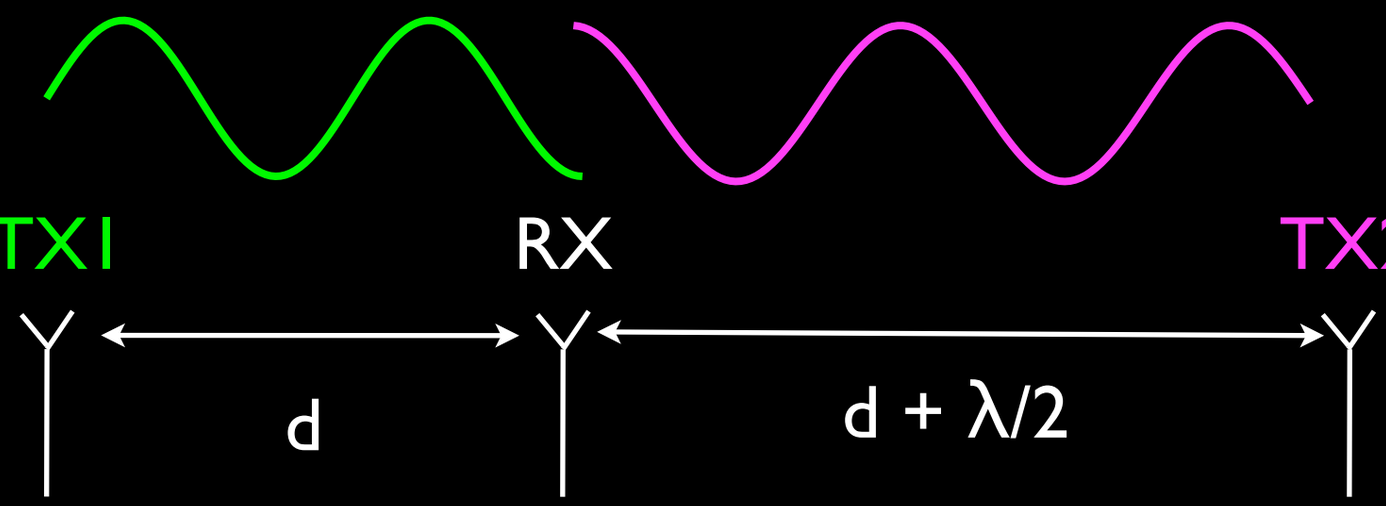

- Does not adapt to channel changes
- Interference pattern can affect intended receivers
- Frequency dependent, narrowband cancellation

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

- New, better RF and digital cancellation techniques
- Adaptive algorithms for auto-tuning cancellation
- Real-time full-duplex MAC layer implementation

Talk Outline

- RF Cancellation using Signal Inversion
- Adaptive RF Cancellation
- System Performance
- Implications to Wireless Networks
- Looking Forward

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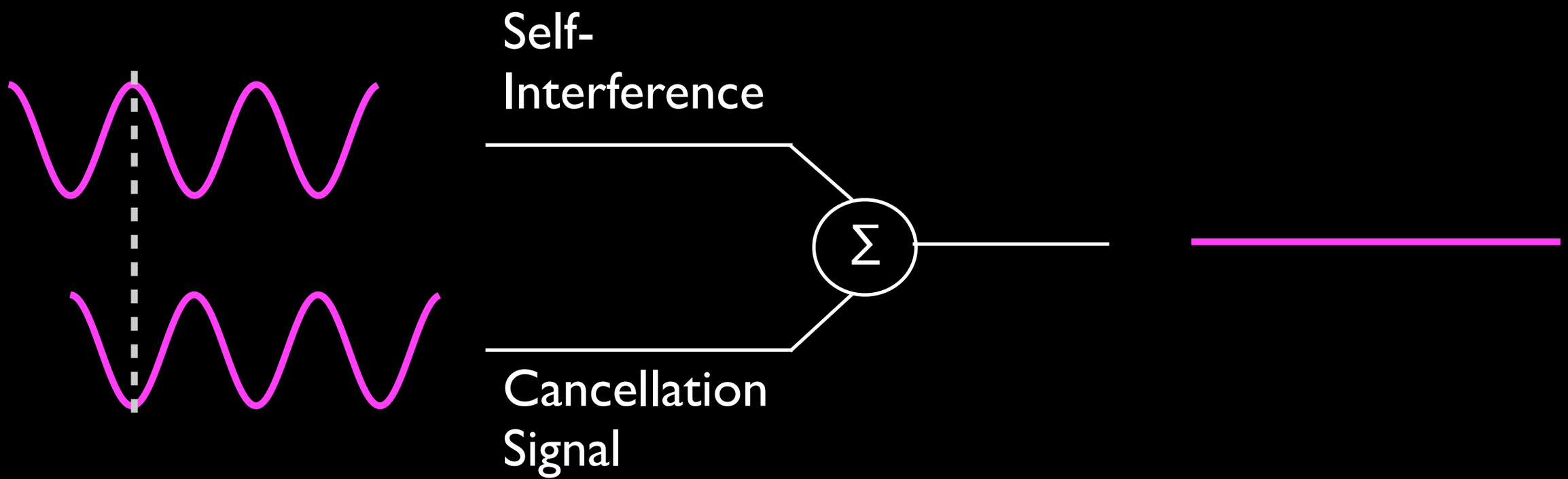
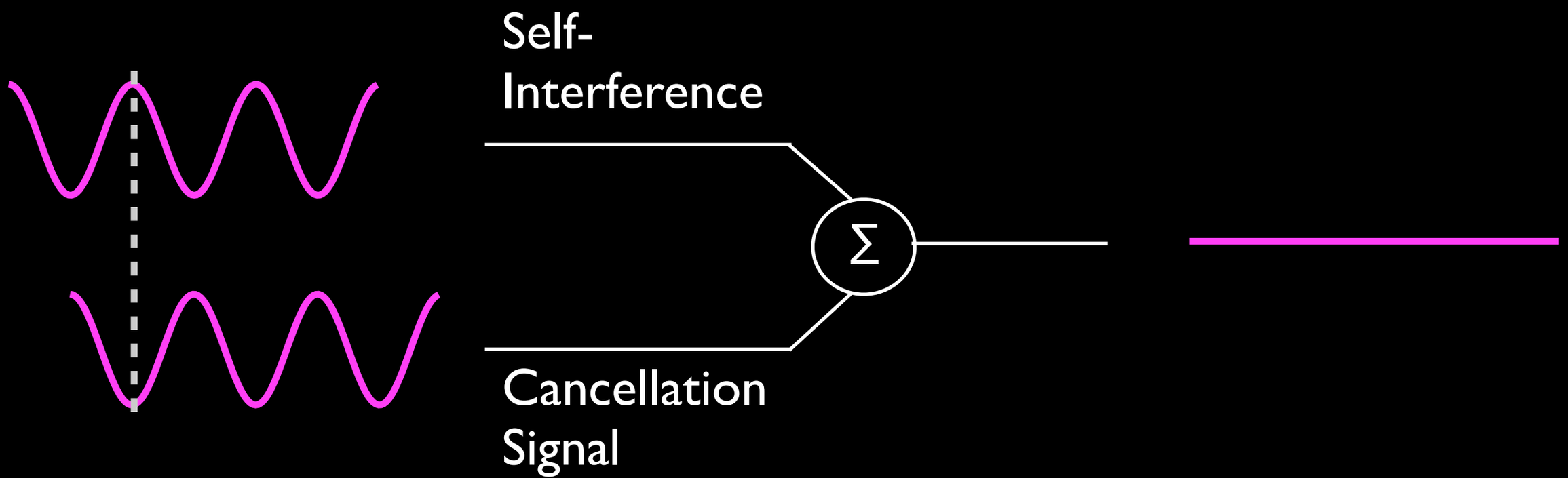
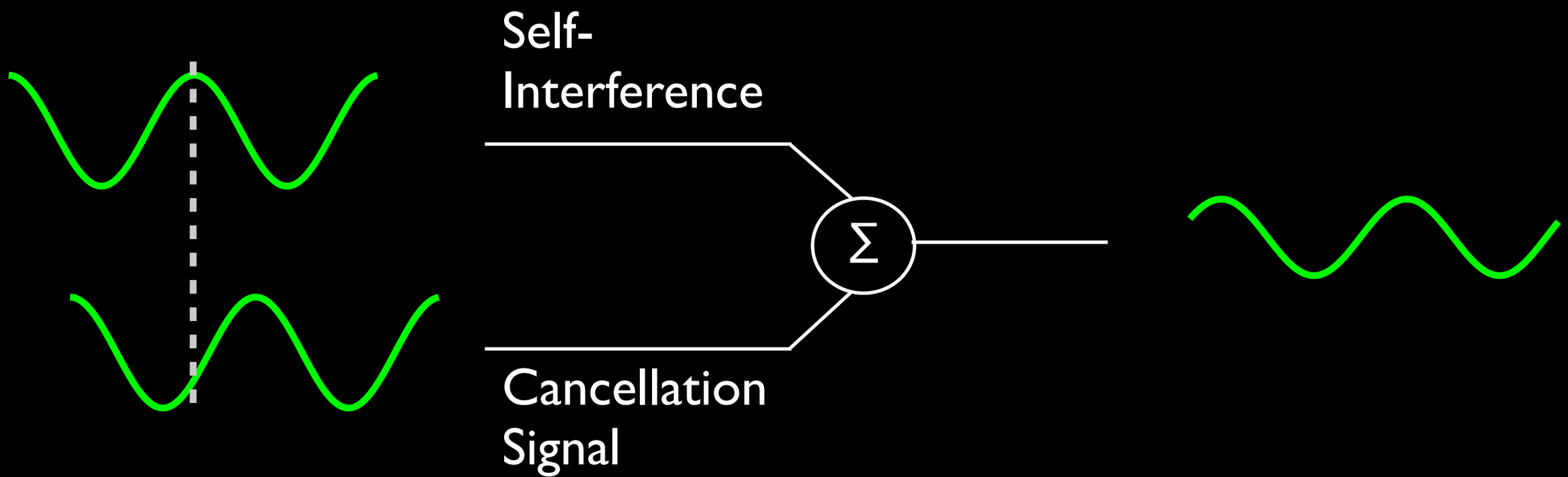
Cancellation using Phase Offset



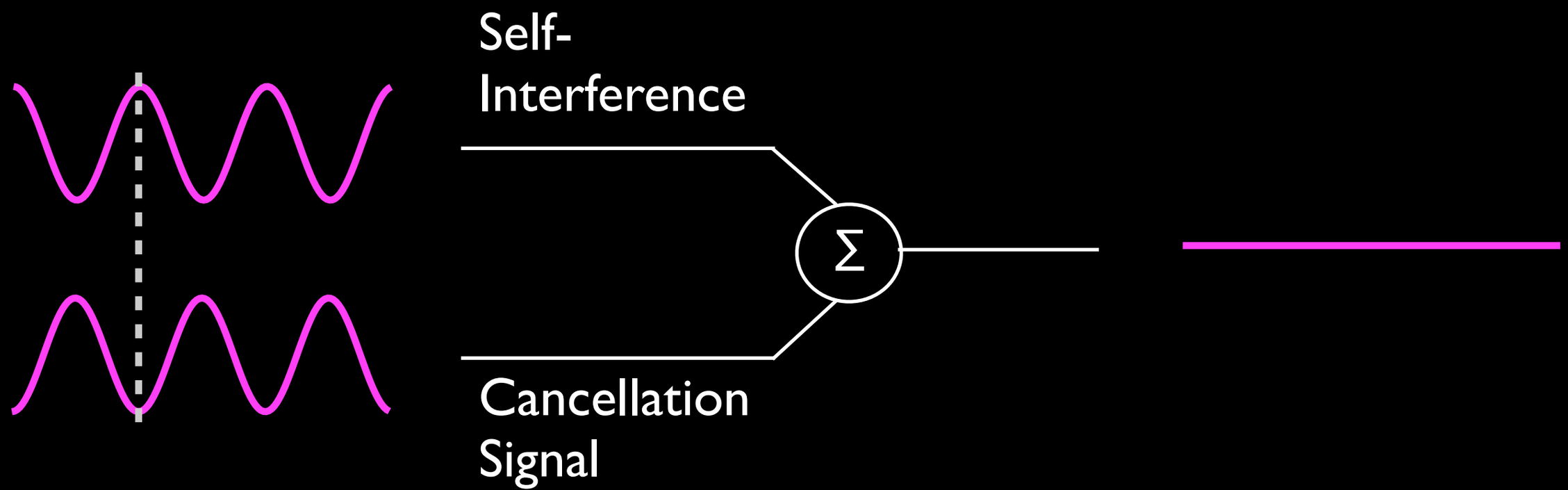
Cancellation using Phase Offset



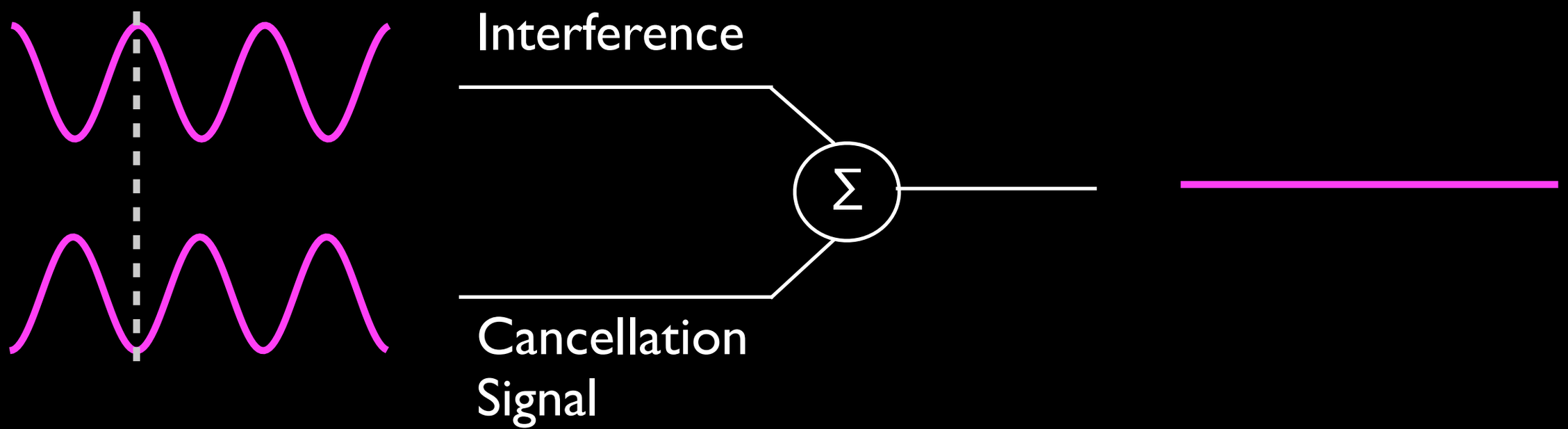


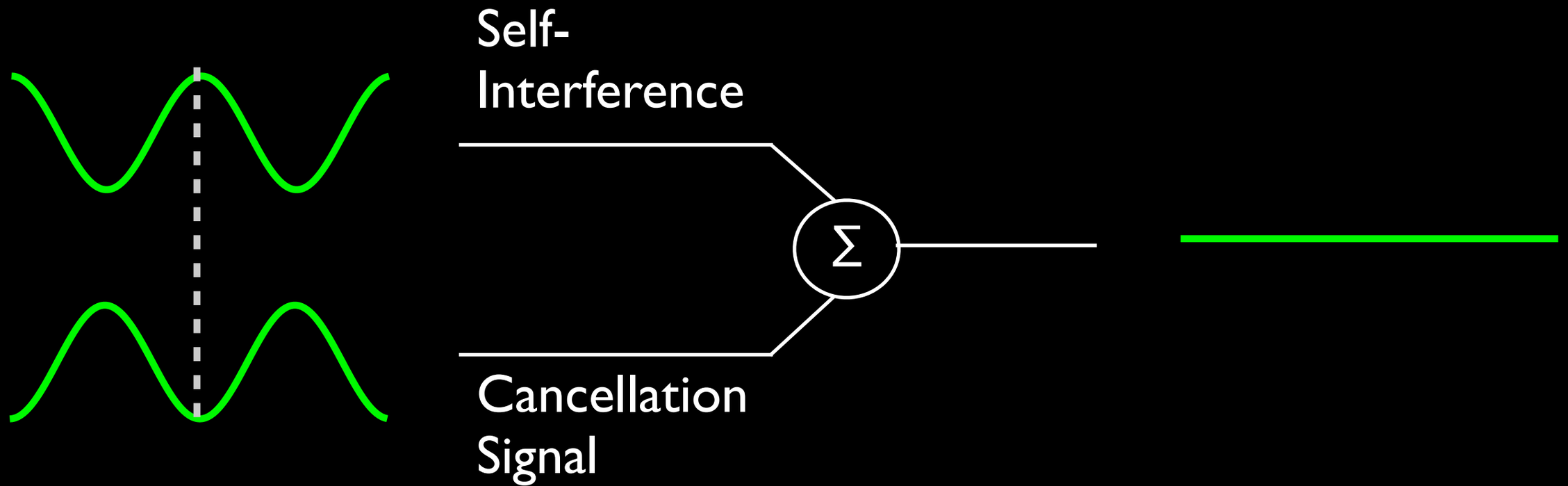
Frequency dependent, narrowband

Cancellation using Signal Inversion



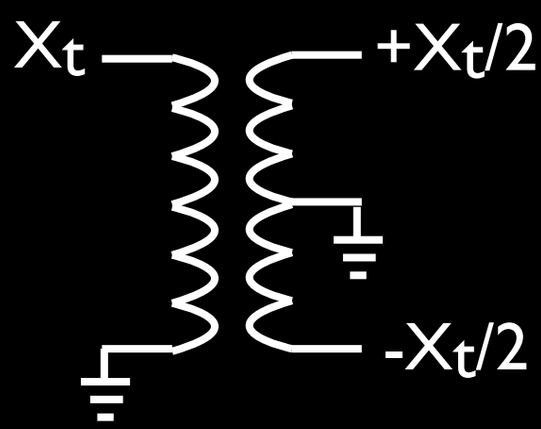
Cancellation using Signal Inversion





Frequency and bandwidth independent

BALUN : Balanced to Unbalanced Conversion



BALUN

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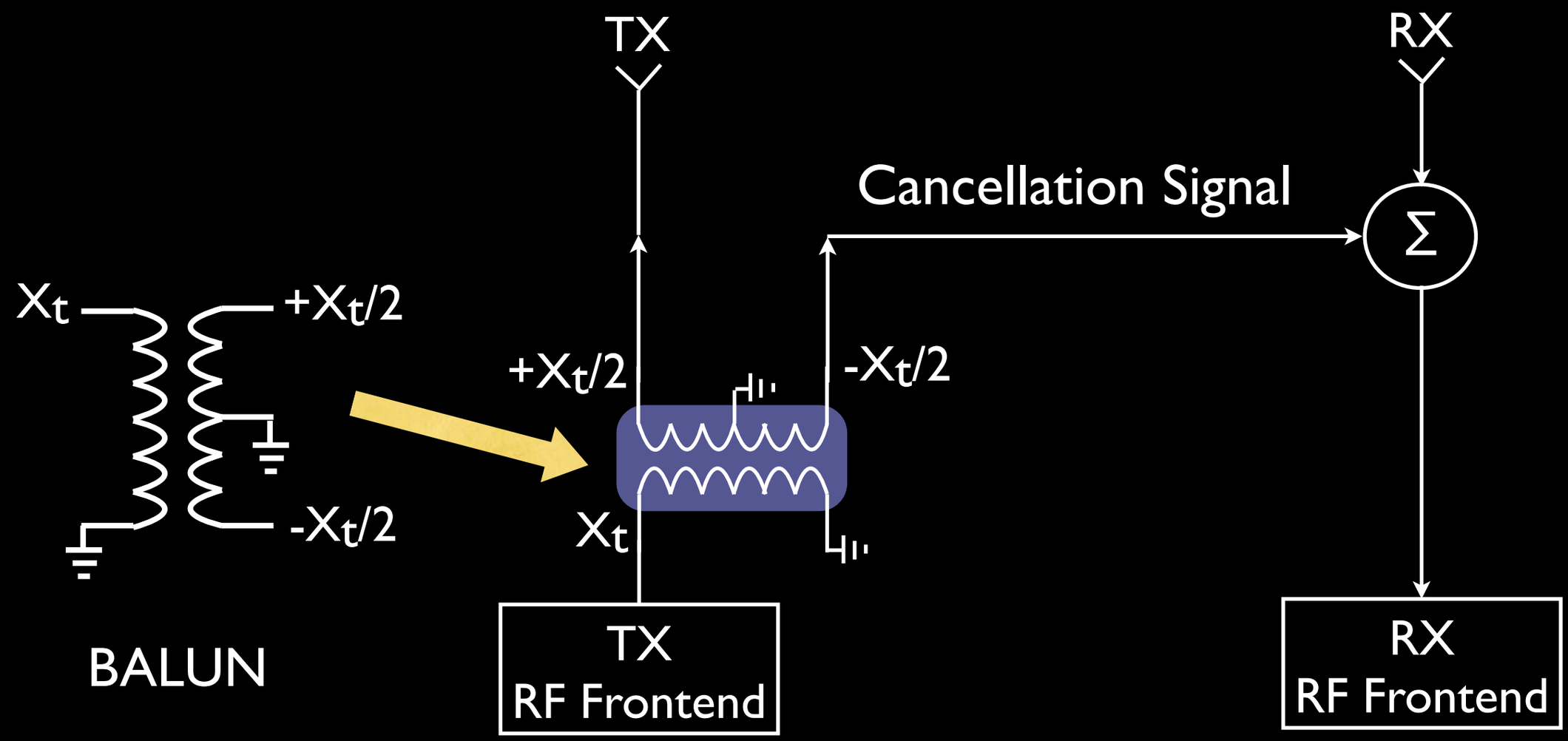
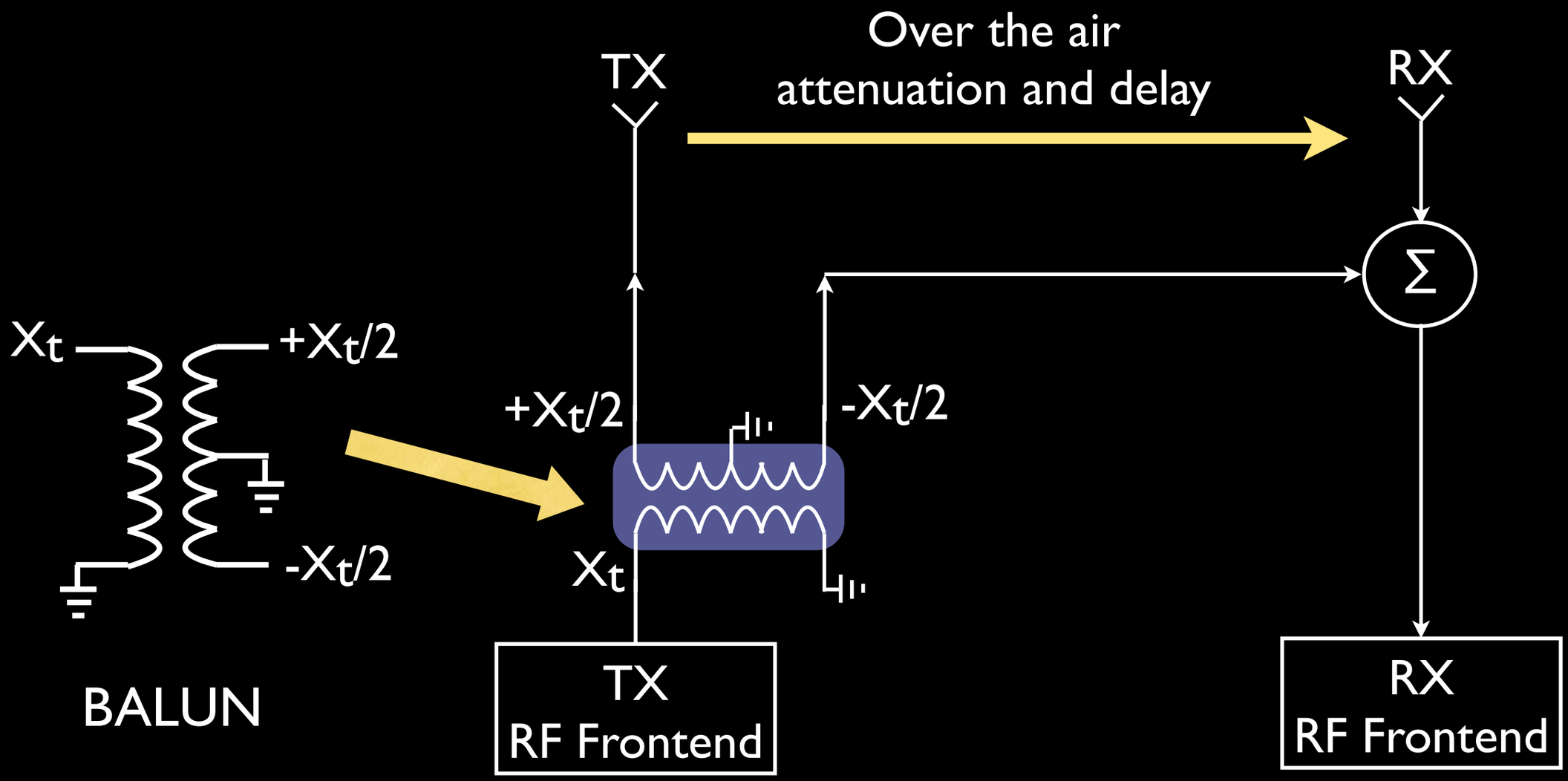
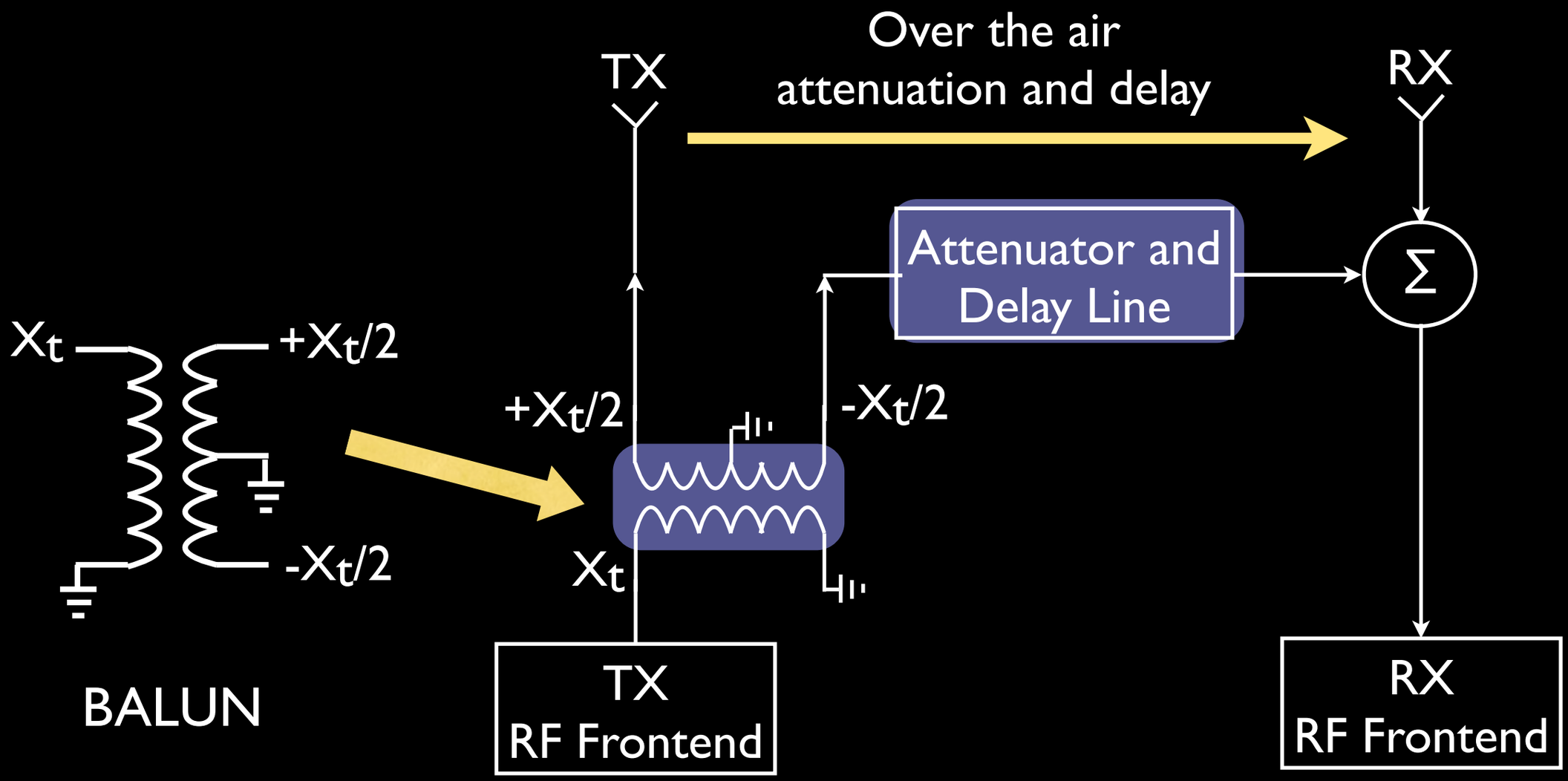



Over the air
attenuation and delay
TX
RX
Σ
Xt
+Xt/2
-Xt/2
+Xt/2
-Xt/2
Xt
BALUN
TX
RF Frontend
RX
RF Frontend

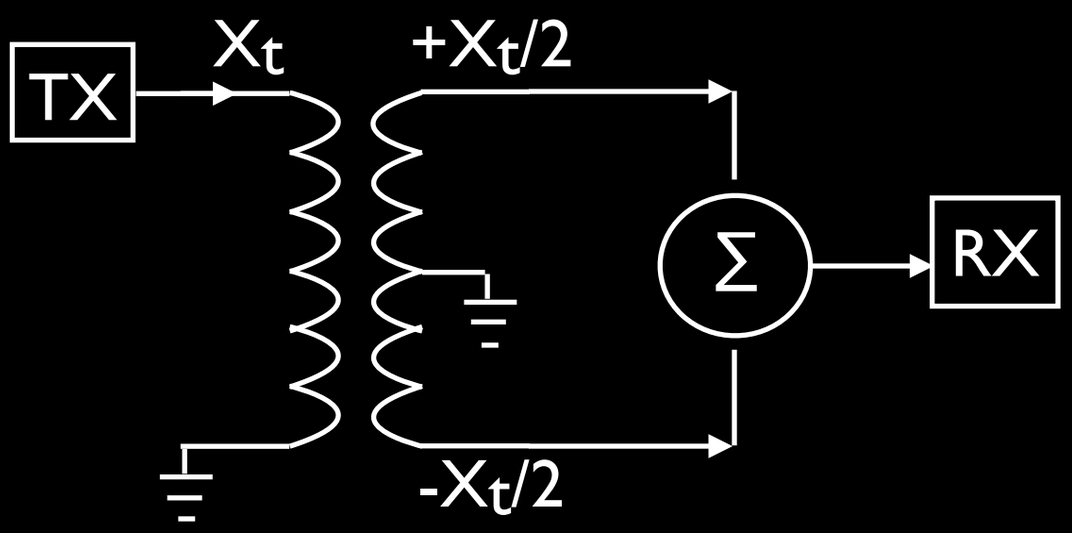
Signal Inversion Cancellation



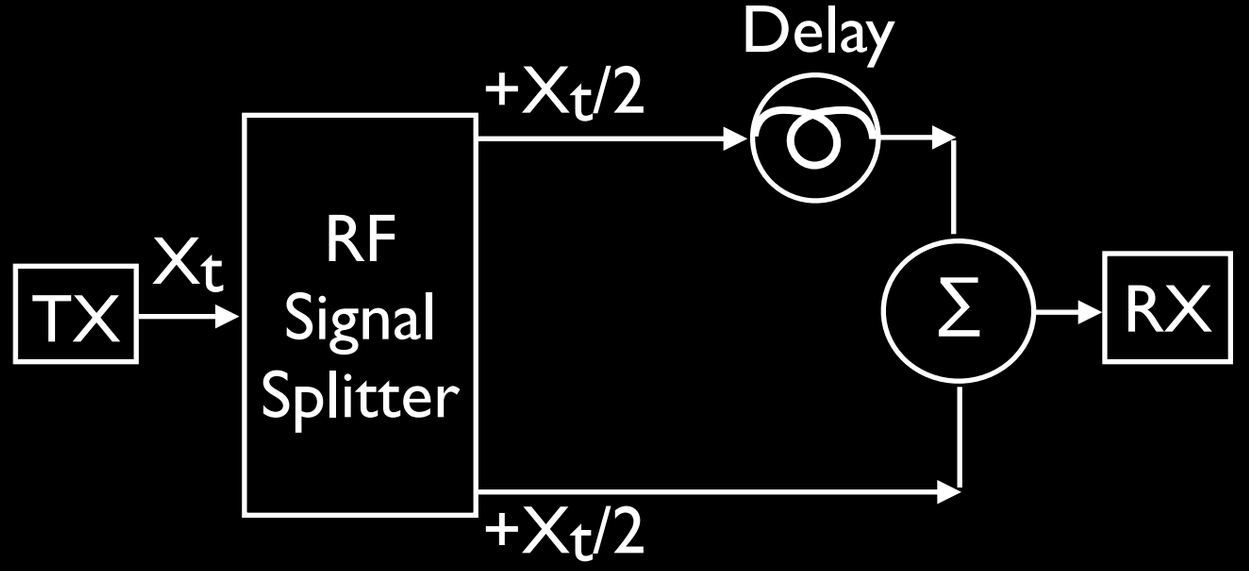
Signal Inversion Cancellation: Wideband Evaluation

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

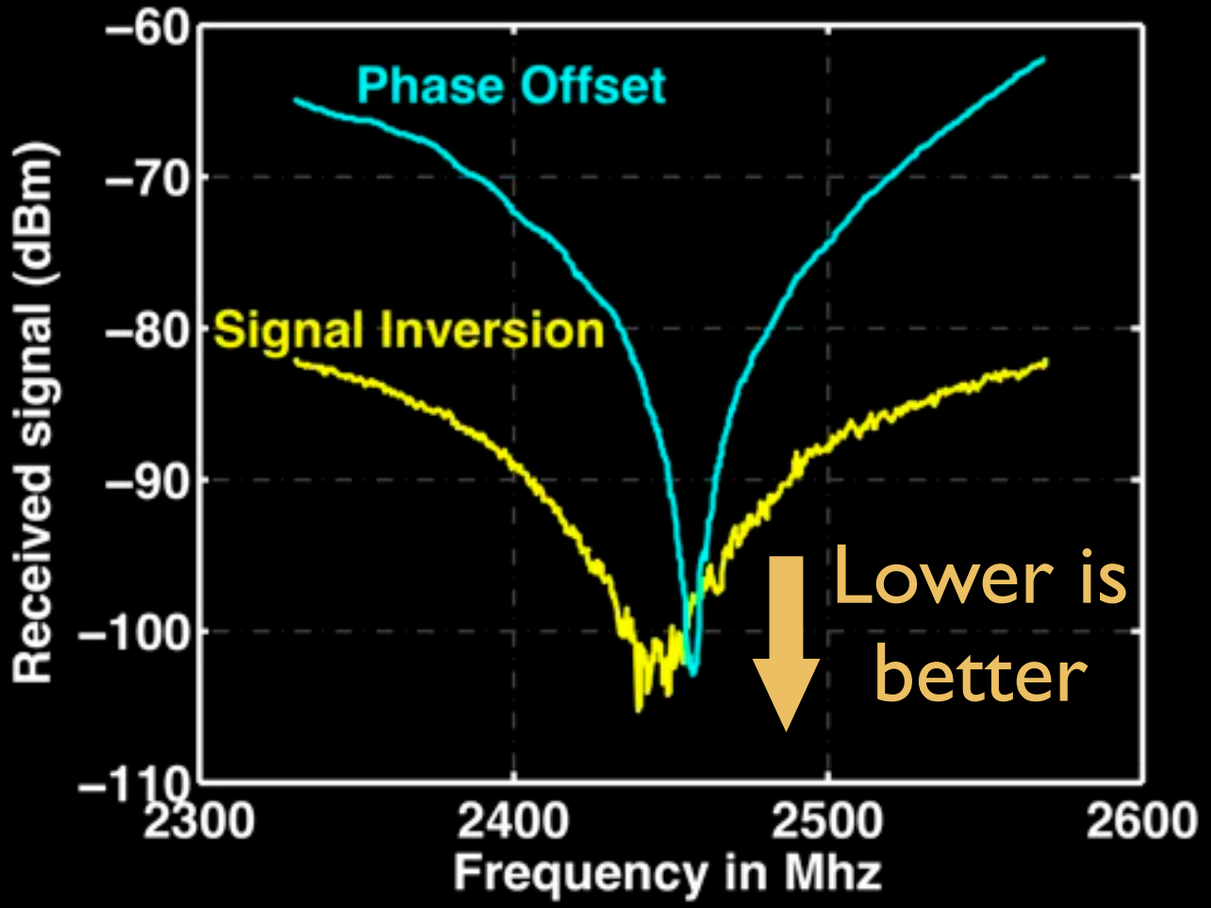
λ/2

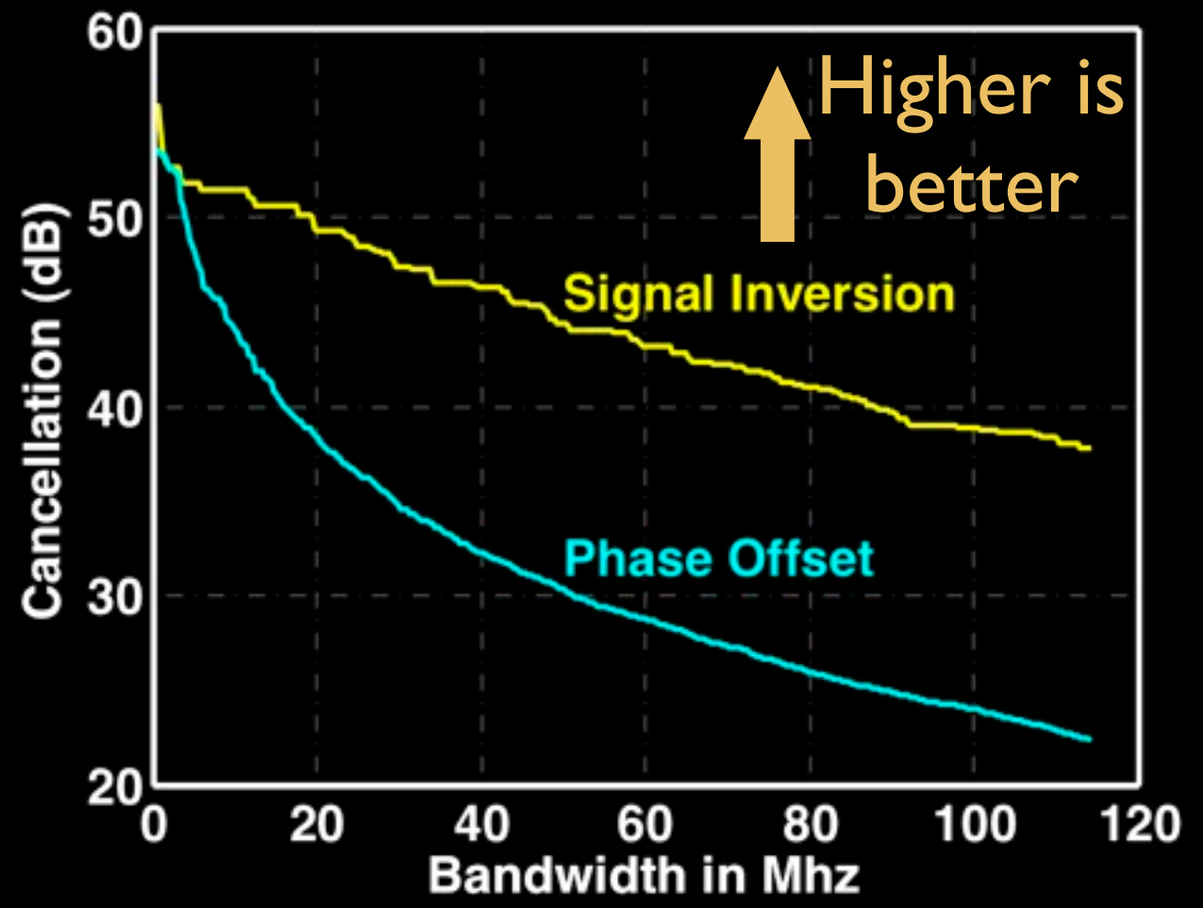


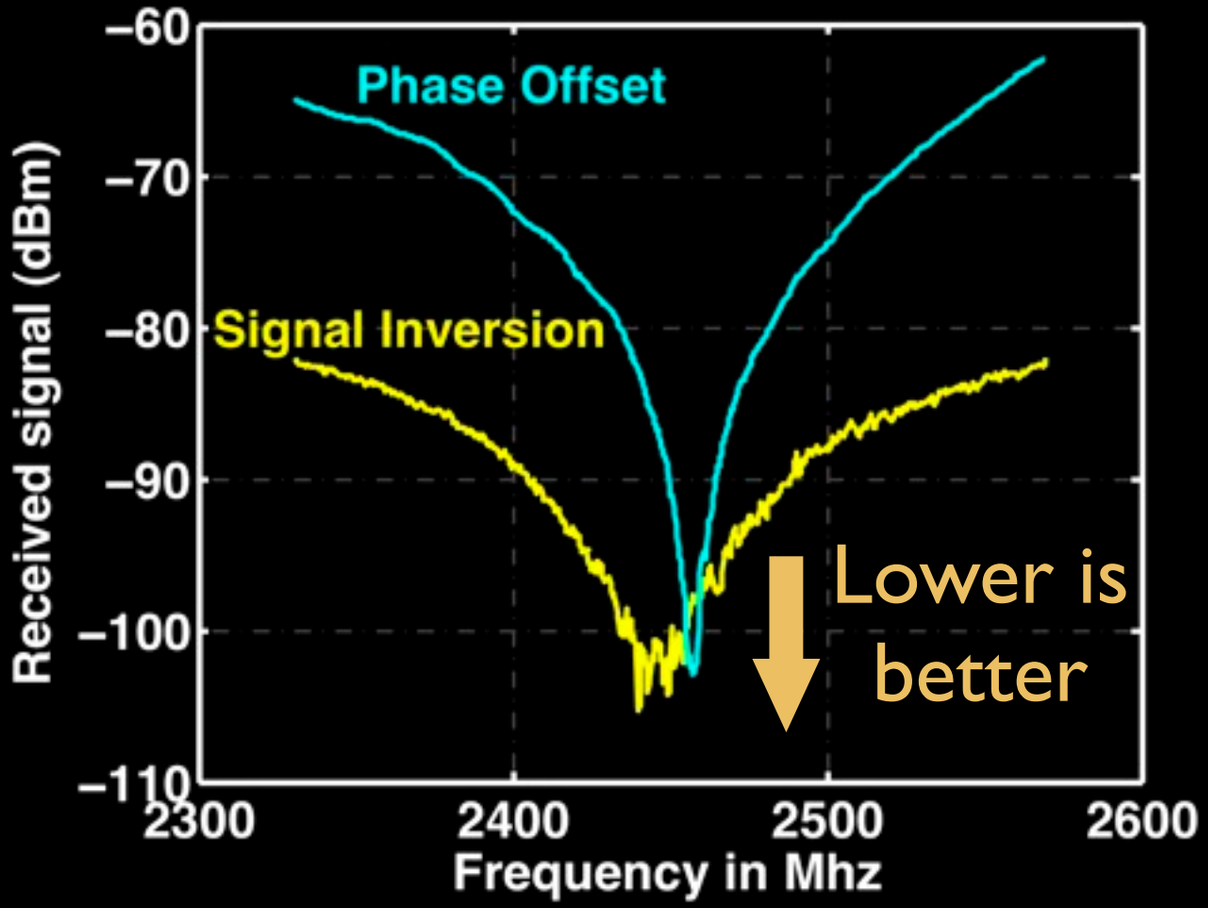
Signal Inversion Cancellation Setup

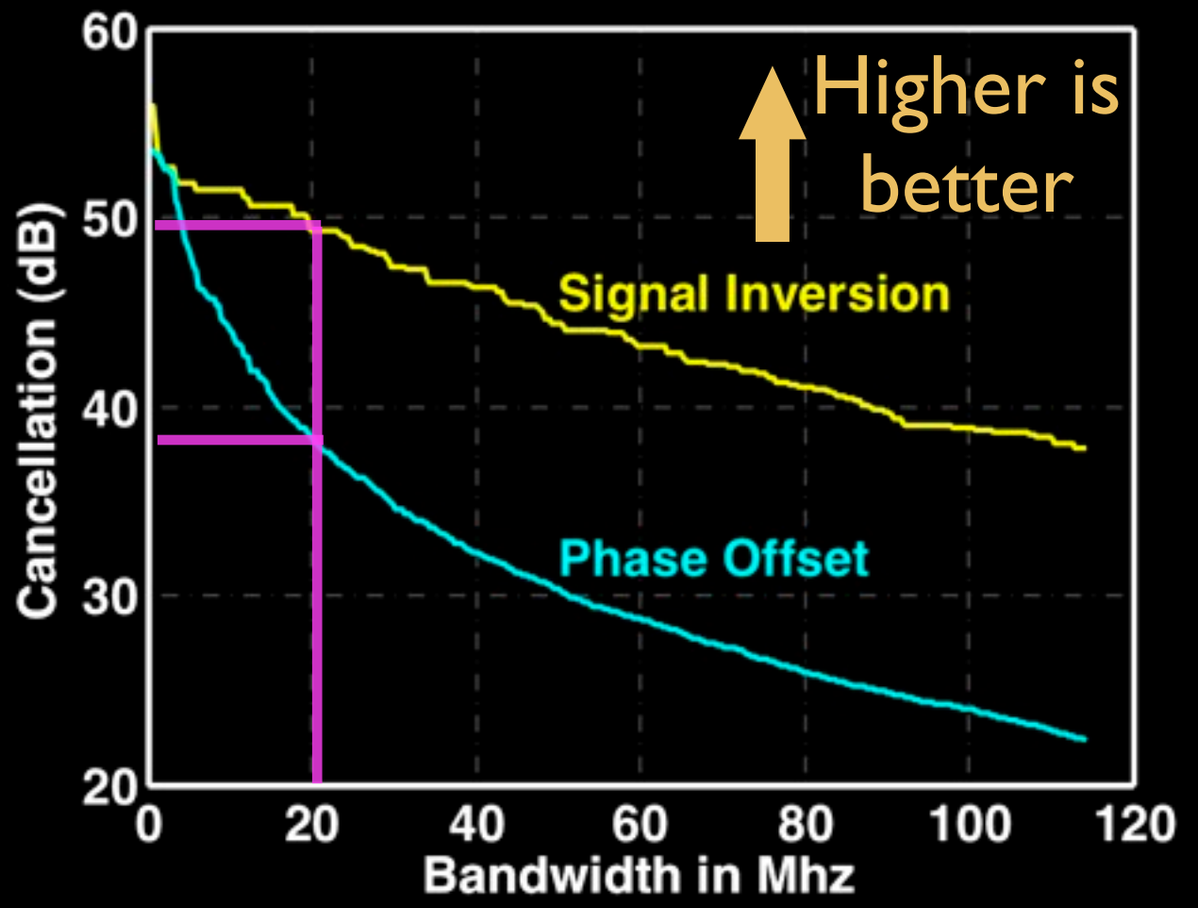


Phase Offset Cancellation Setup


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


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

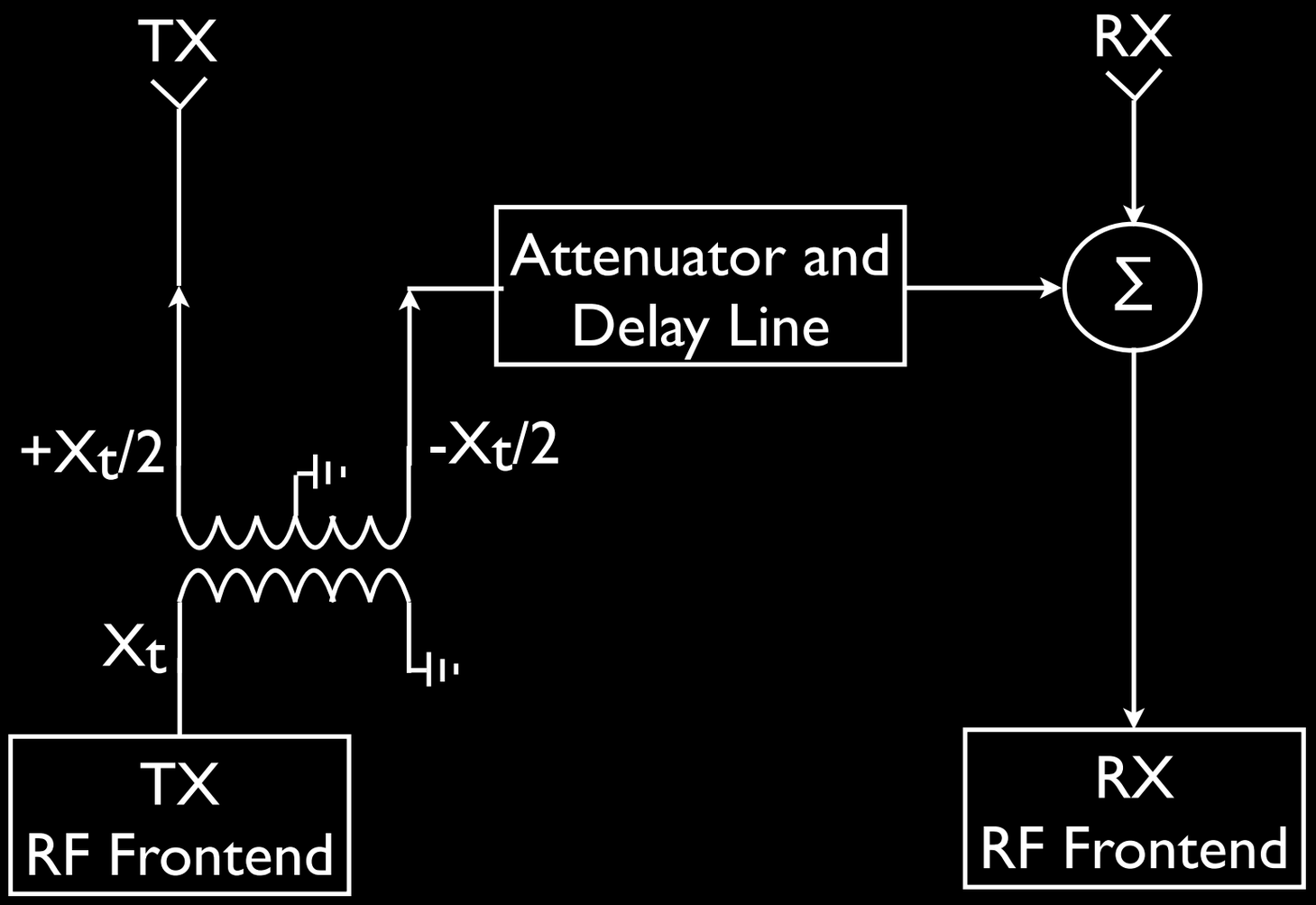




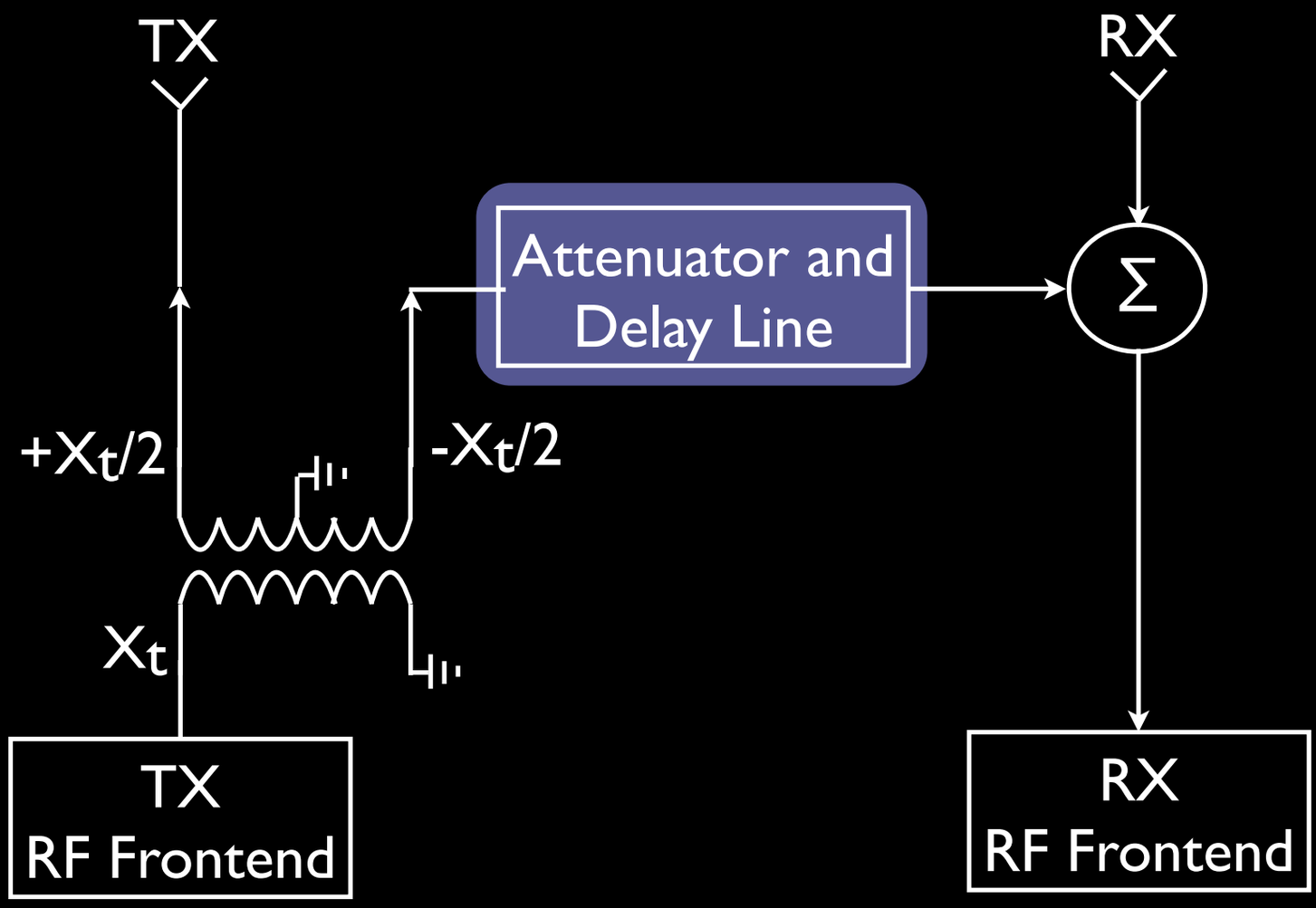
~50dB cancellation at 20MHz bandwidth with balun vs ~38dB with phase offset cancellation.

Significant improvement in wideband cancellation

Other advantages



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



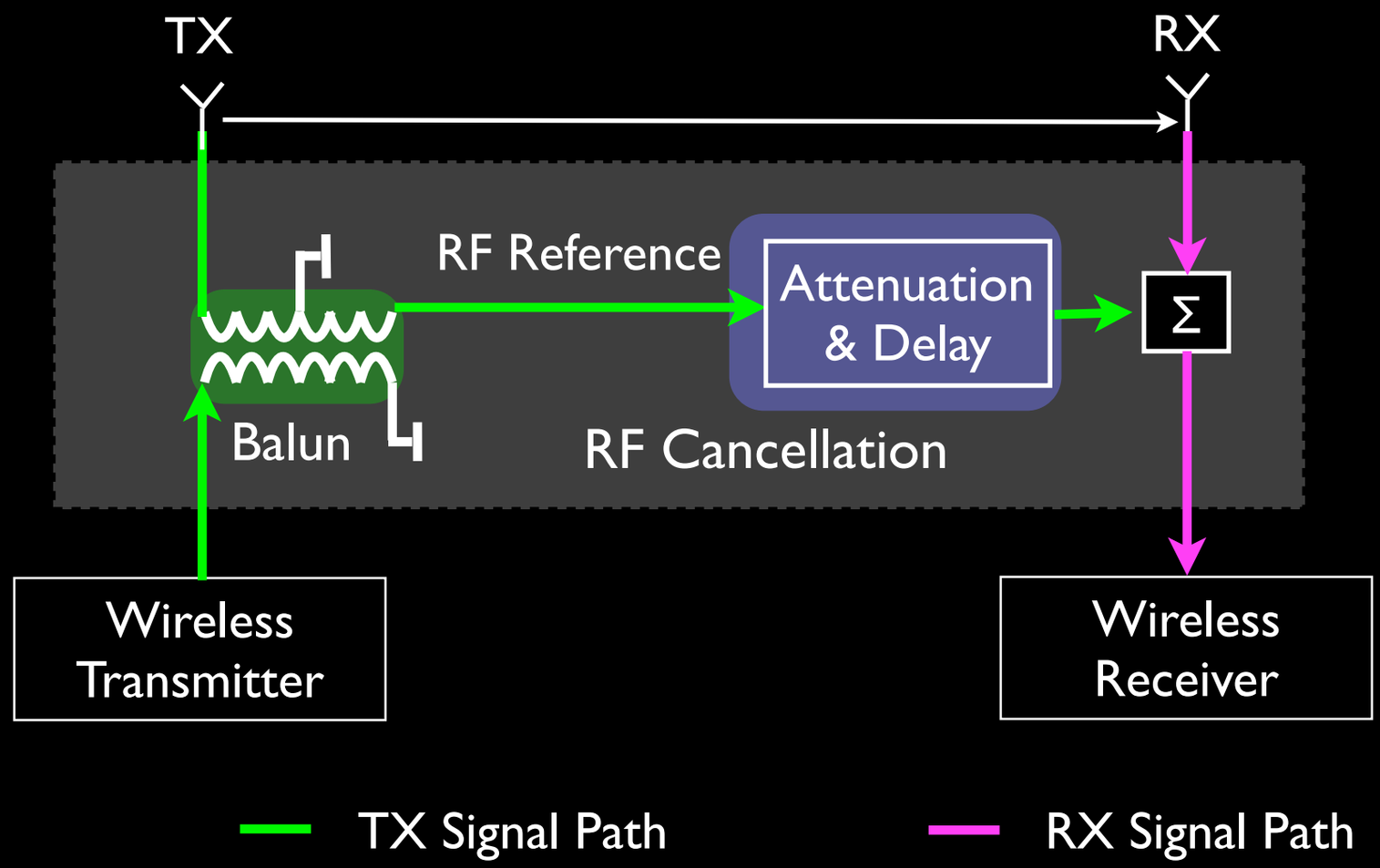
Passive components better than active components

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

Talk Outline

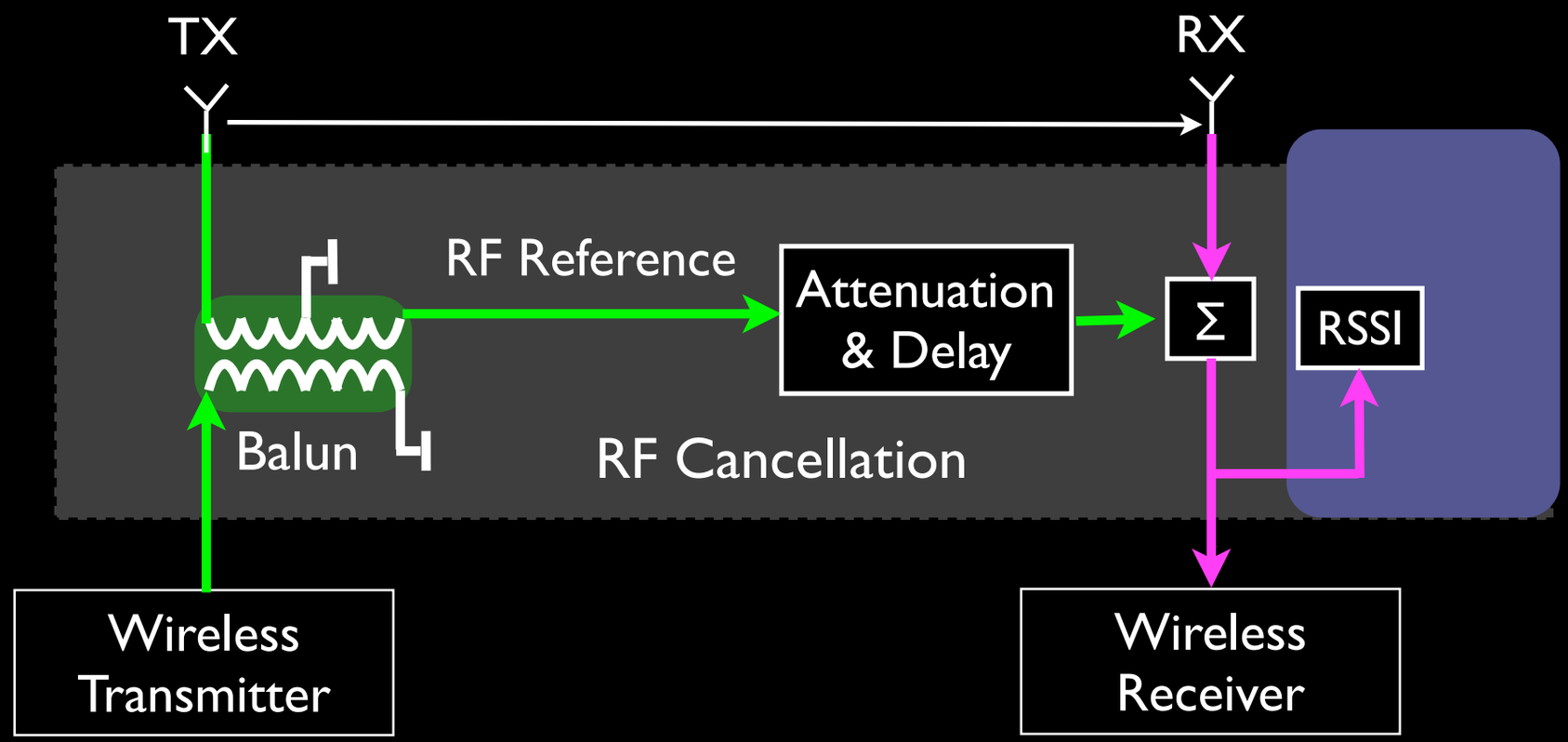
- RF Cancellation using Signal Inversion: ~50dB for 20Mhz
- Adaptive RF Cancellation
- Adaptive Digital Cancellation
- System Performance
- Implications to Wireless Networks
- Looking Forward

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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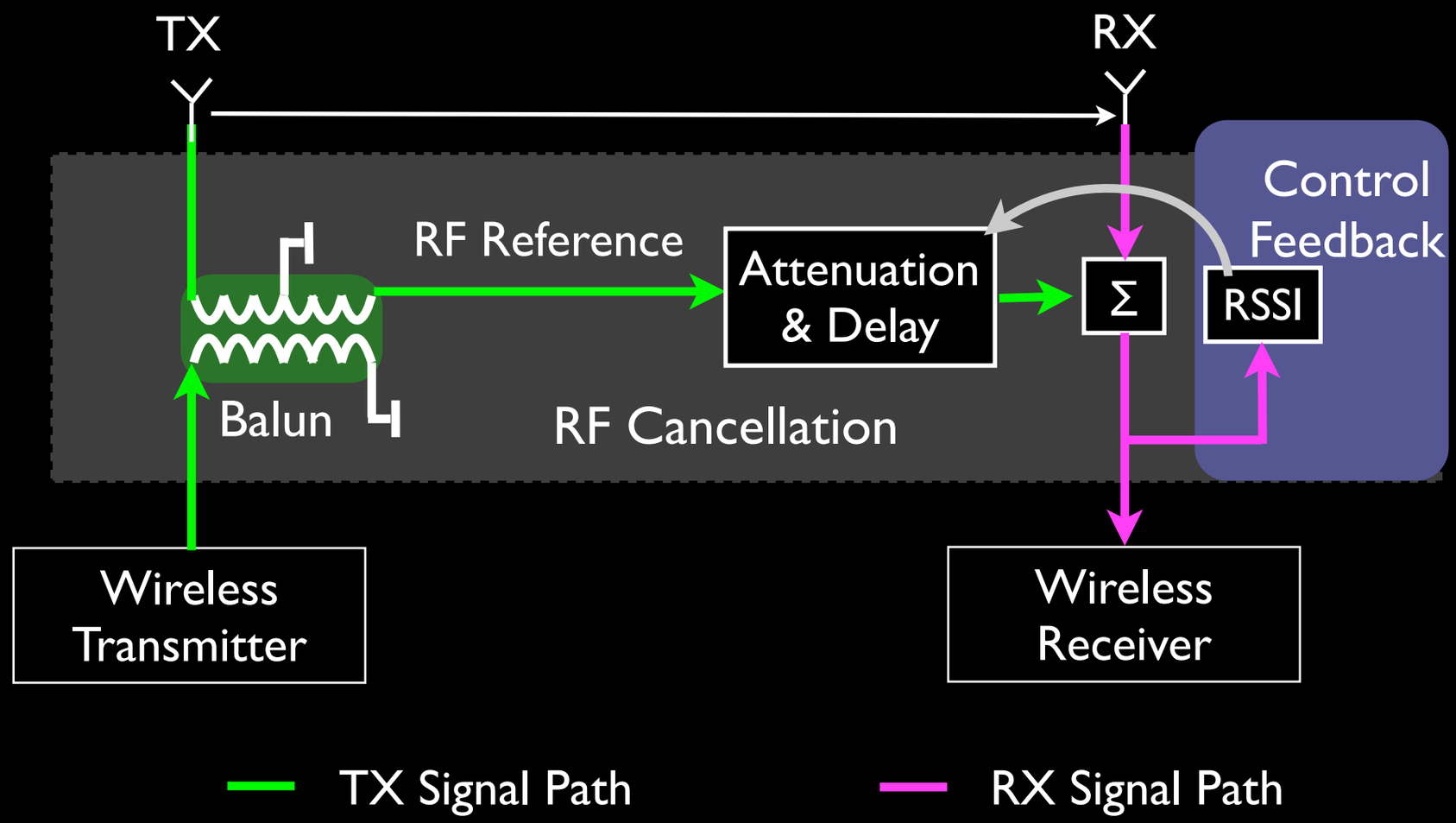
RSSI : Received Signal Strength Indicator

Adaptive RF Cancellation



- Need to match self-interference power and delay
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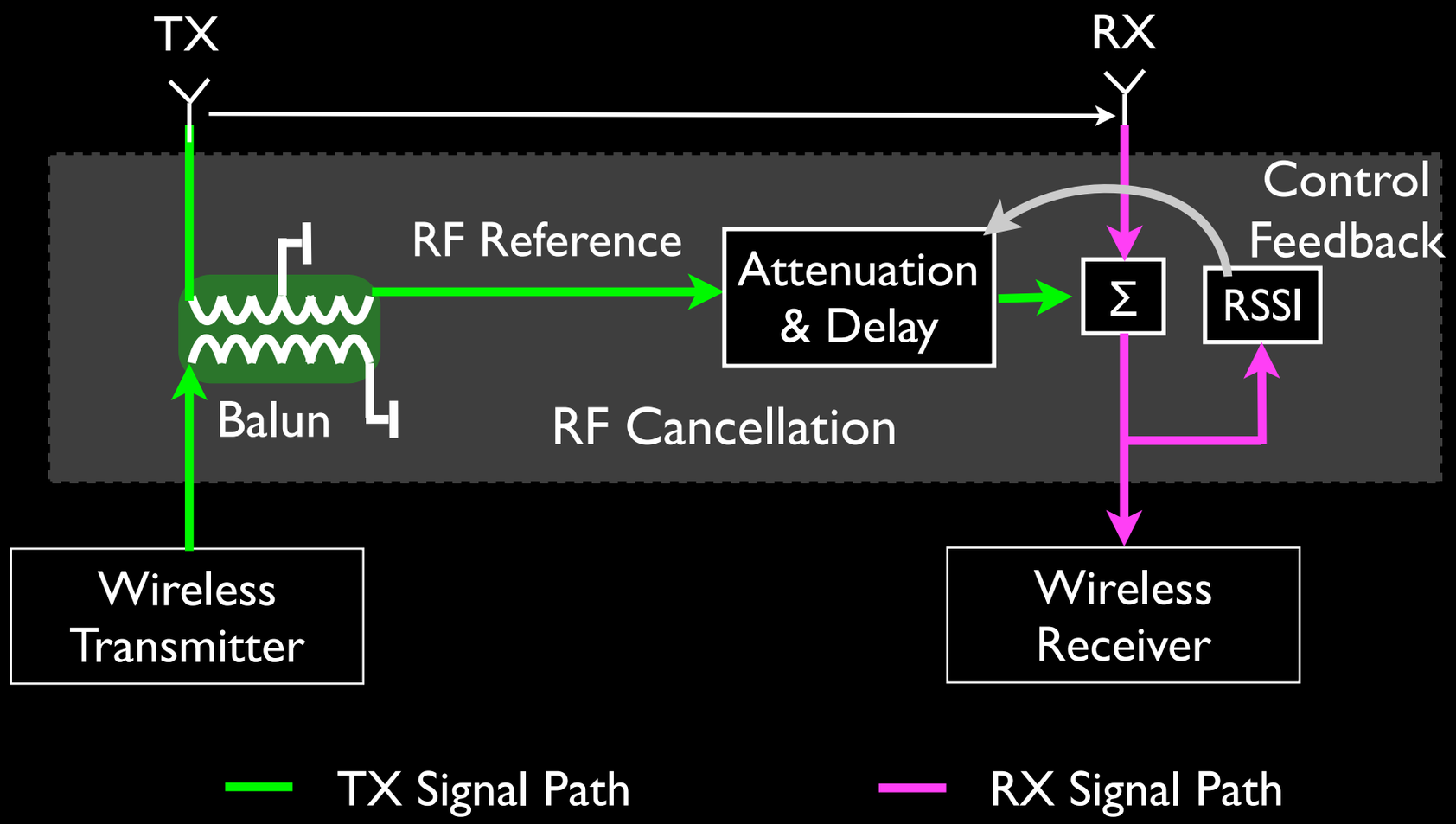
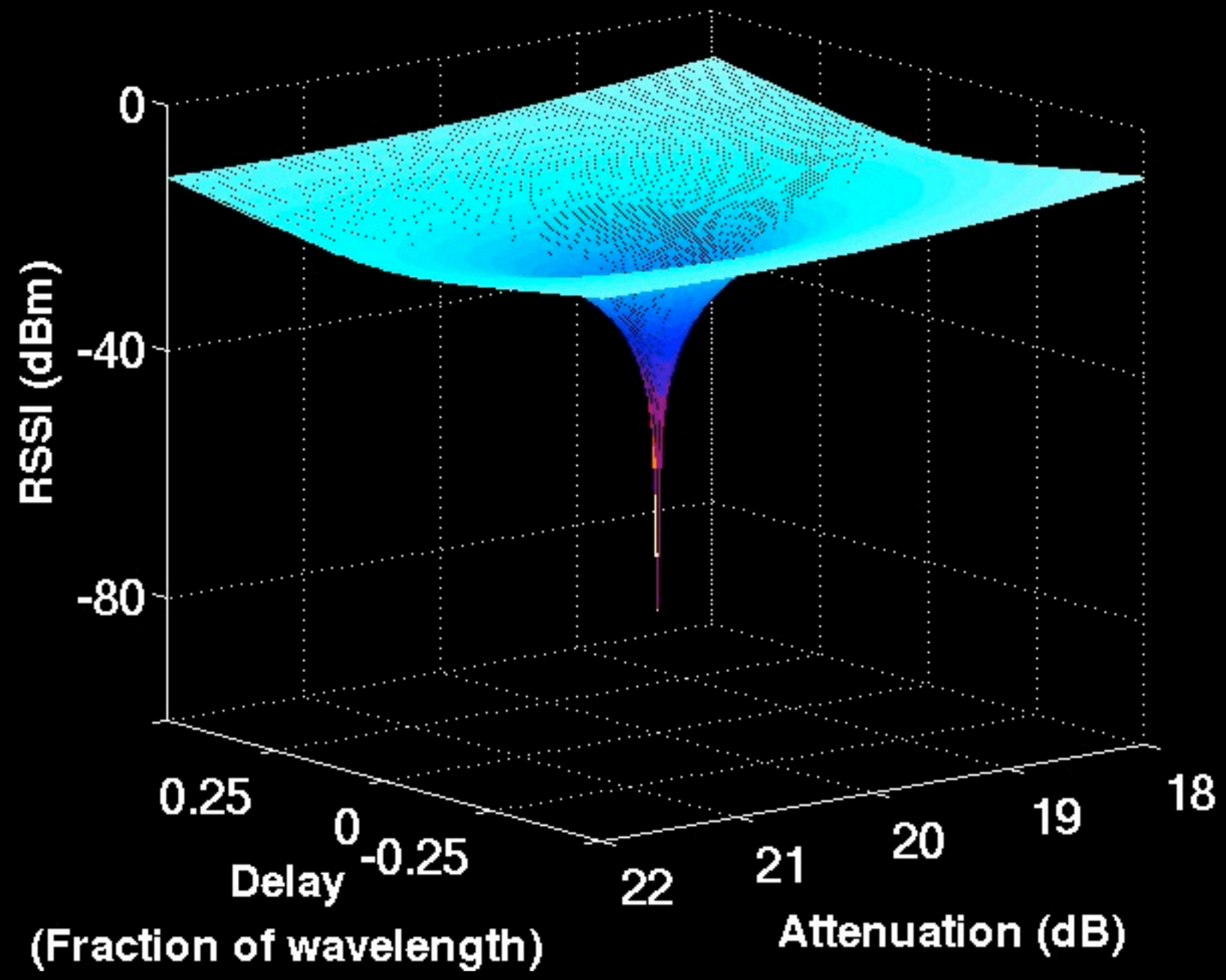
Use RSSI as an indicator of self-interference



Objective: Minimize received power

Control variables: Delay and Attenuation



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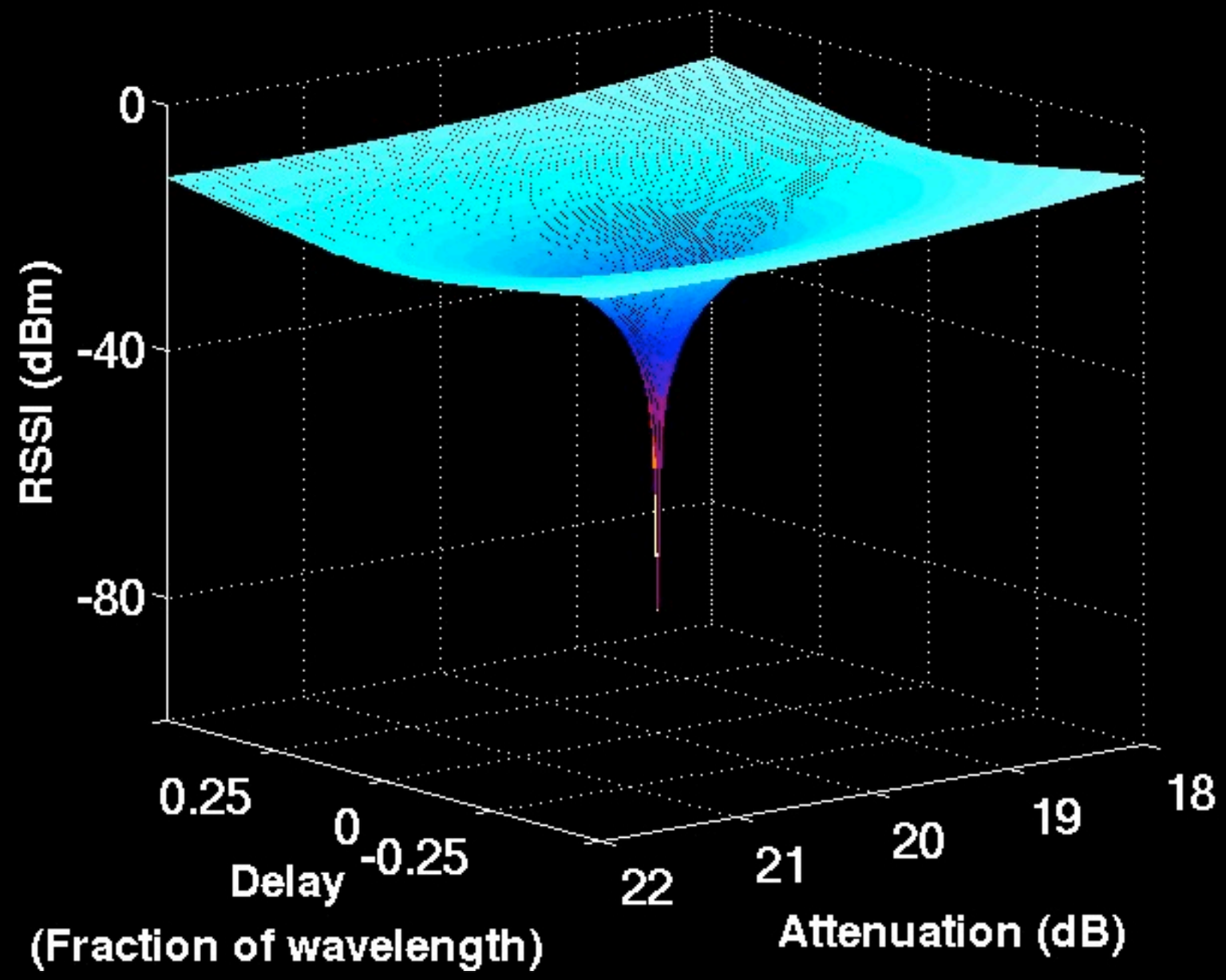

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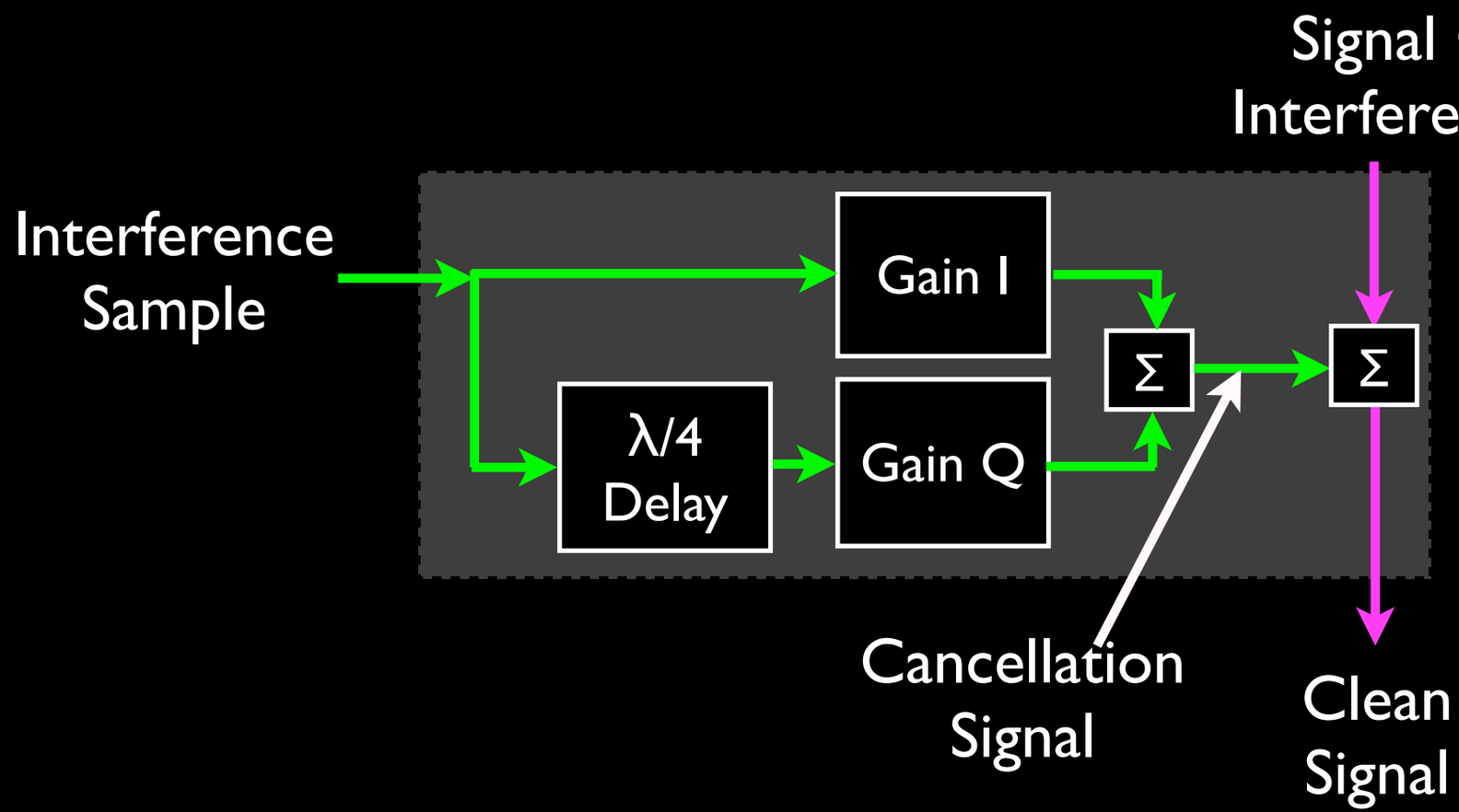
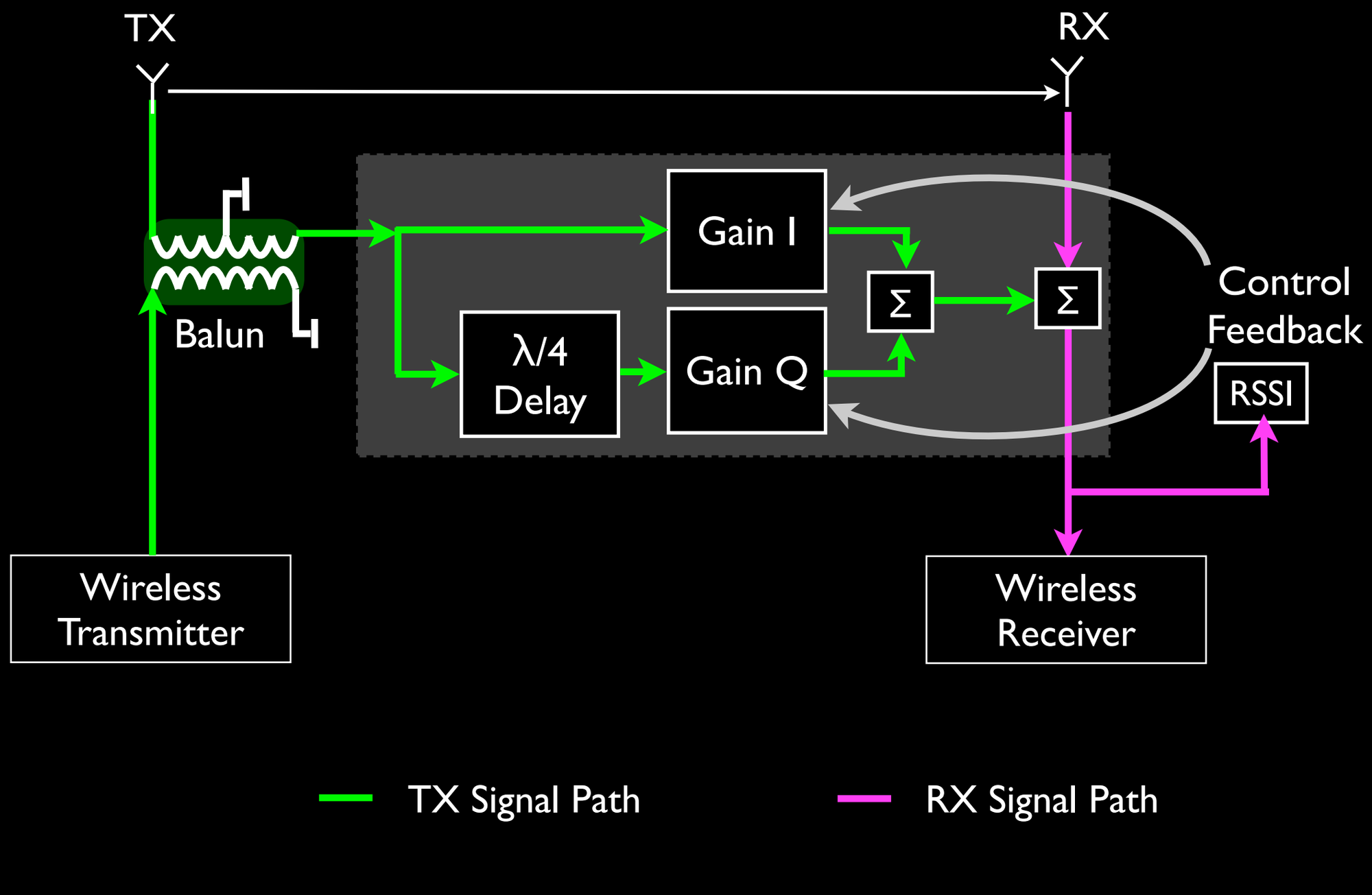
→ Simple gradient descent approach to optimize

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



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

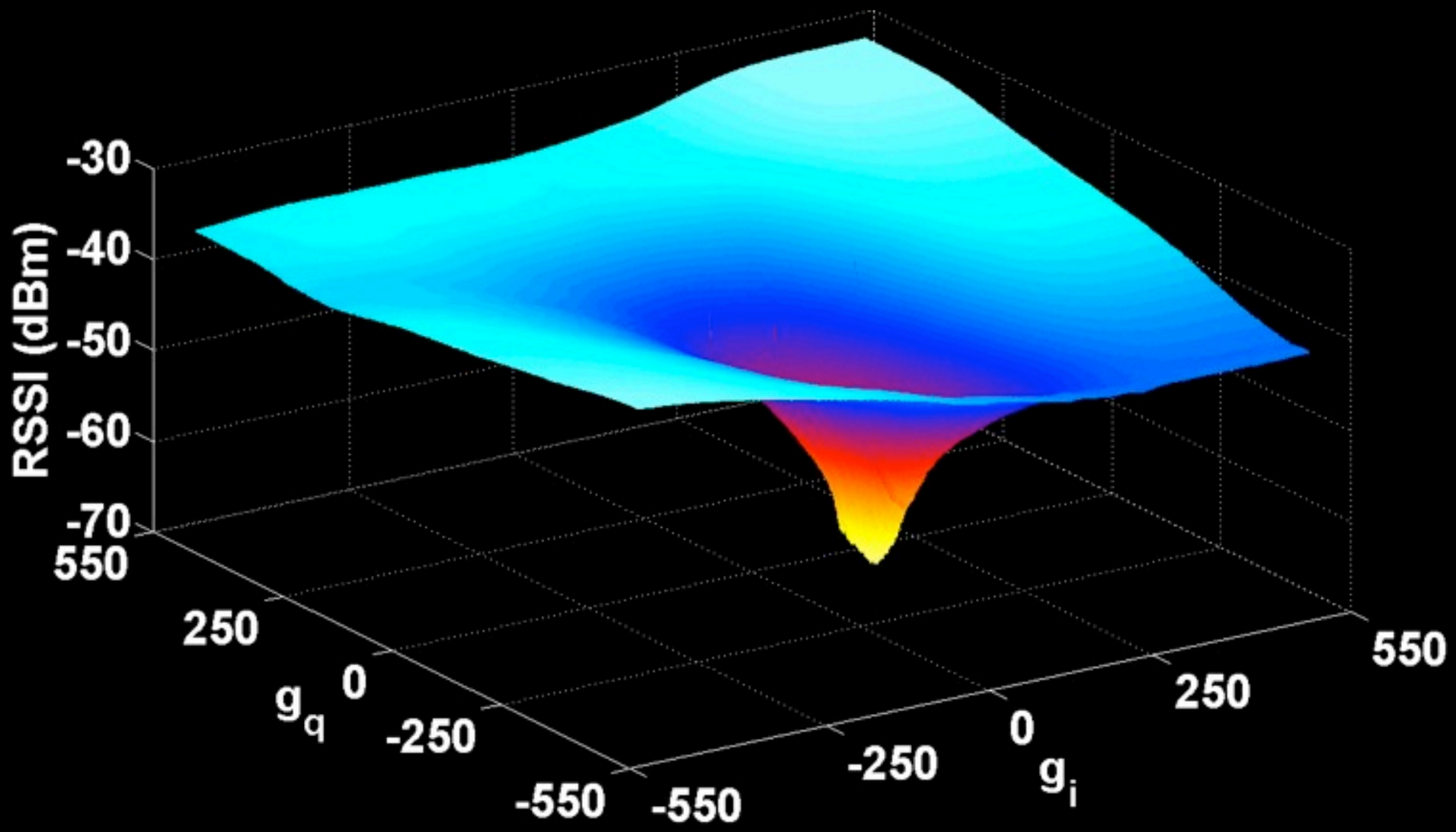


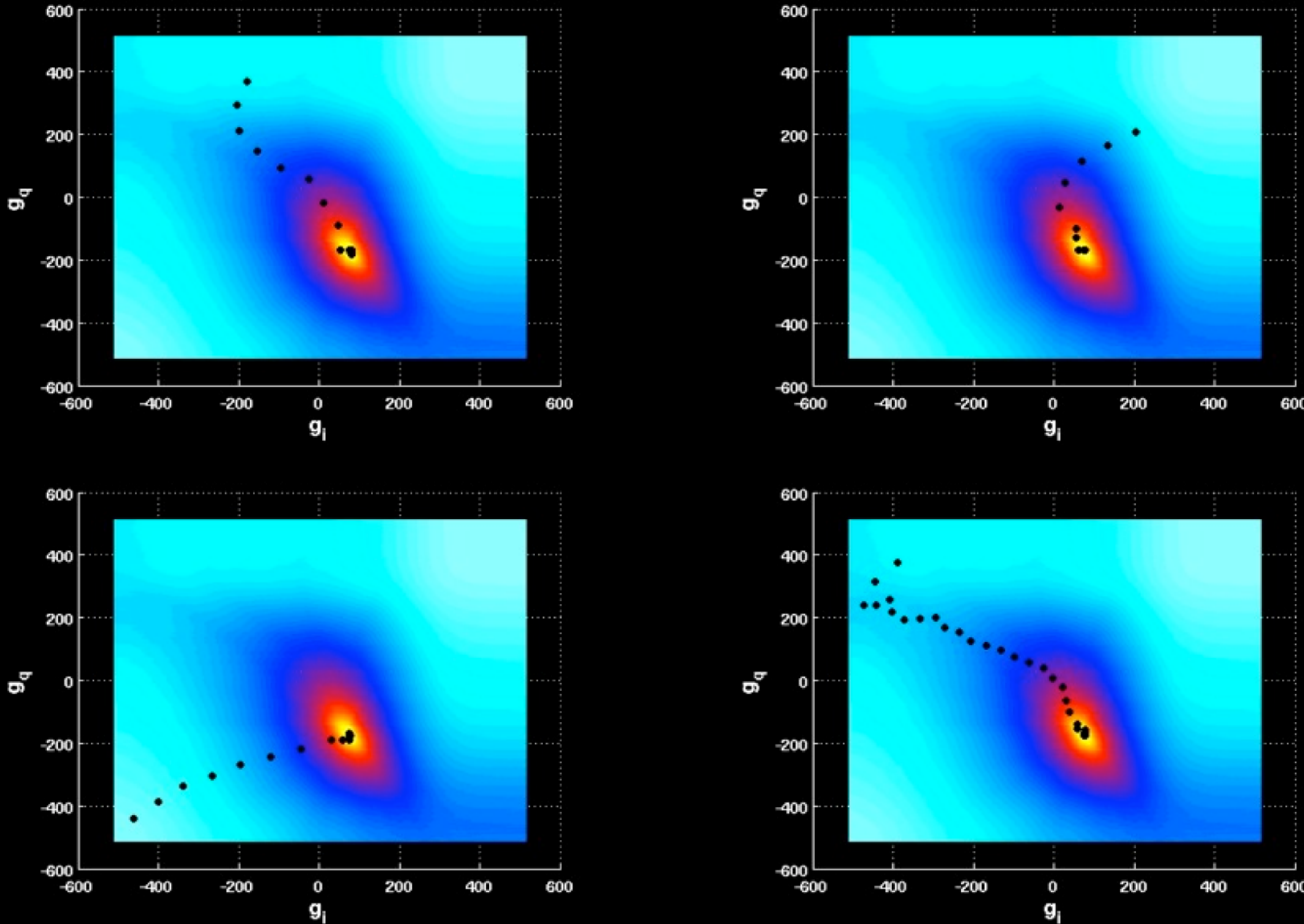
Off-the-shelf electronically tunable hardware approximation: QHx220 noise canceler

But ...

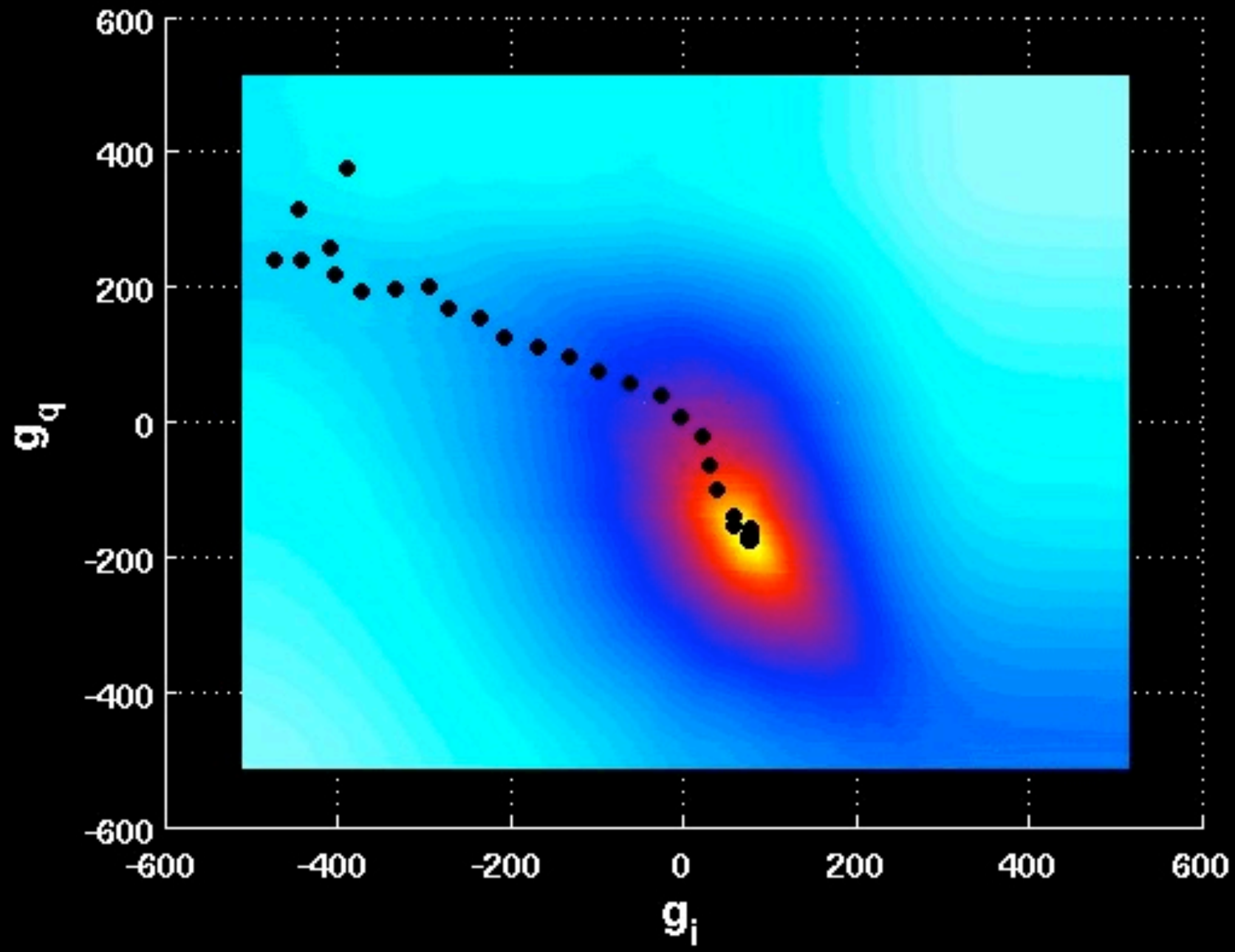
- Uses λ/4 delay to generate quadrature component: Not precise for all frequencies
- Active components for gain: saturation leading to non-linearities

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

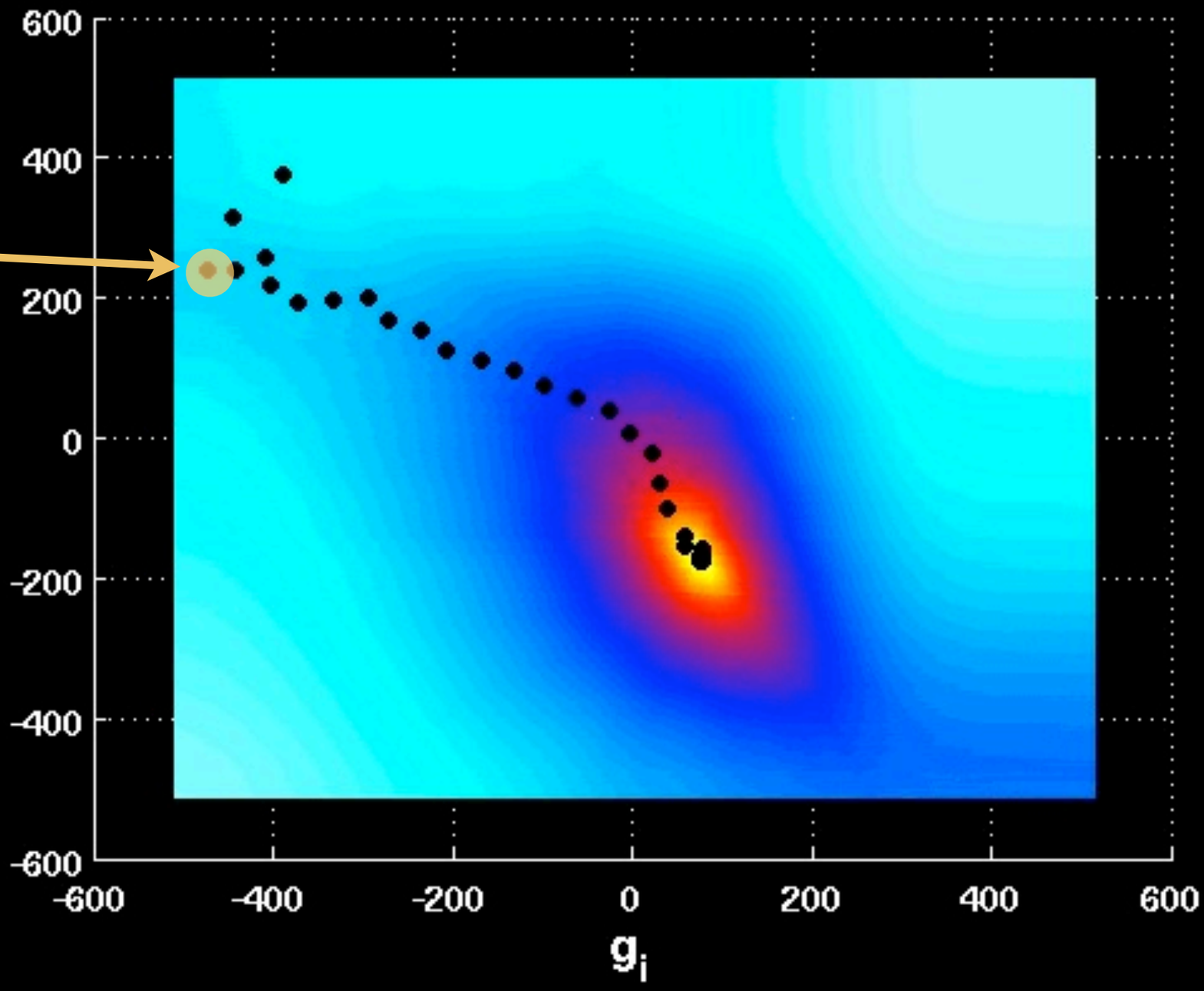




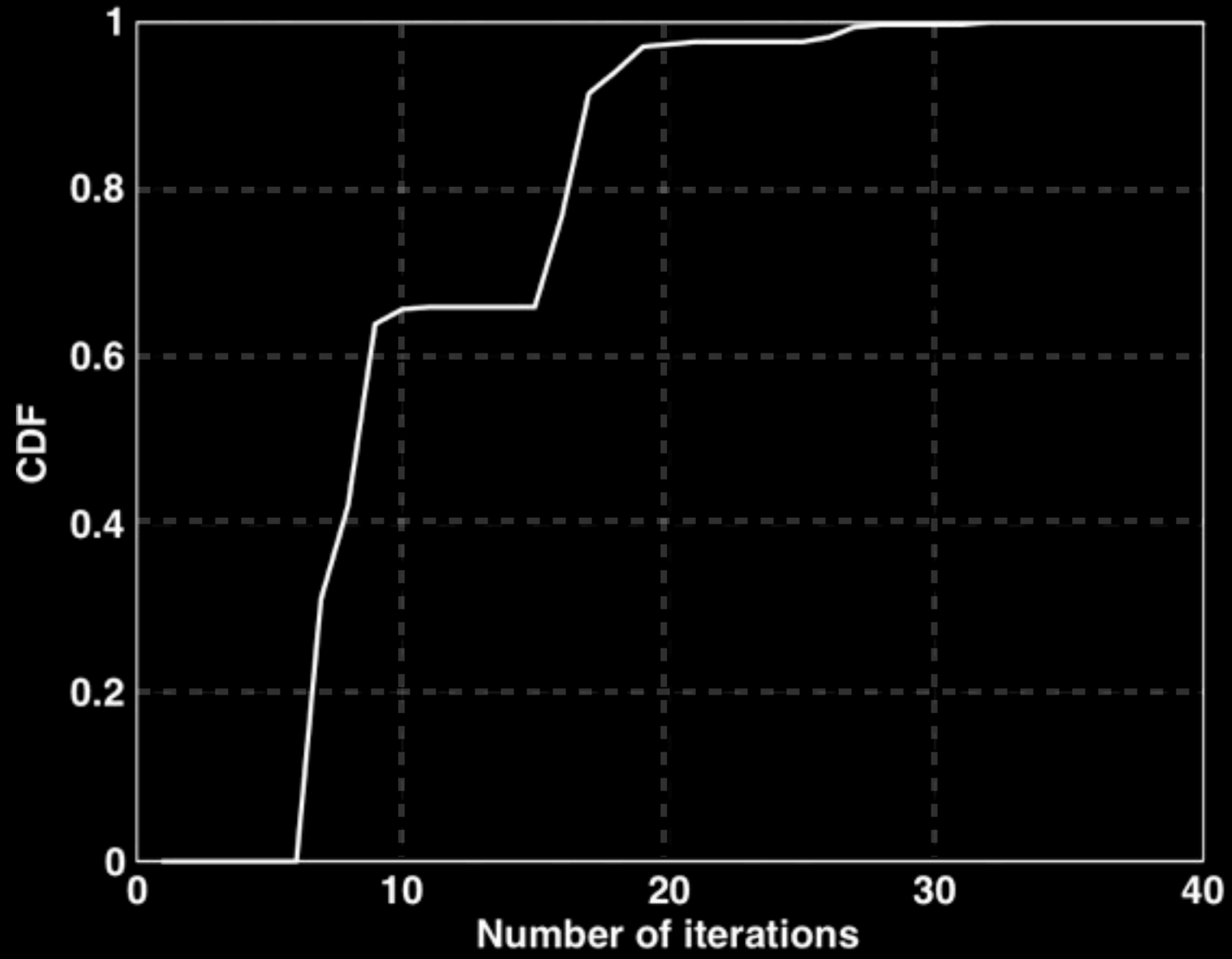
Typical convergence within 8-15 iterations (~1ms total)


600
400
200
0
-200
-400
-600
-600
-400
-200
0
200
400
600
g_q
g_i

Saddle Point



Recovery from local minimas and saddle points possible, needs more iterations



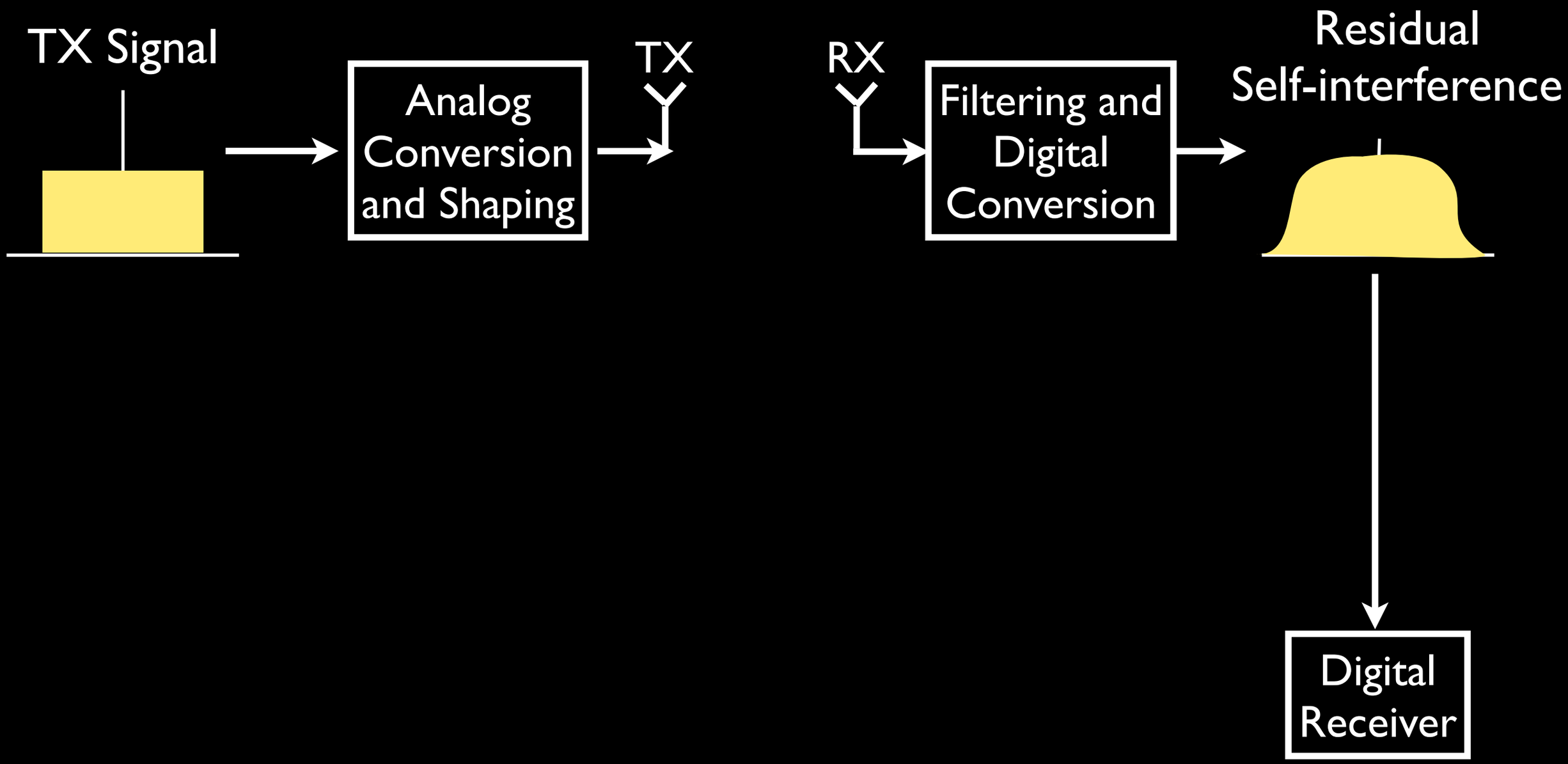
- ~65% converge without going through a local minima
- 98% converge in <20 iterations

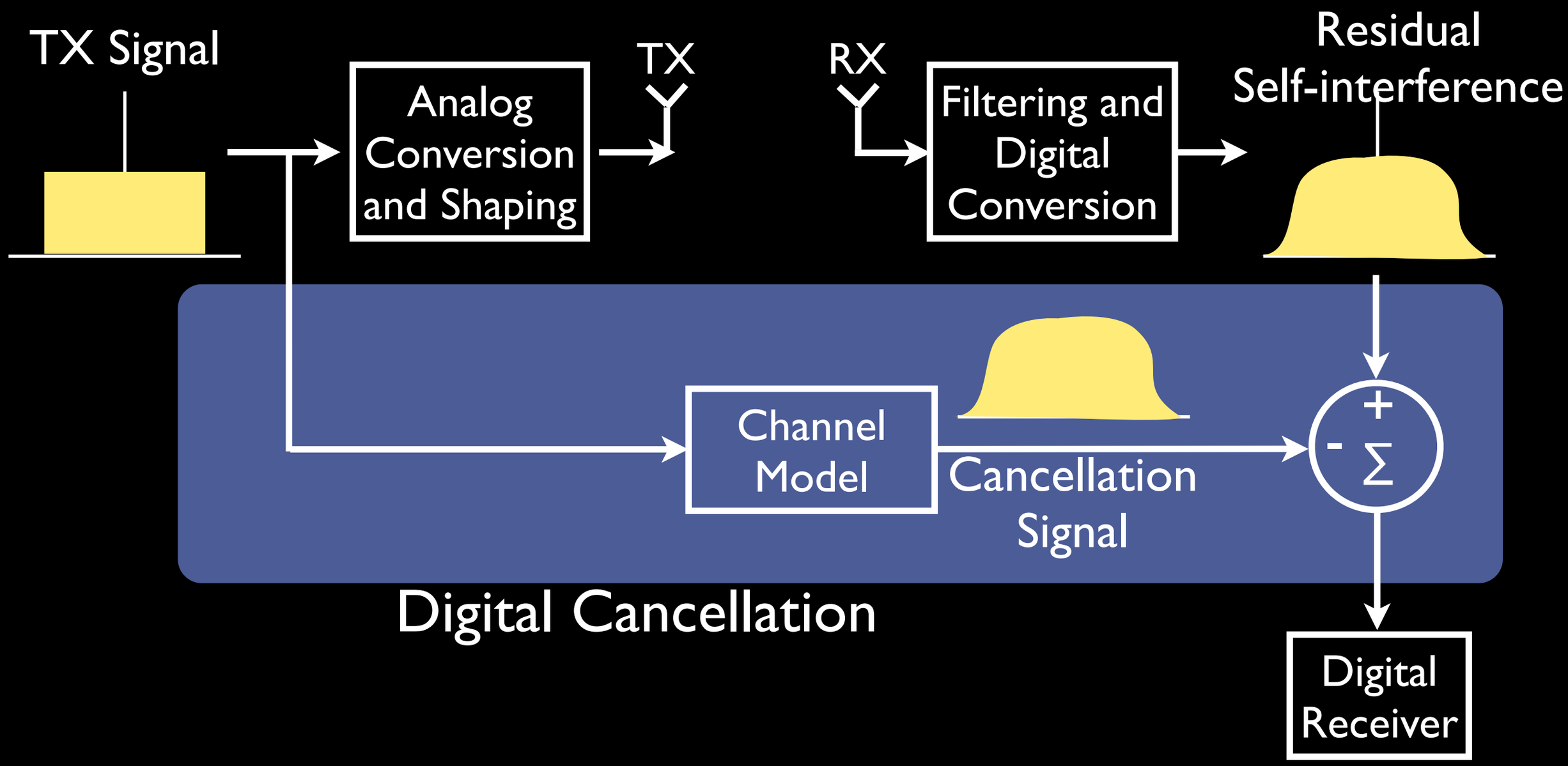
Talk Outline

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

Digital Cancellation

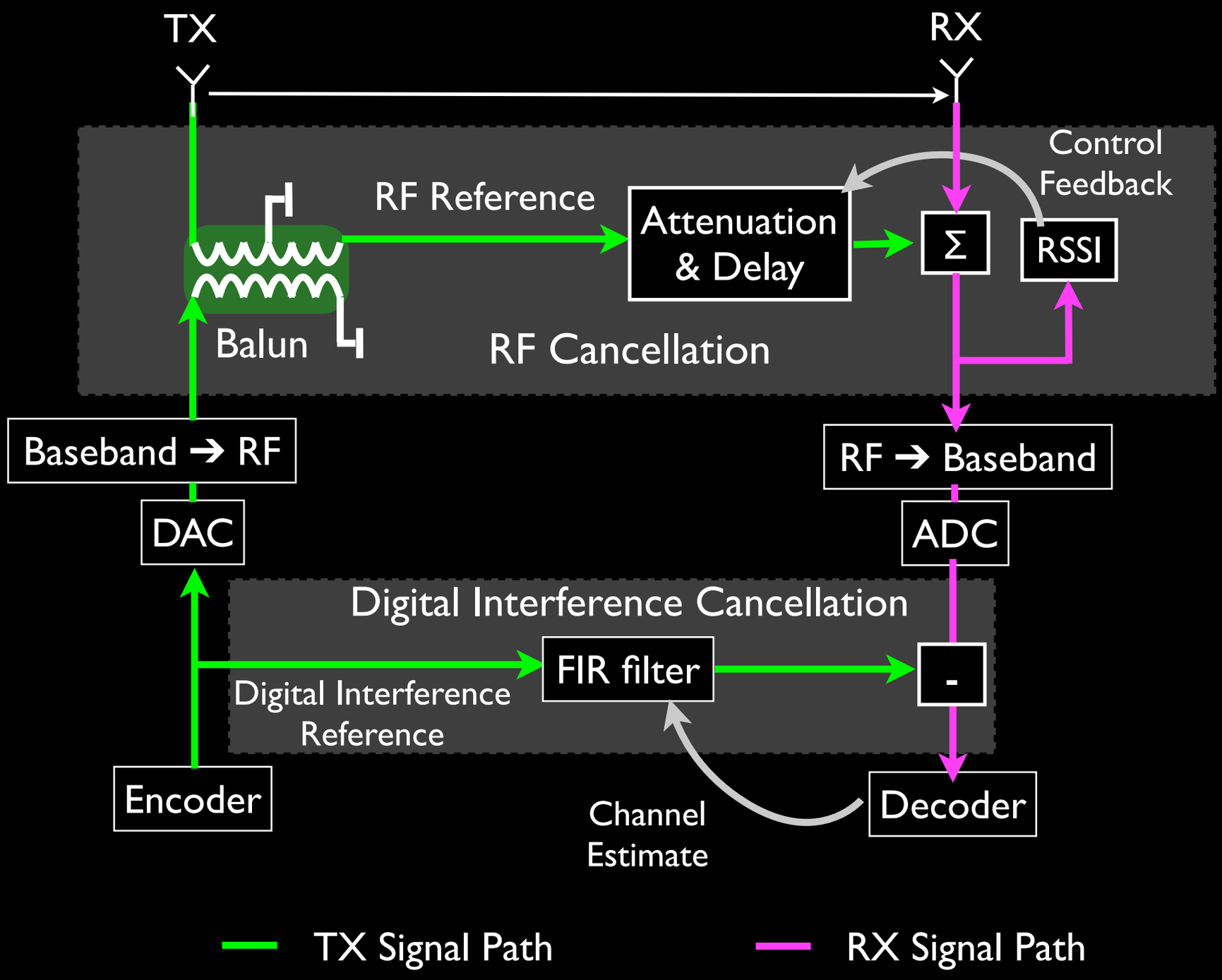
- Measure residual self-interference after RF cancellation
- Subtract self-interference from received digital signal


TX Signal
Analog Conversion and Shaping
TX
RX
Filtering and Digital Conversion
Residual Self-interference
Digital Receiver

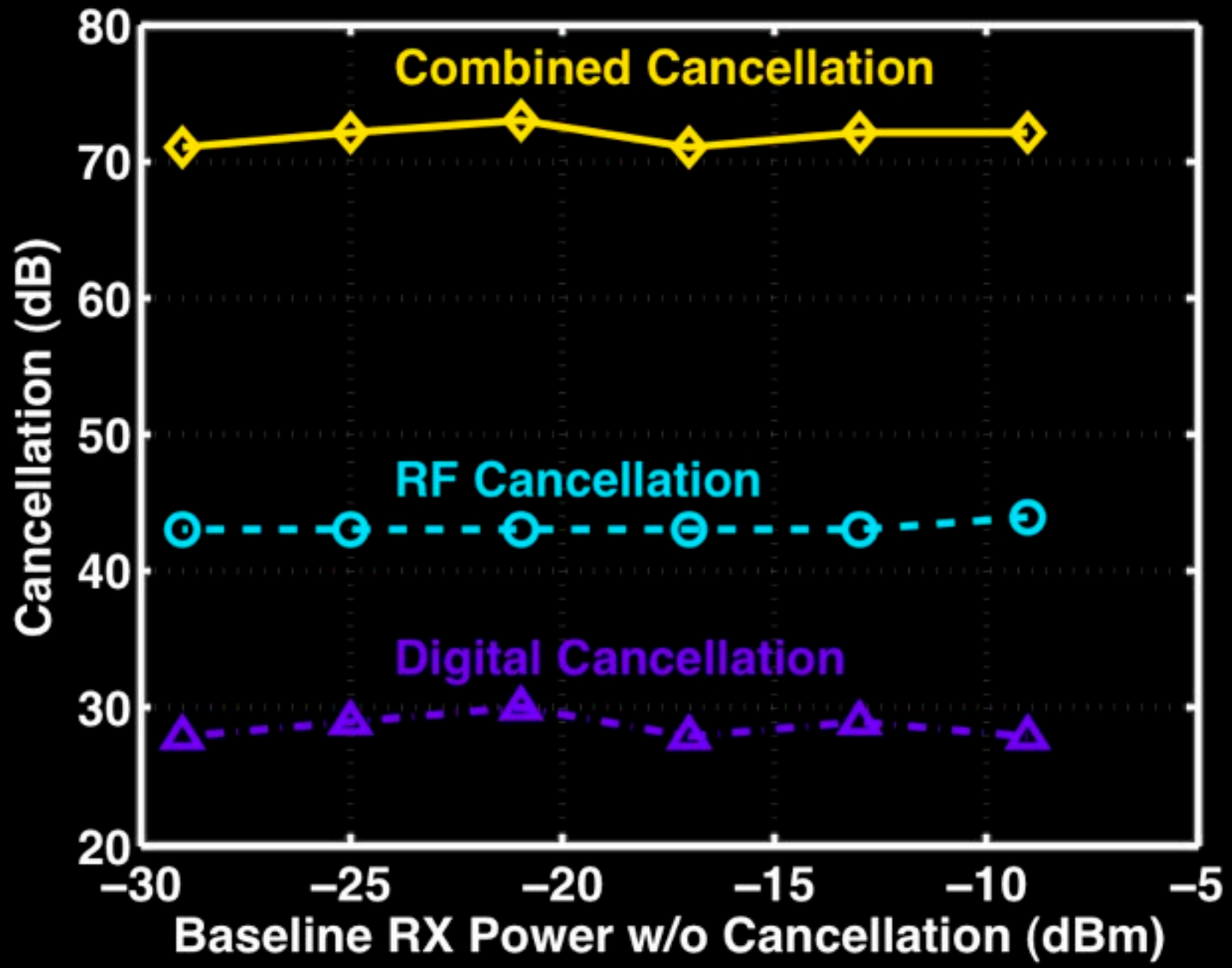


Digital Cancellation

Bringing It All Together

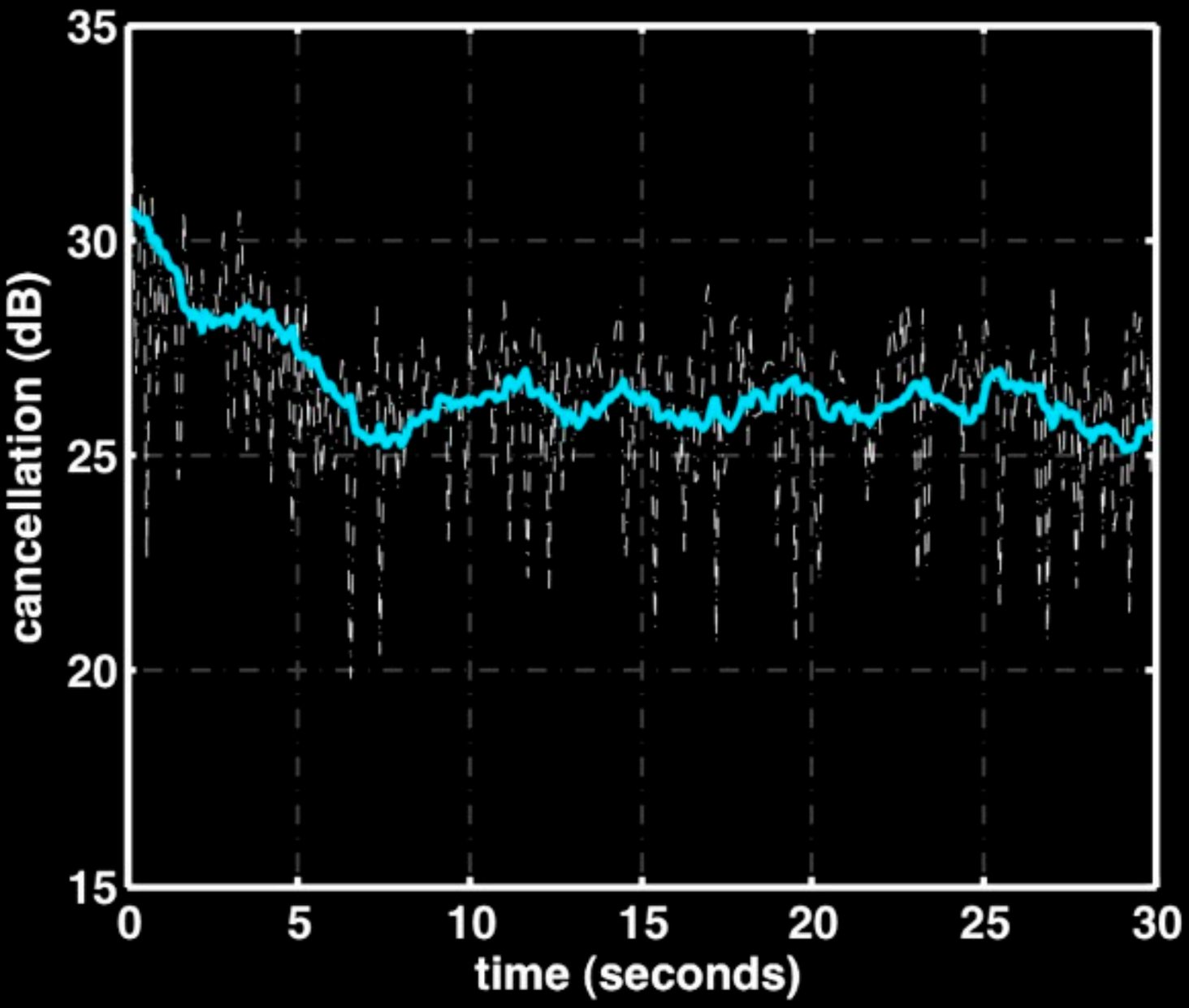


Performance



- ~73 dB cancellation
- WLAN full-duplex: Yes, with reasonable antenna separation
- Not enough for cellular full-duplex

Channel Coherence



~3dB reduction in cancellation in 1-2 seconds

~6dB reduction in <10 seconds

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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

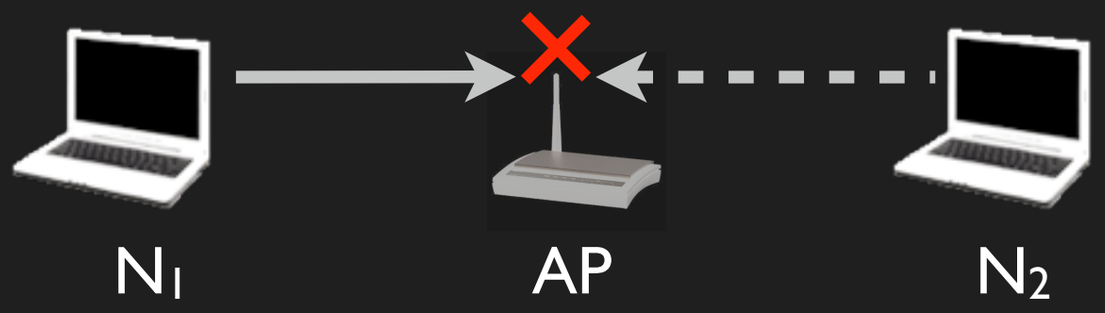
[1] Choi et al. "Achieving single channel, full duplex wireless communication", in Mobicom 2010
[2] Singh et al. "Efficient and Fair MAC for Wireless Networks with Self-interference Cancellation", in WiOpt 2011

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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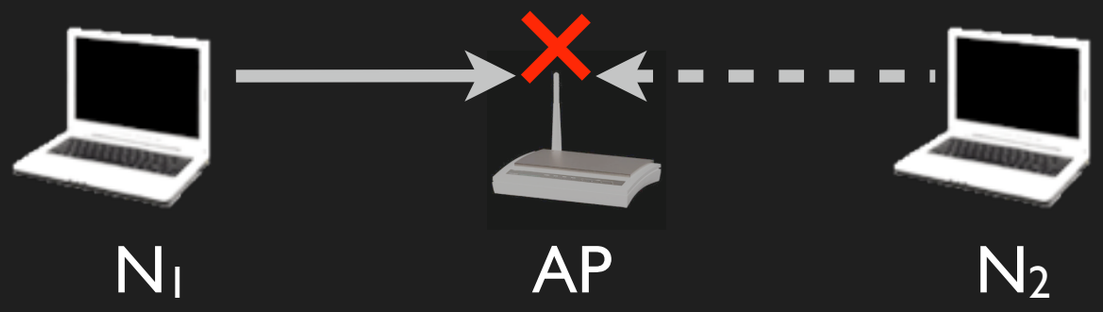

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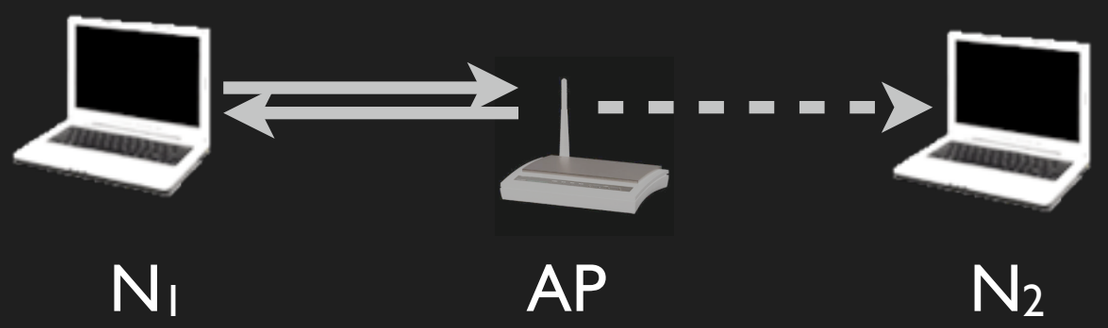
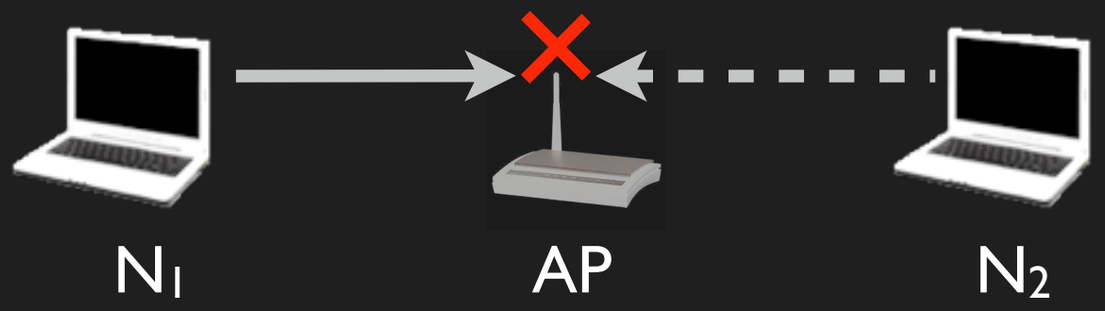
Full Duplex solves hidden terminals



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

Mitigating Hidden Terminals

Current networks have hidden terminals



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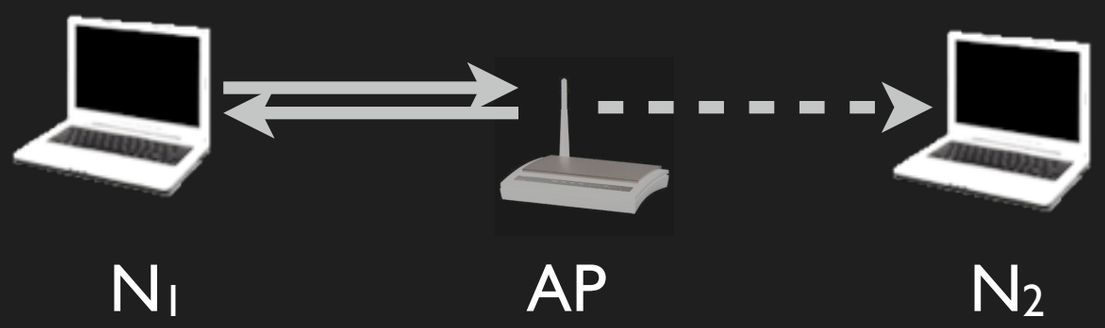
- Schemes like RTS/CTS introduce significant overhead

Full Duplex solves hidden terminals



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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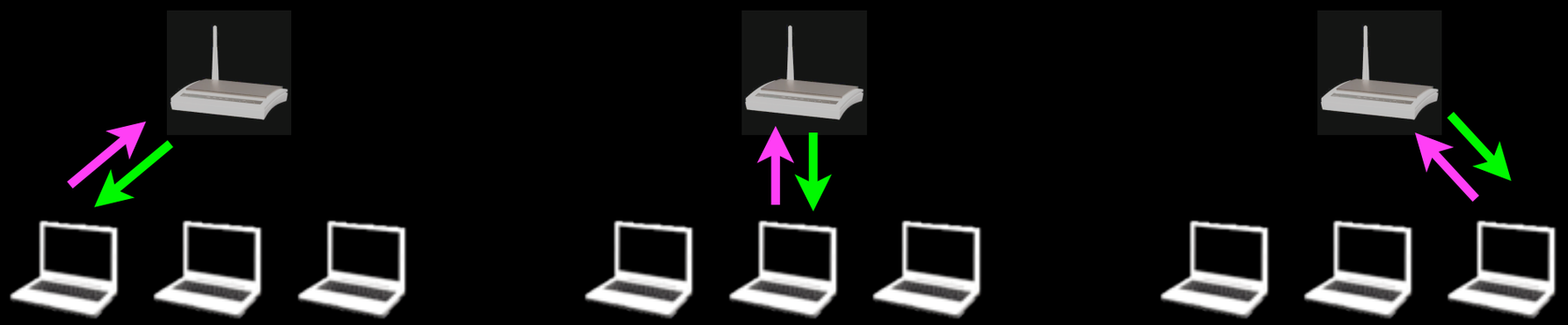


With full-duplex:

- 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

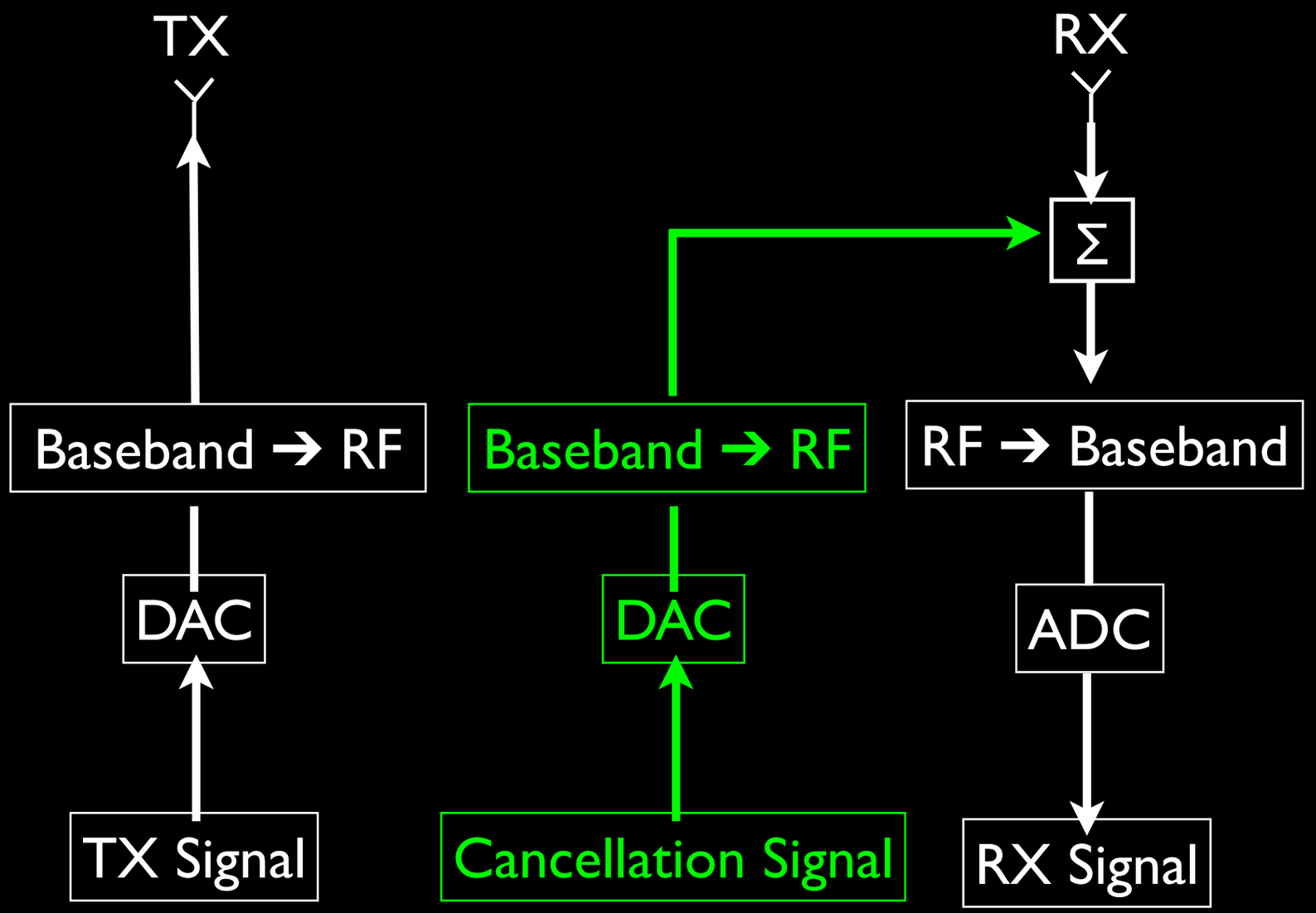
Full-duplex distributes its performance gain to improve fairness

Talk Outline

- RF Cancellation using Signal Inversion: ~50dB for 20Mhz
- Adaptive RF Cancellation: ~1ms convergence
- Adaptive Digital Cancellation: ~30dB cancellation
- System Performance: ~73dB cancellation
- Implications to Wireless Networks: Collisions, Fairness
- Looking Forward

- Other cancellation techniques

  Digital estimation for analog 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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- Non-linear channel response

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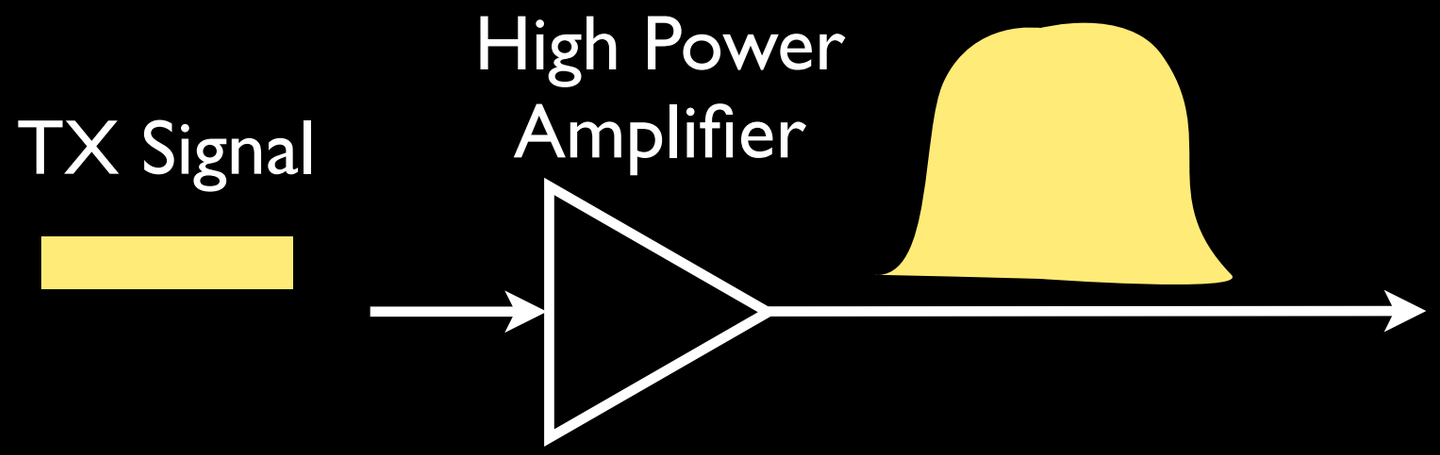

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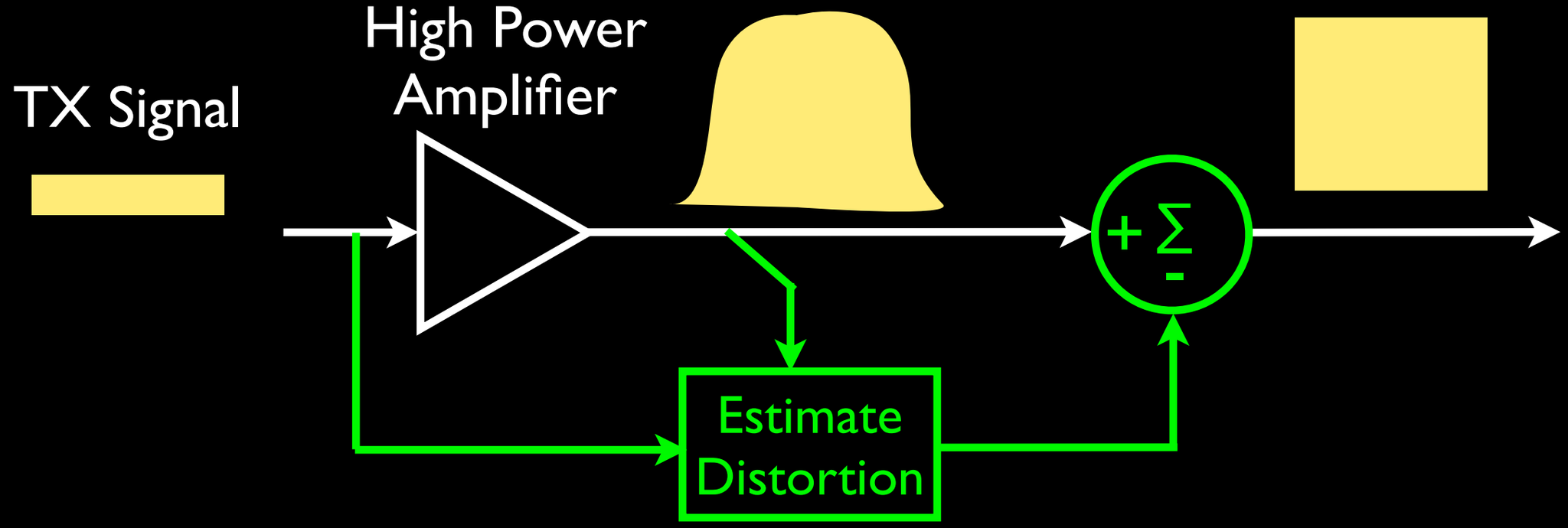

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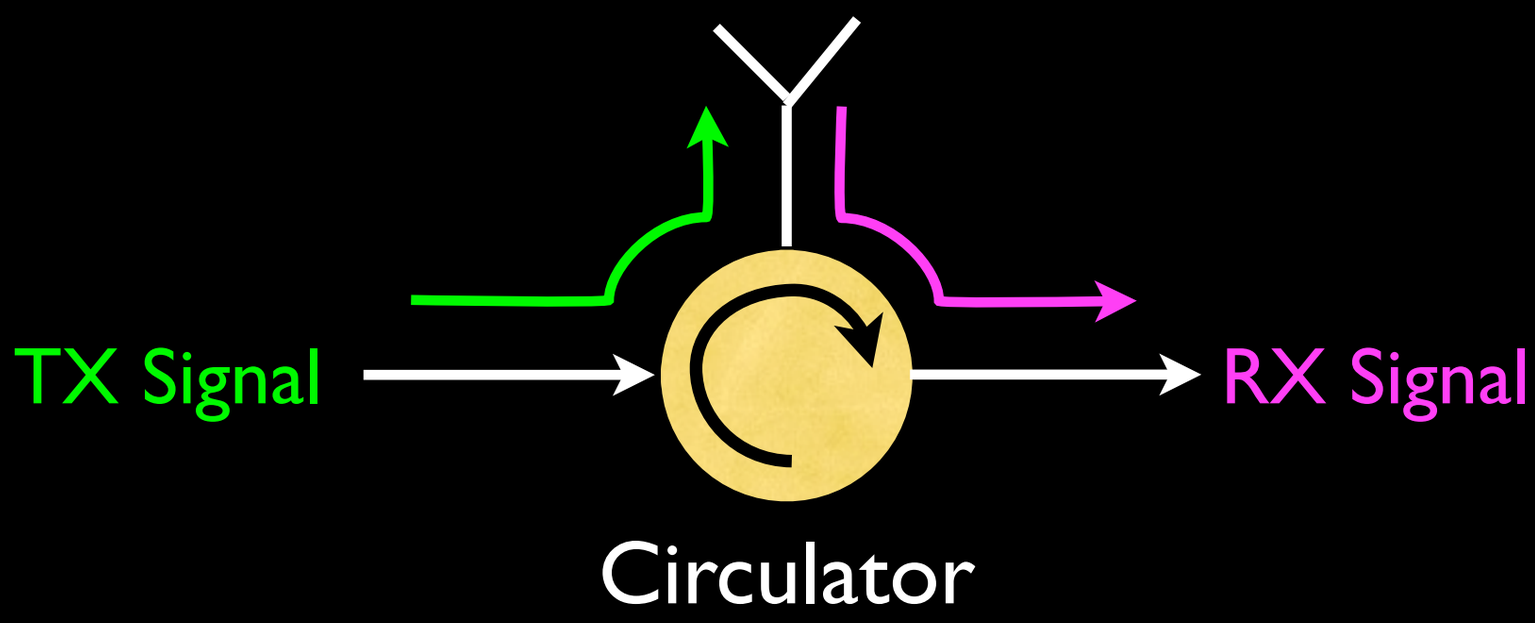

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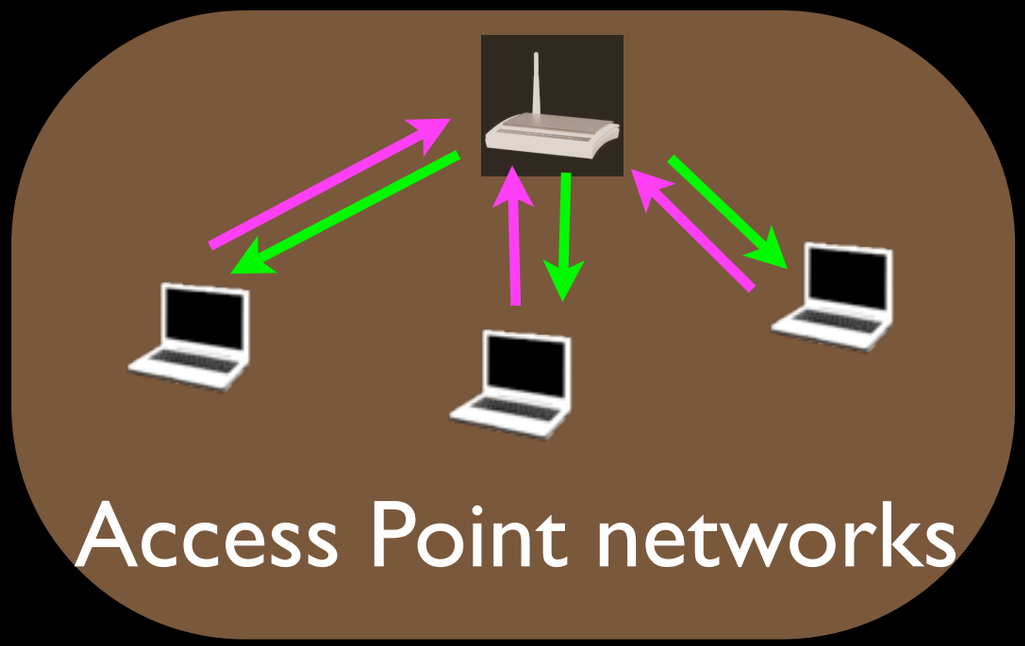
- Going mobile: Higher cancellation, faster adaptation
- MIMO full-duplex

Full-duplex Networking



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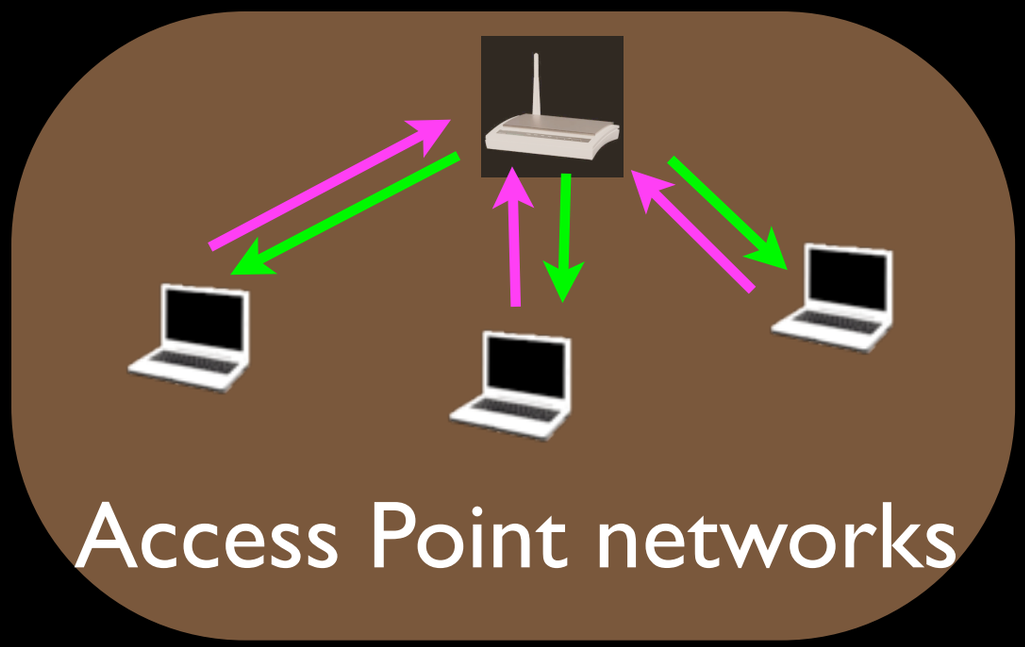

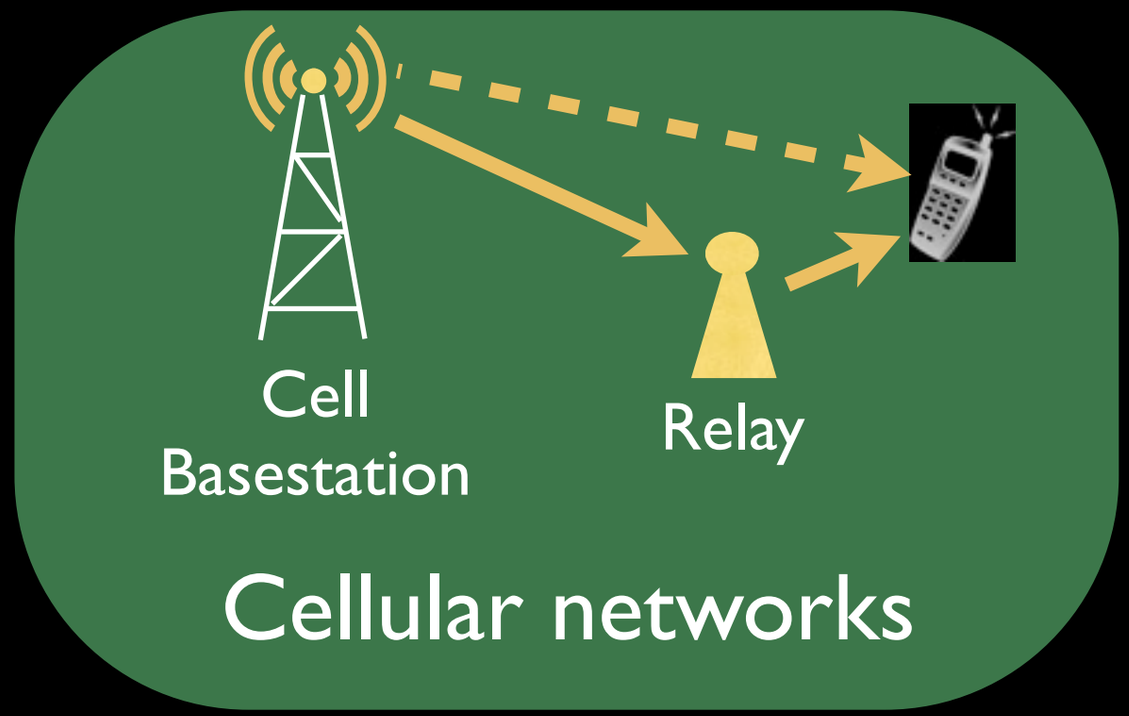

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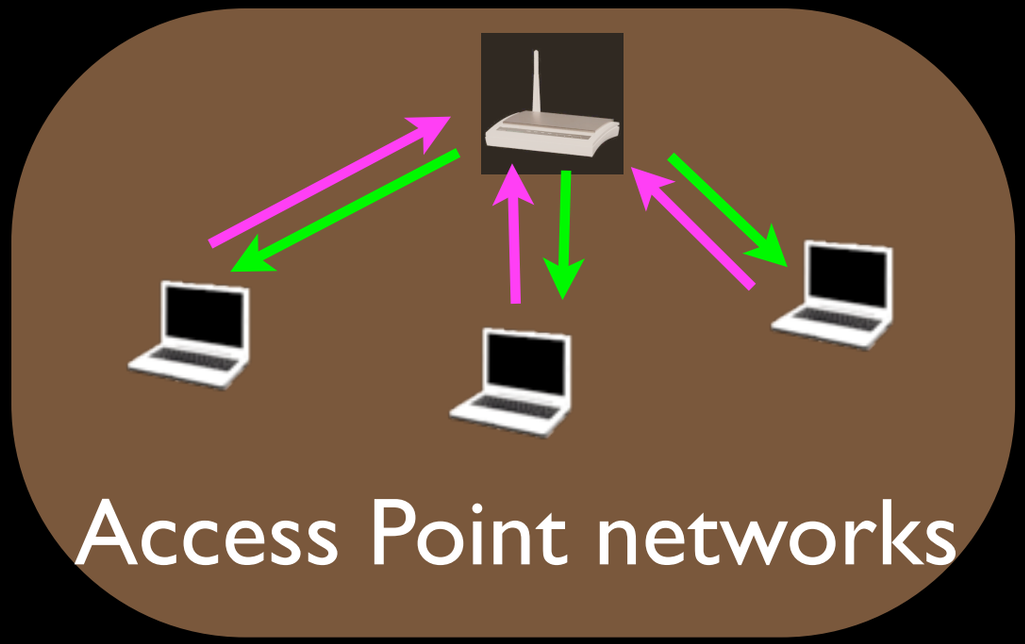

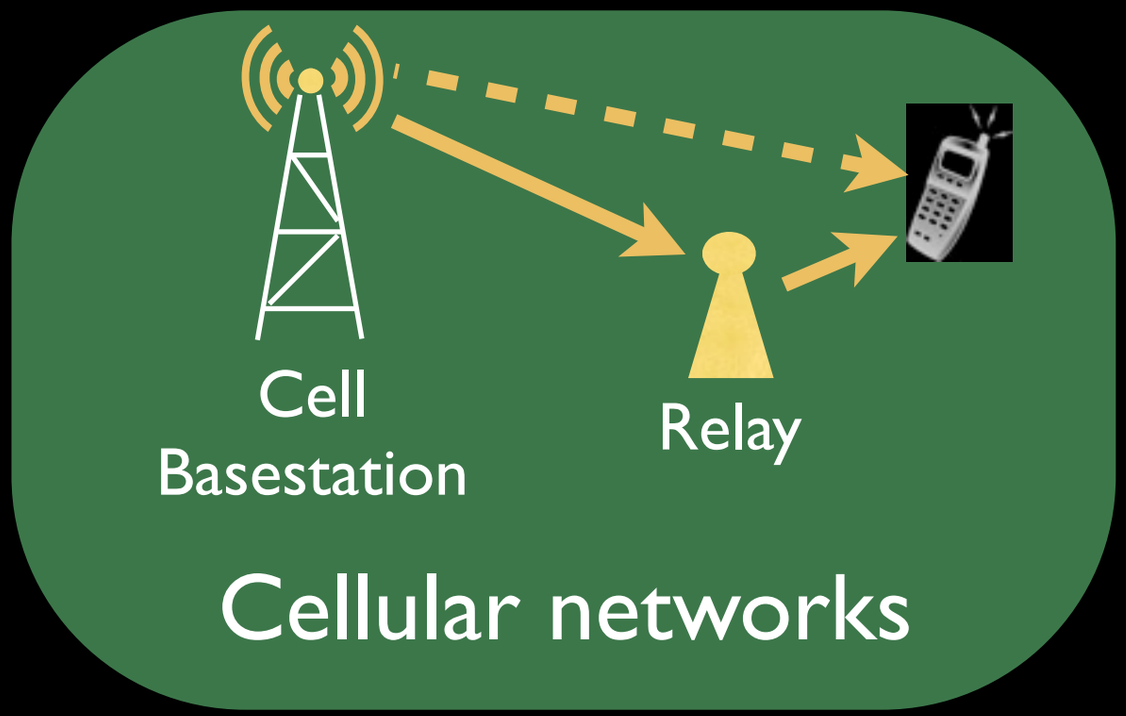

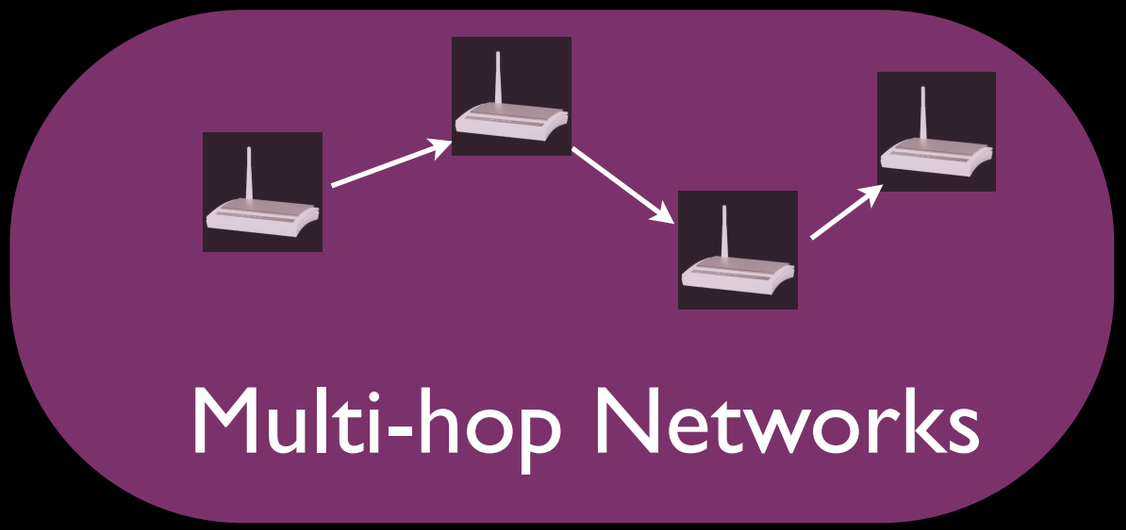

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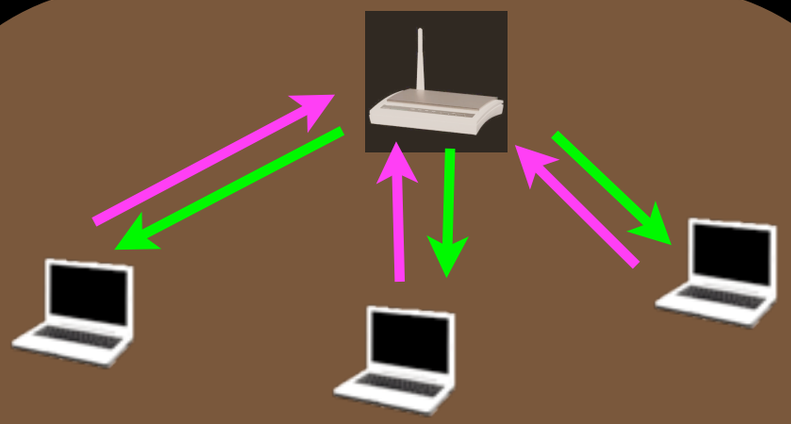
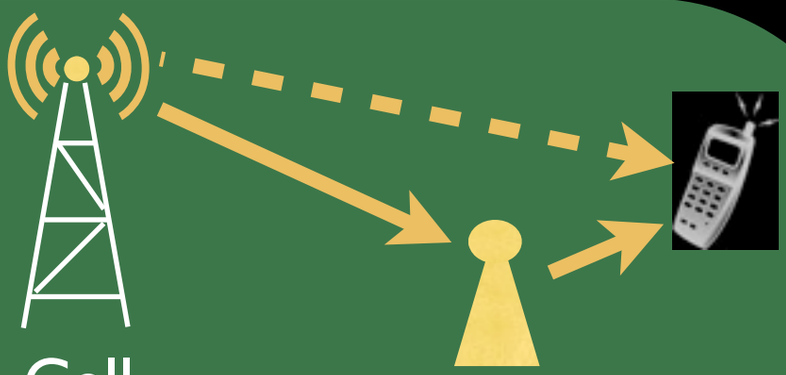
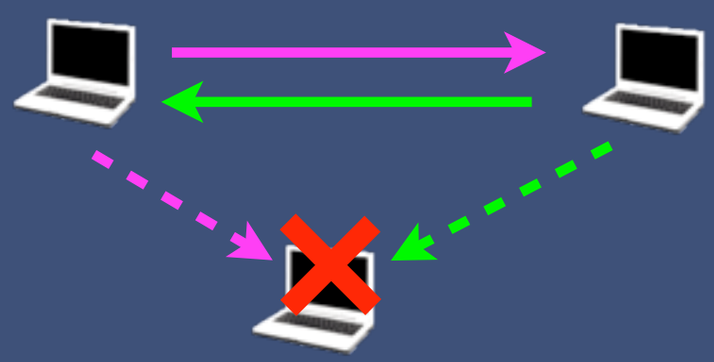


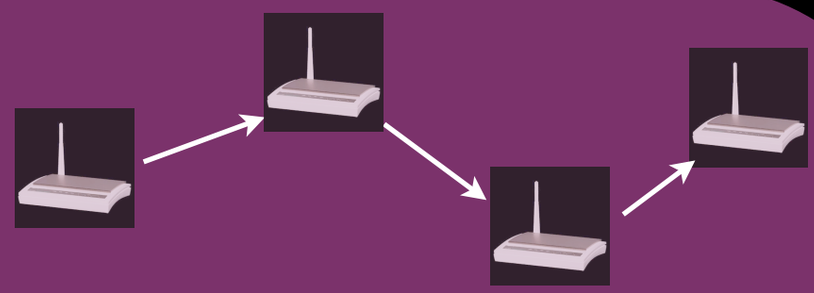
Access Point networks



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.

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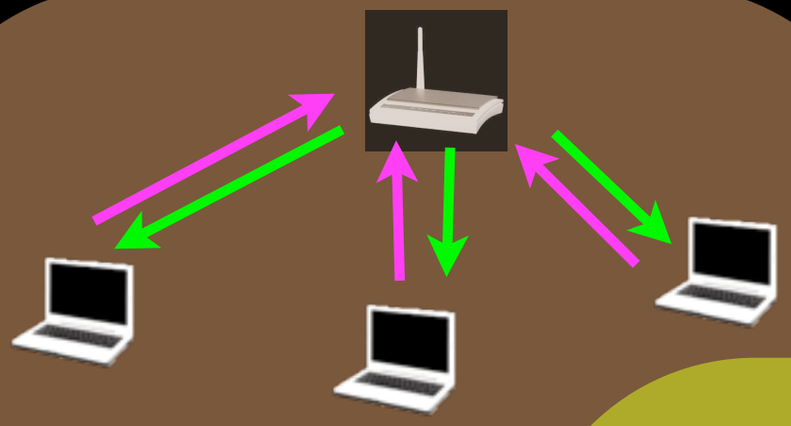
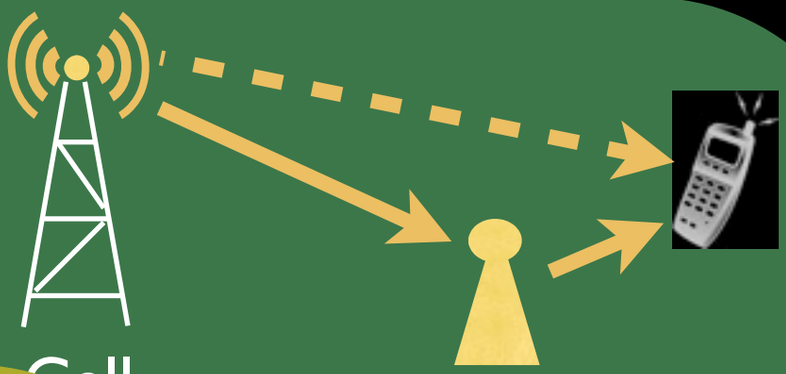
Full-duplex Networking



Access Point n



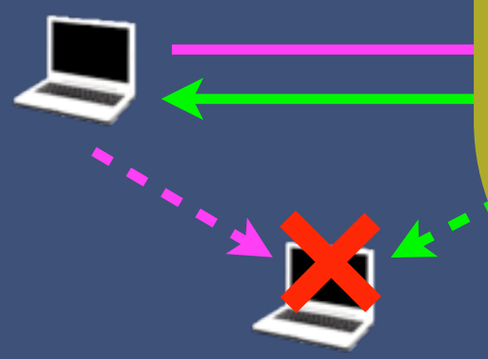
Cell

ion

Relay

ar networks

?



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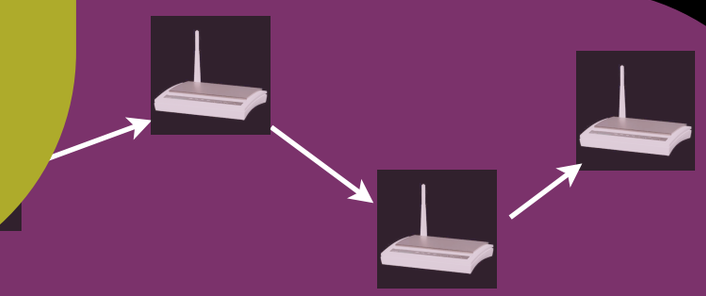

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Thank You

Questions?

Backup

Talk Outline

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

Digital Cancellation

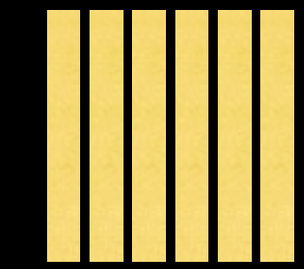
- Create a precise "digital replica" of the self-interference signal using TX digital samples
- Subtract self-interference replica from received digital signal

Requires ADC not saturated: RF cancellation

OFDM processing

Signal Band

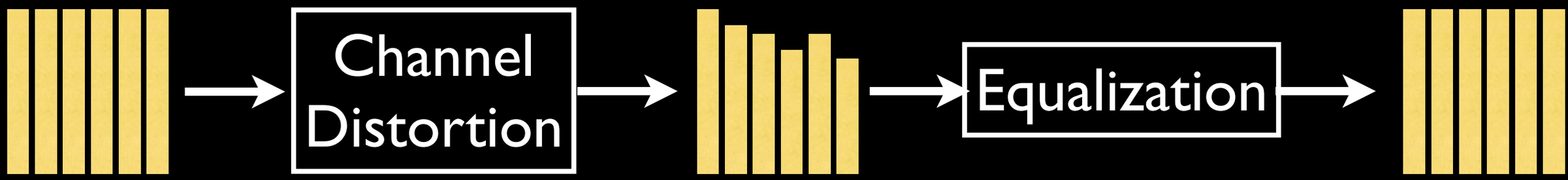
OFDM processing



Sub-bands

OFDM processing

OFDM processing



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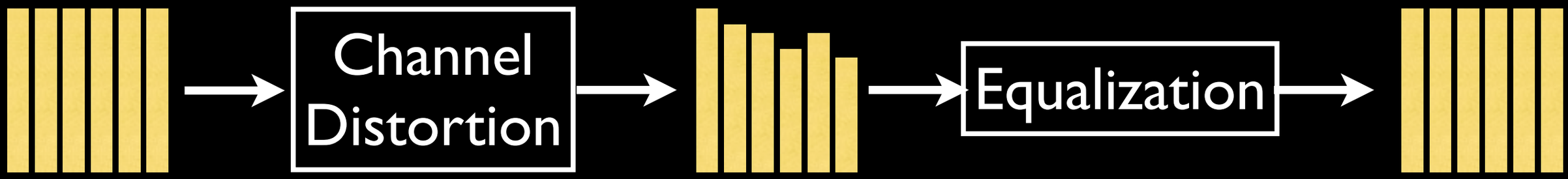
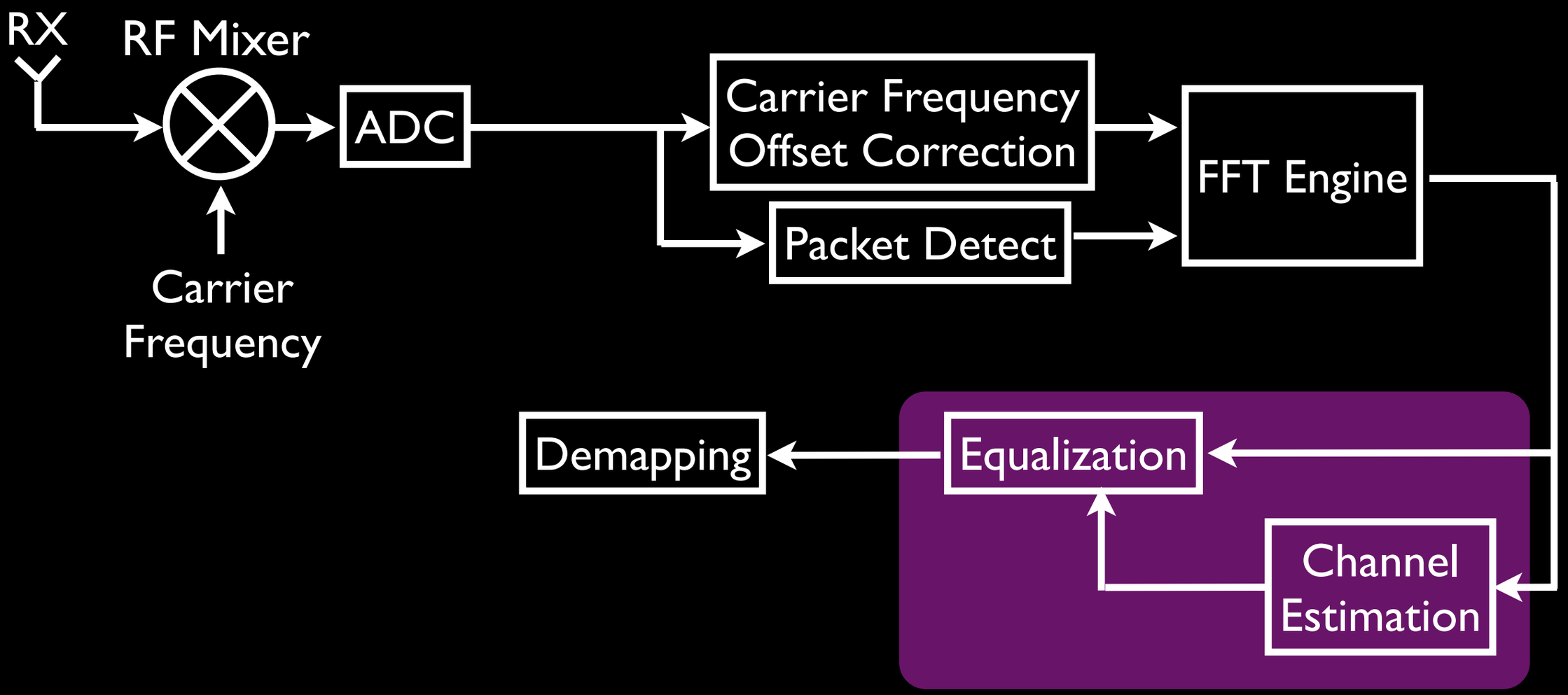
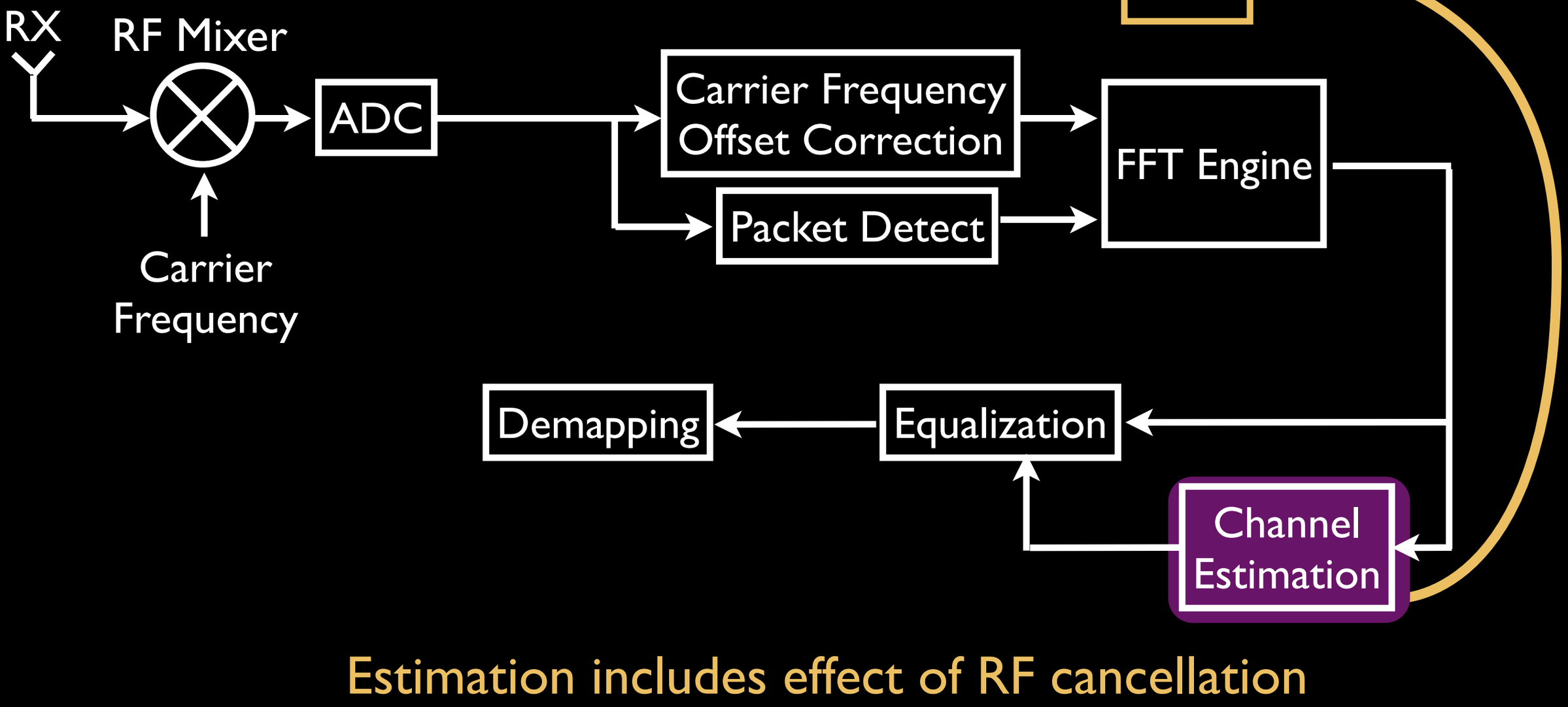




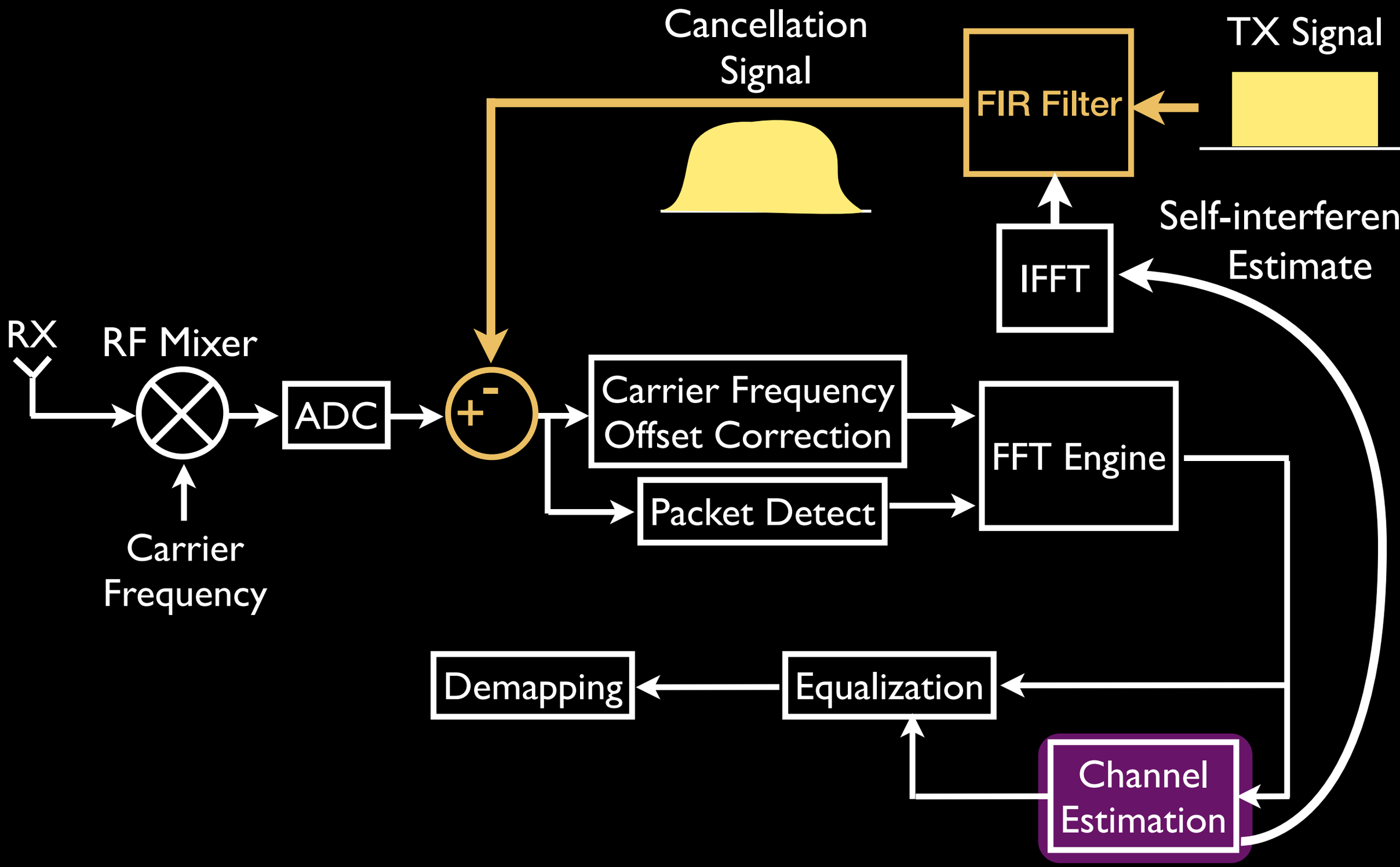
Step 1: Estimation

Self-interference Sounding



Estimation includes effect of RF cancellation

Step 2: Cancellation



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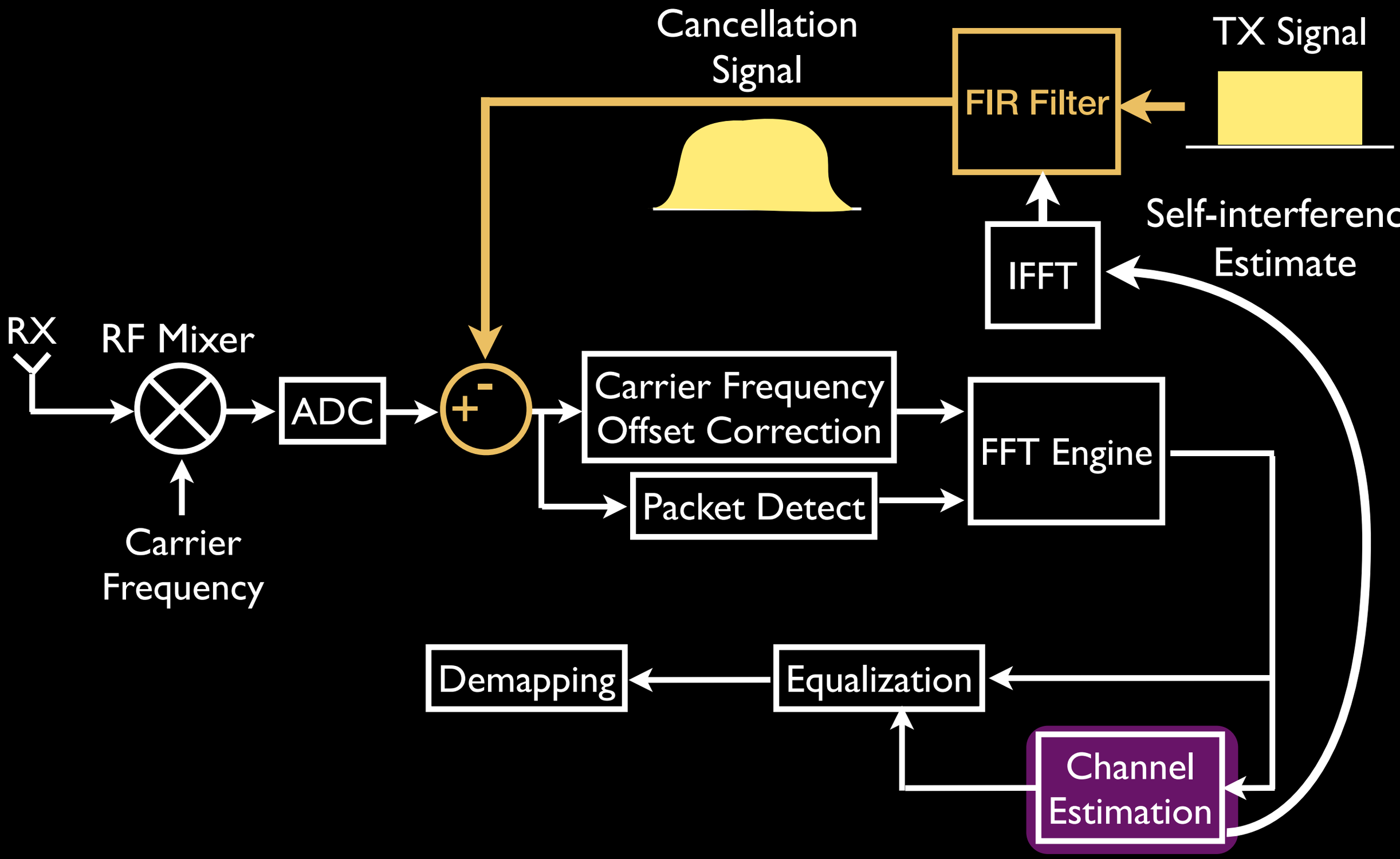
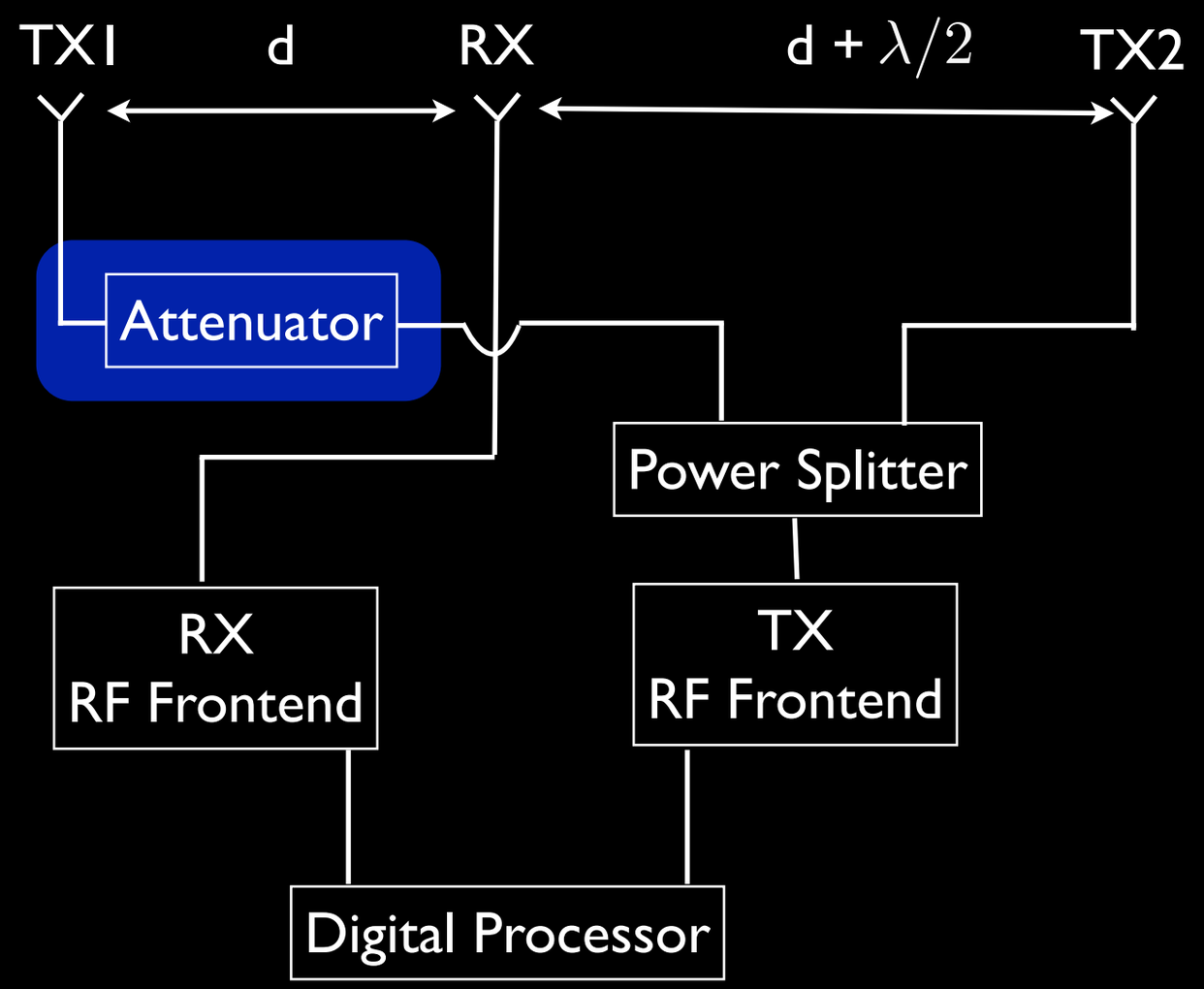


30dB Cancellation

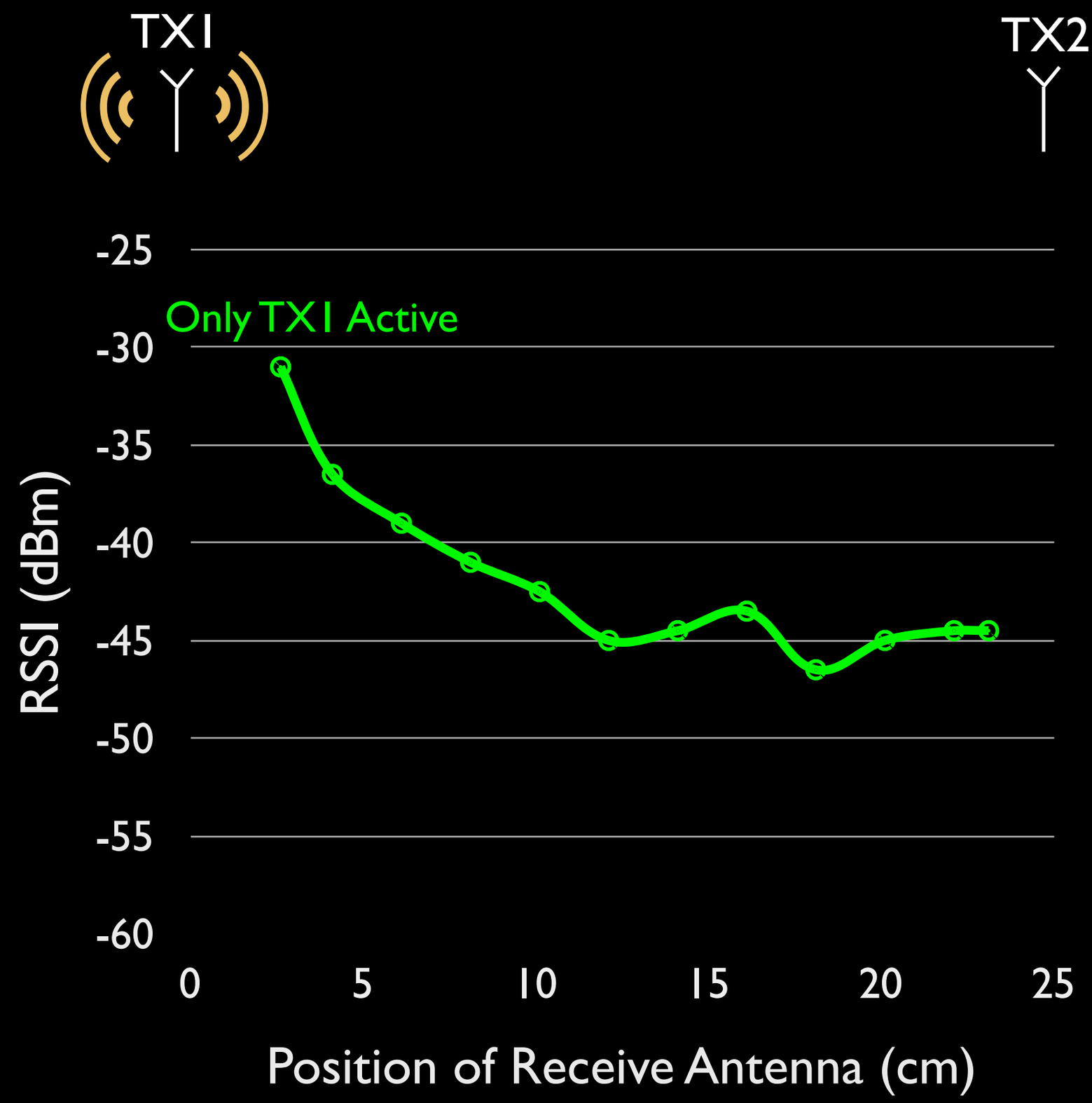
Talk Outline

- 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



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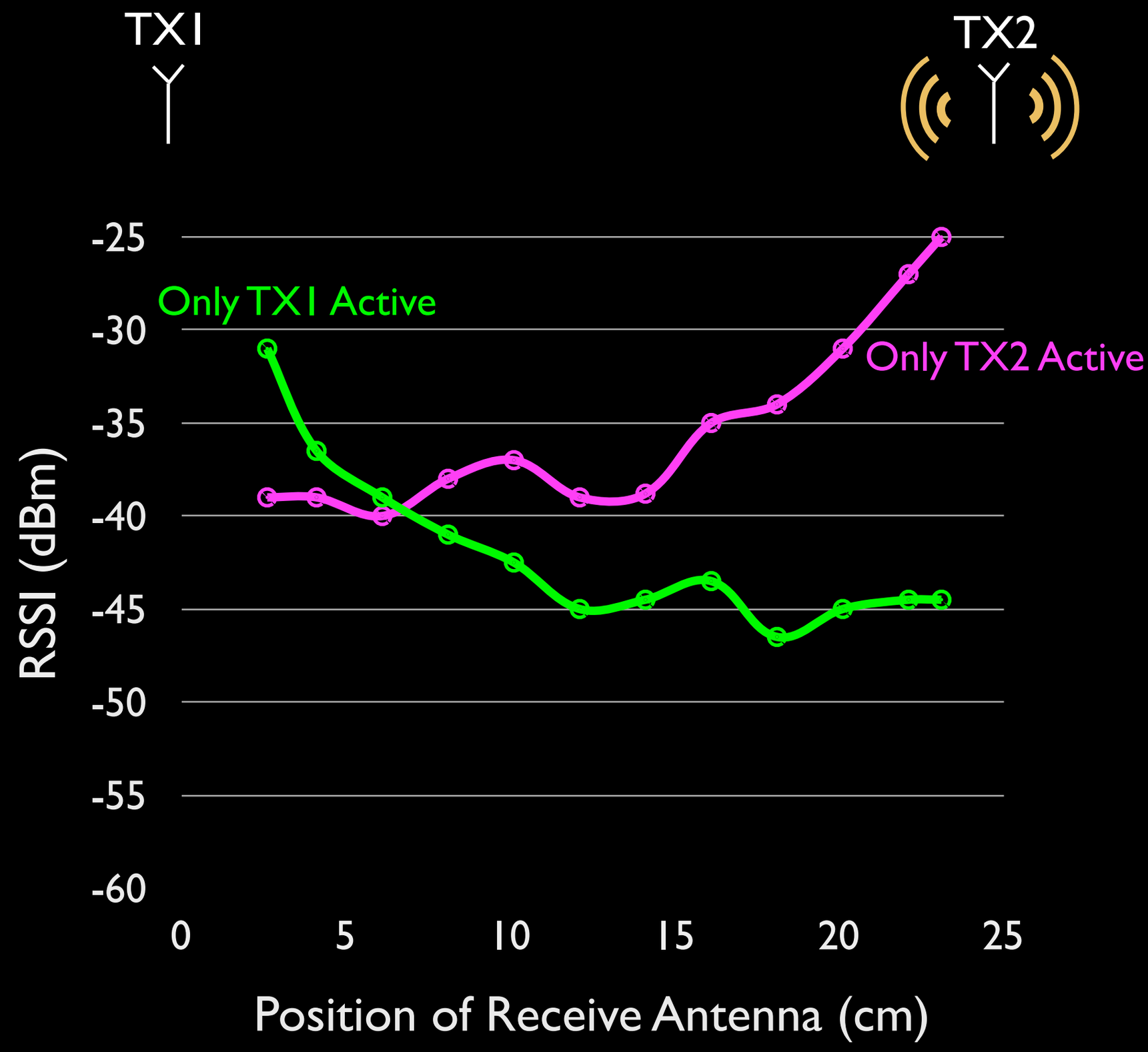

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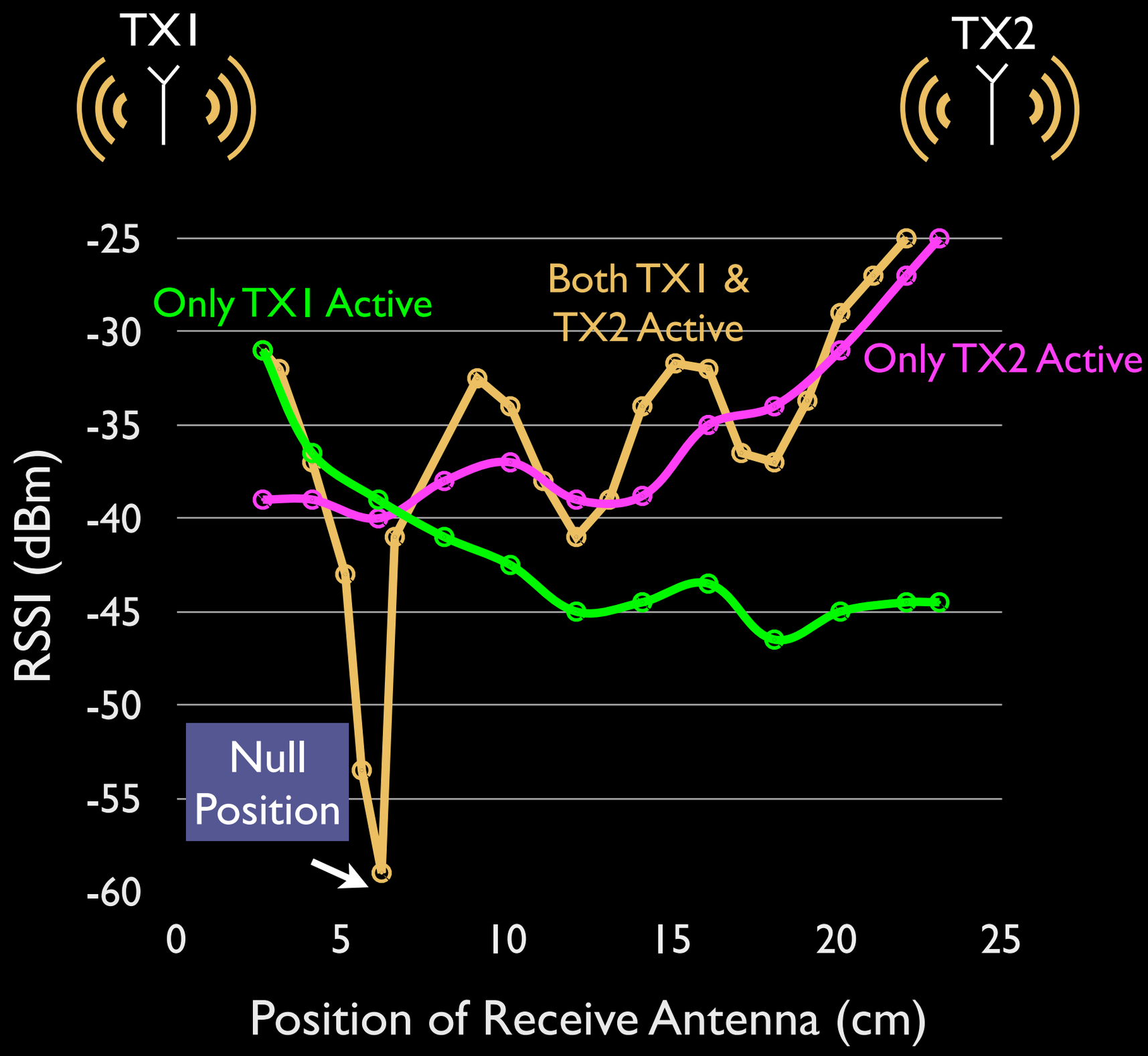

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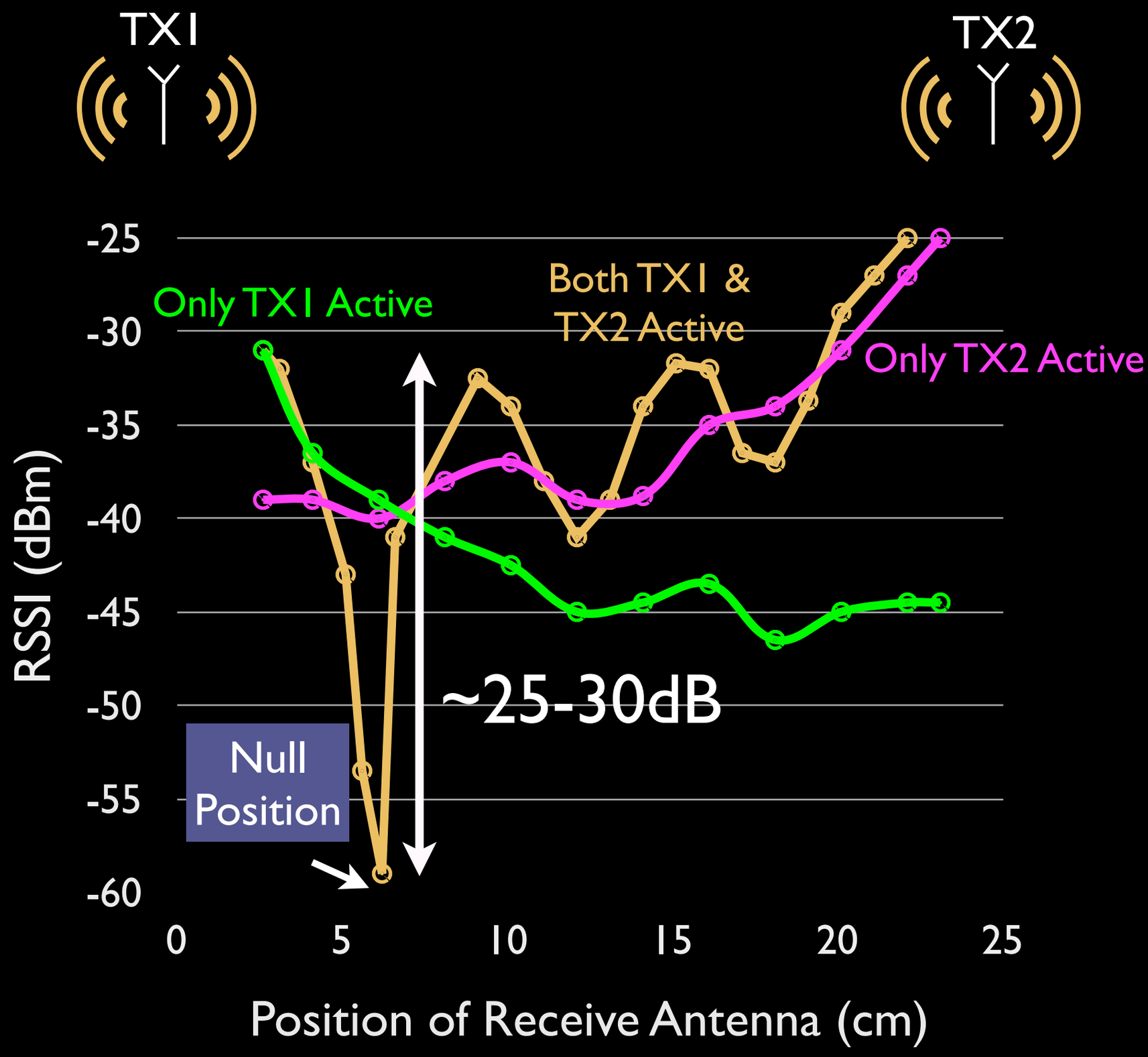
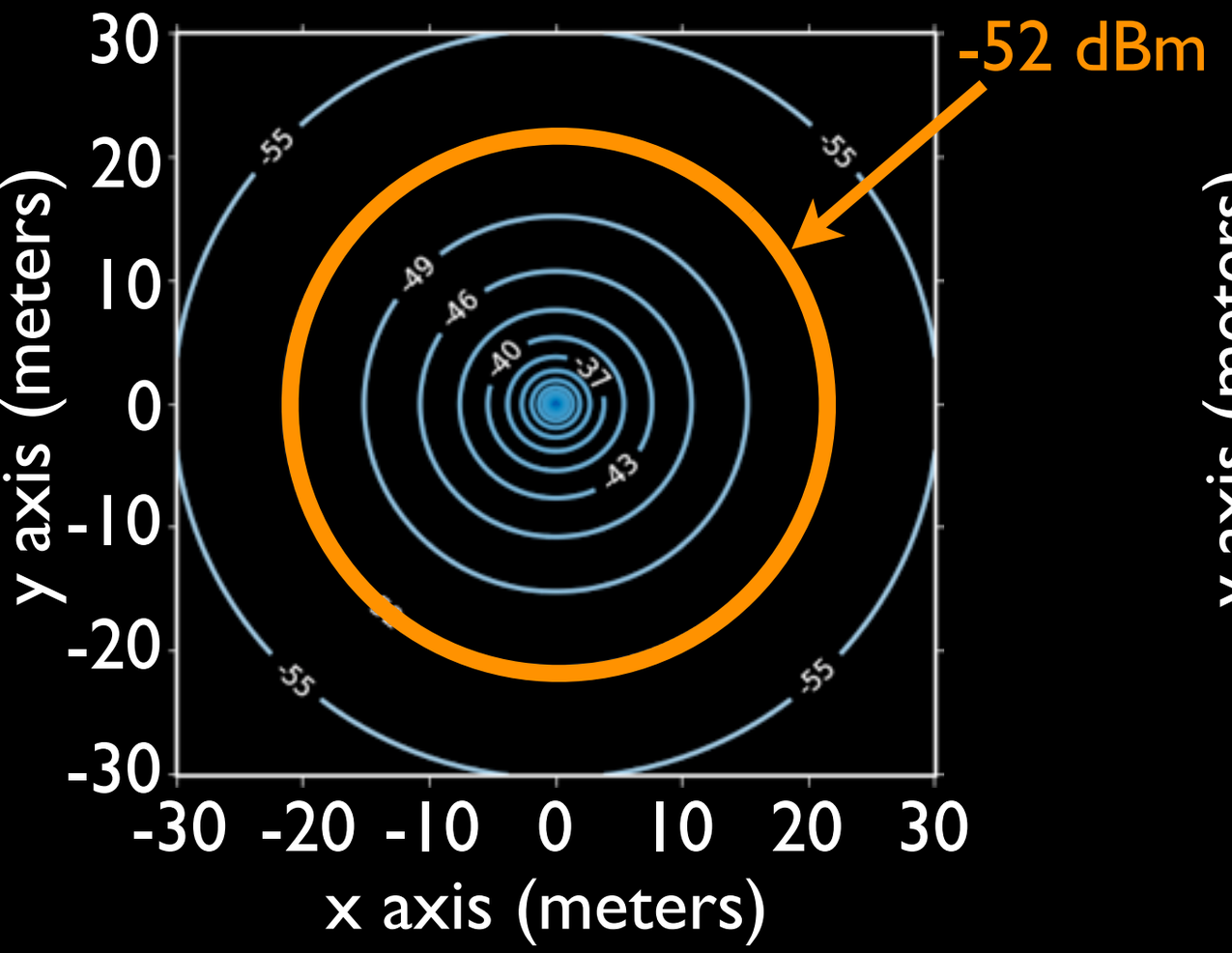
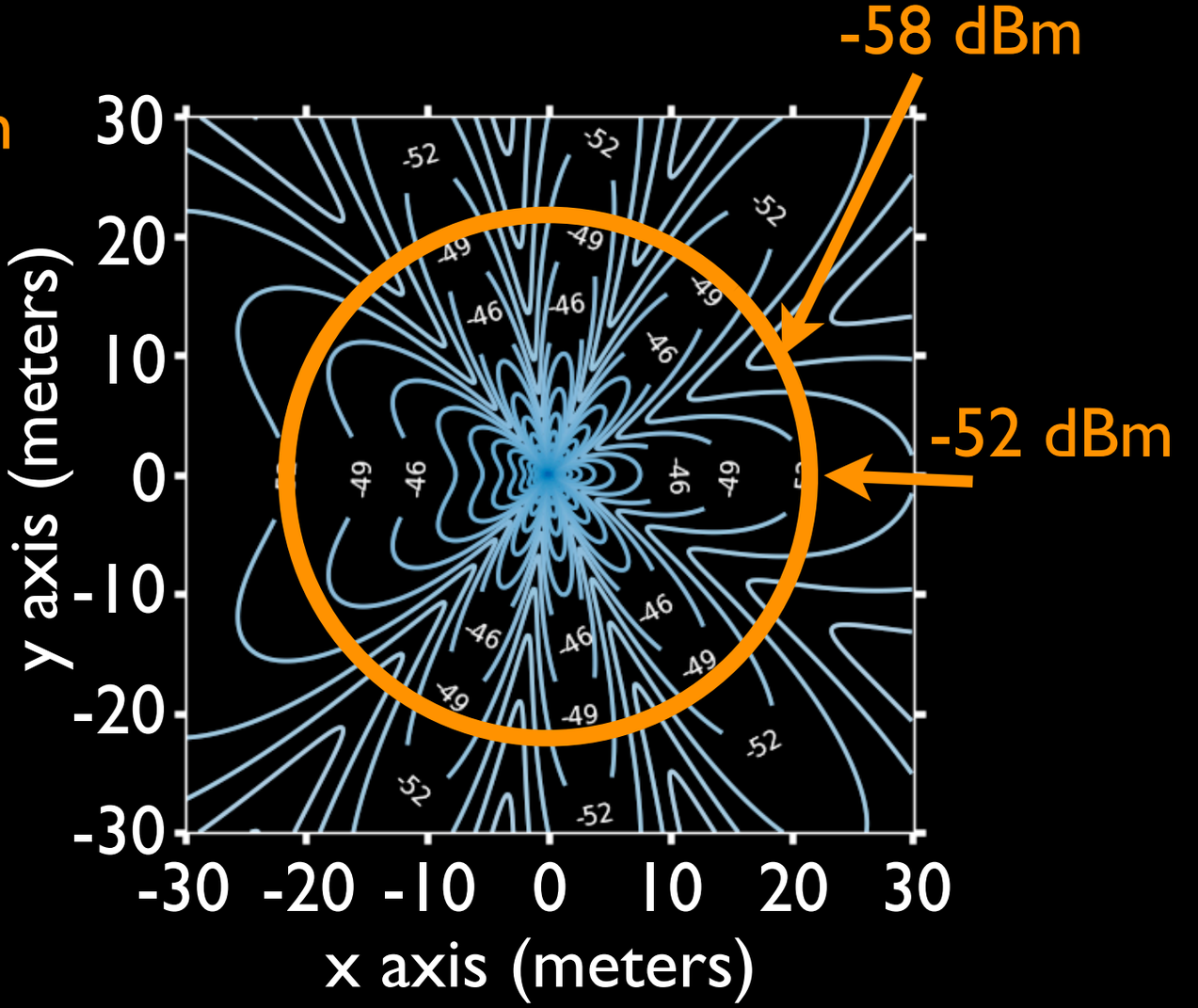


What about attenuation at intended receivers?
Destructive interference can affect this signal too!

- Different transmit powers for two TX helps

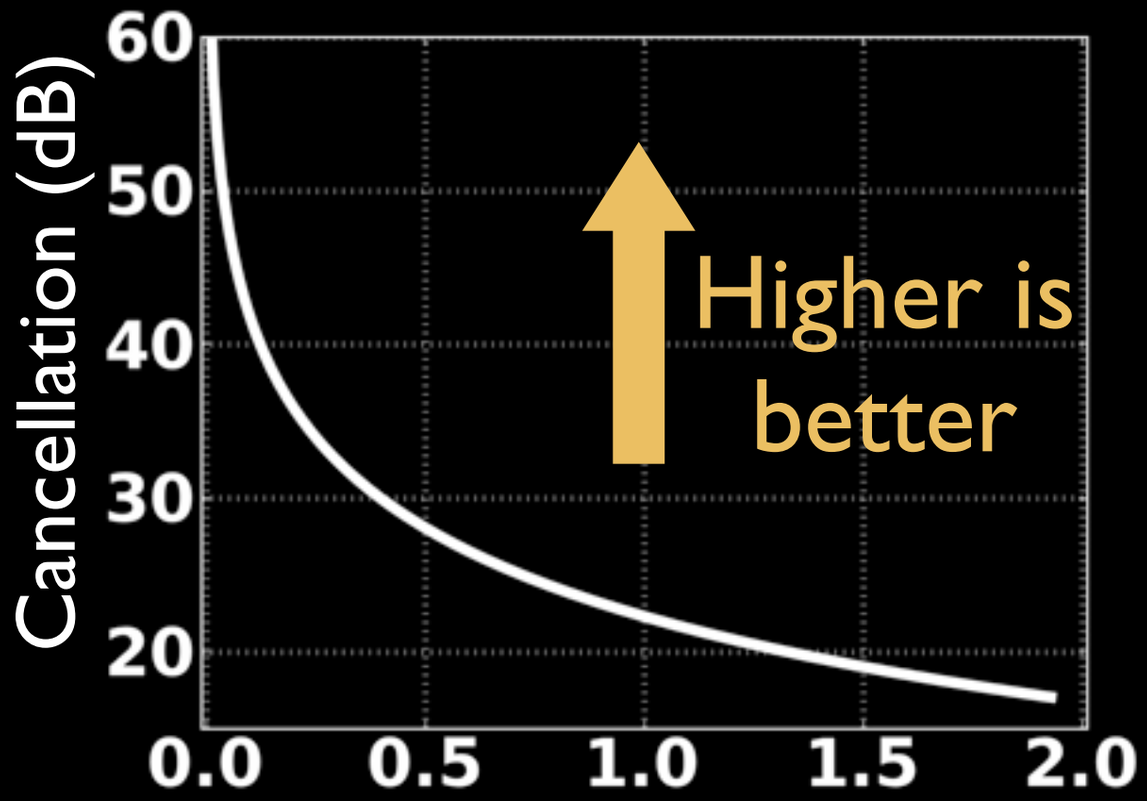


Single Transmit Antenna

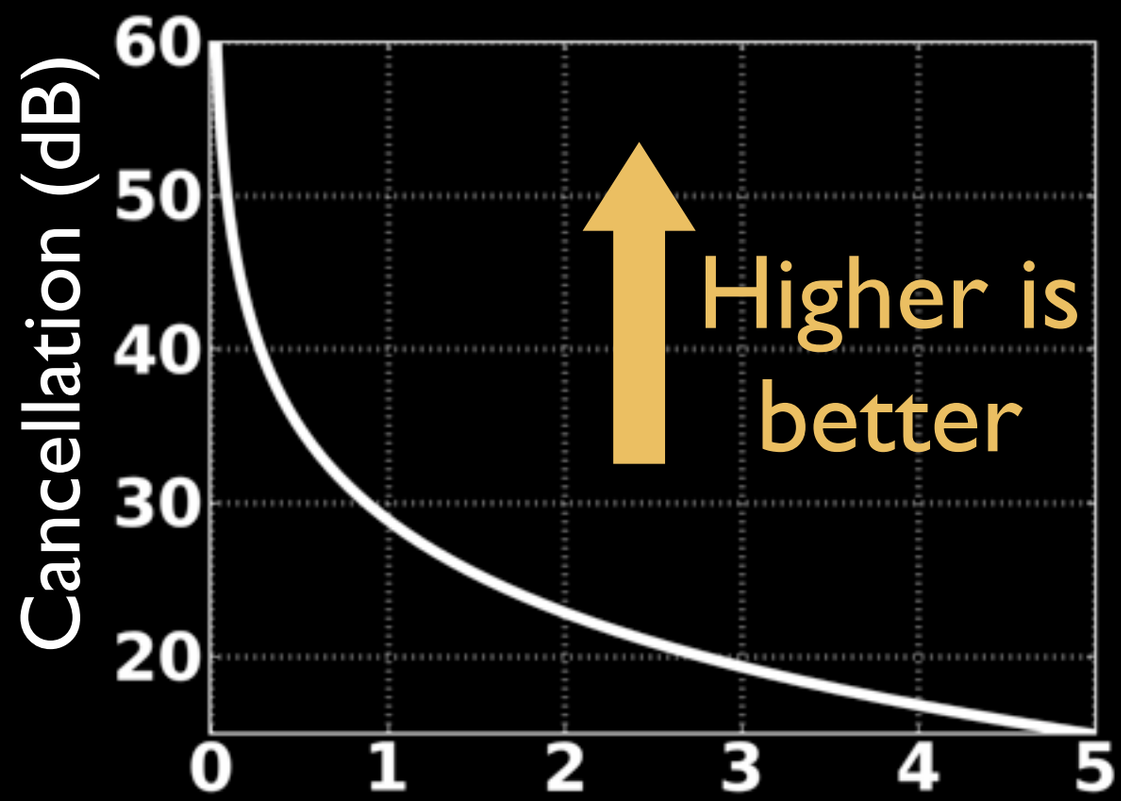


Two Transmit Antennas

Sensitivity of Phase Offset Cancellation

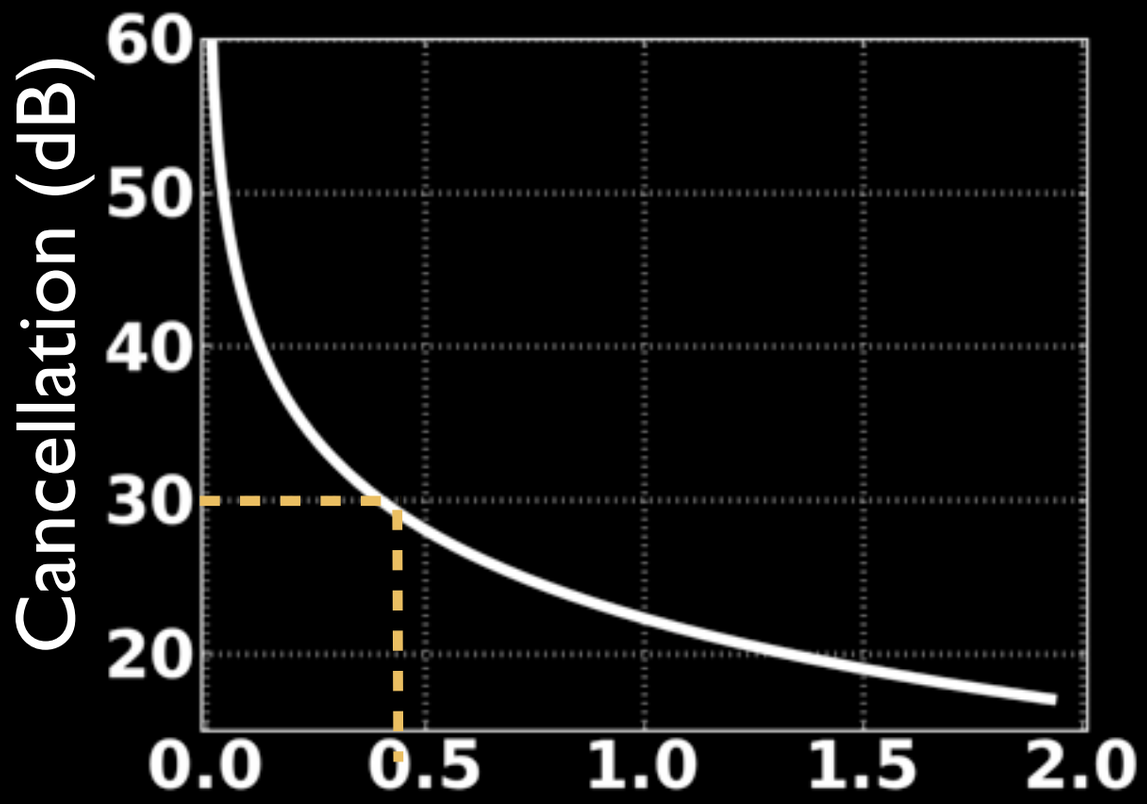


Amplitude Mismatch between TX1 and TX2



Placement Error for RX

Sensitivity of Phase Offset Cancellation



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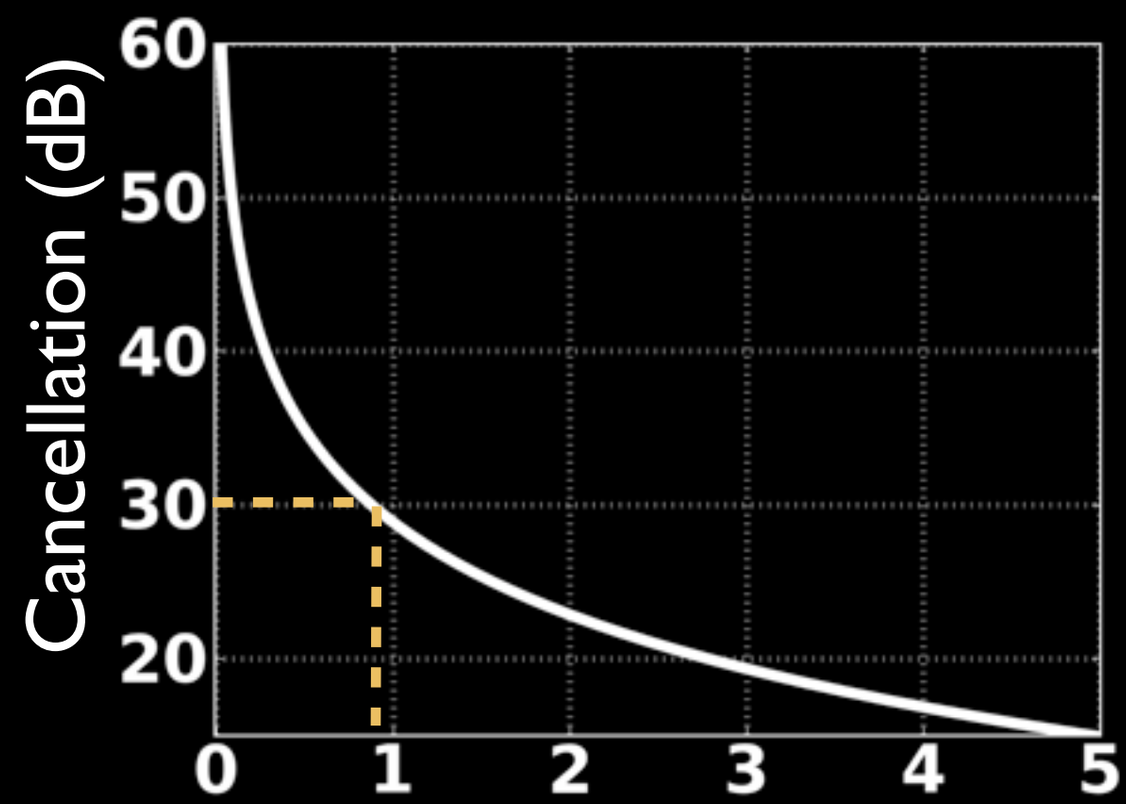
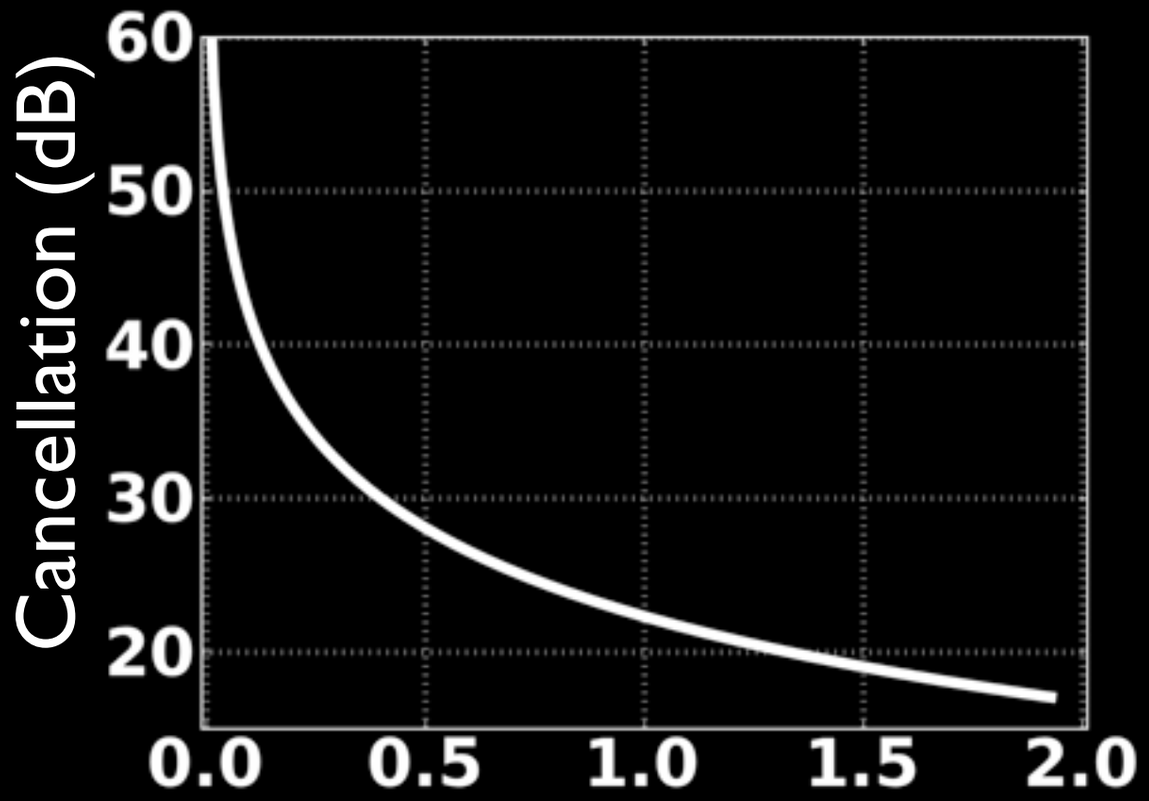


Placement Error
for RX

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

Sensitivity of Phase Offset Cancellation



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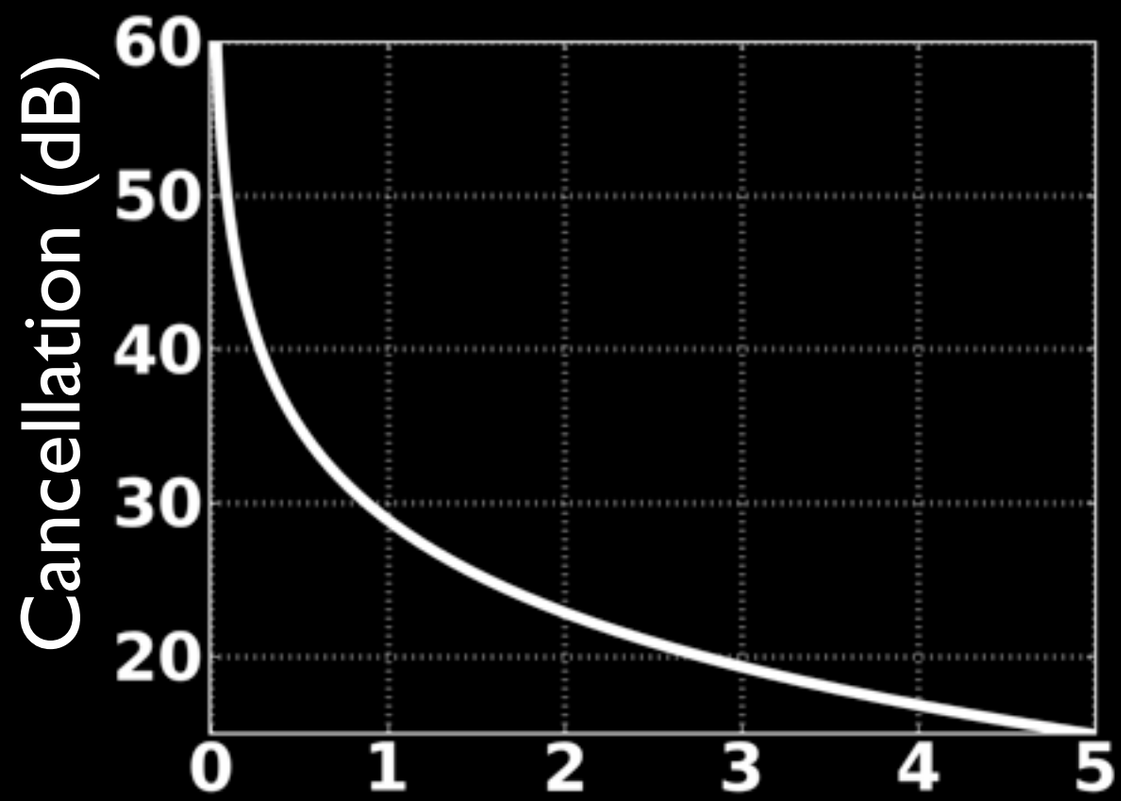
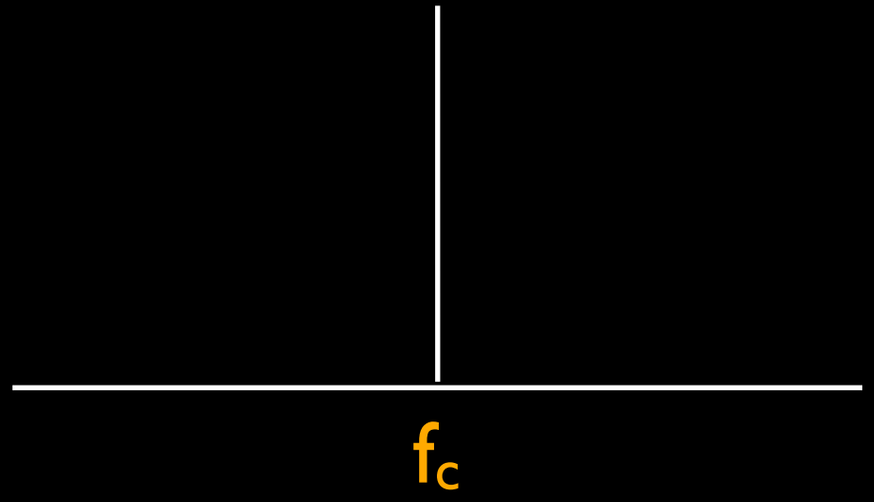


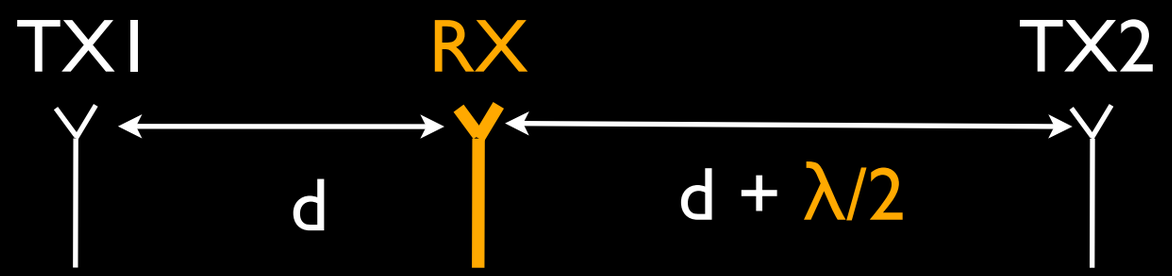
Placement Error for RX

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

Bandwidth Constraint

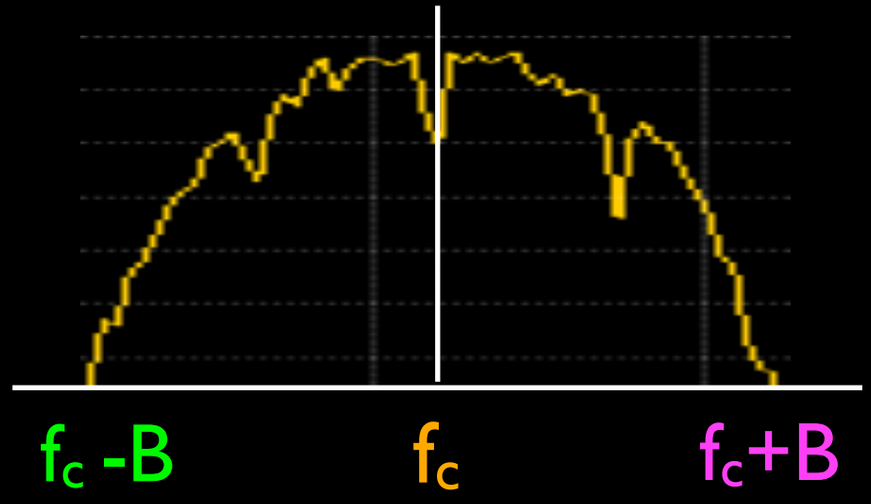
A λ/2 offset is precise for one frequency

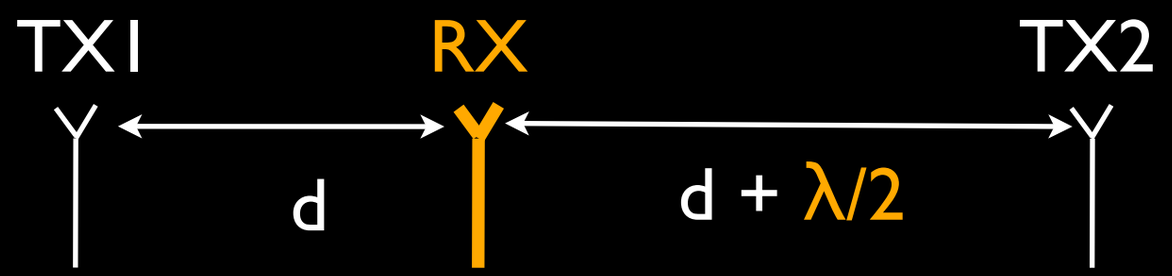




Bandwidth Constraint

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





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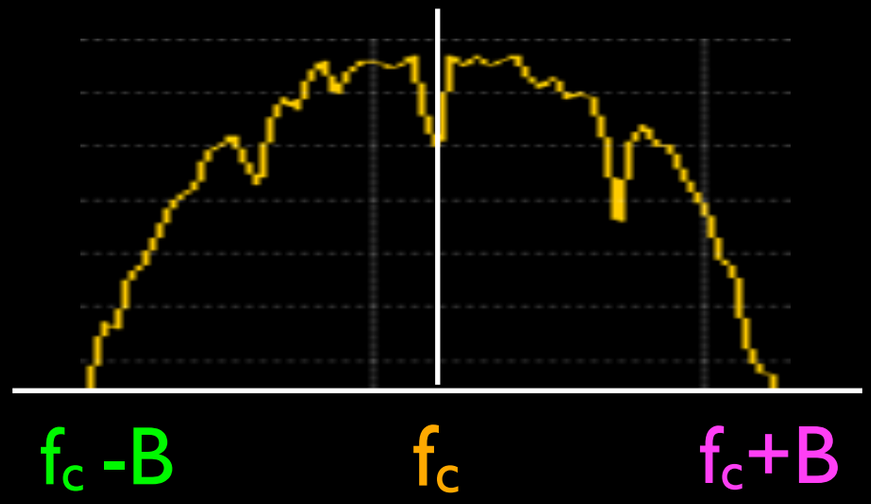

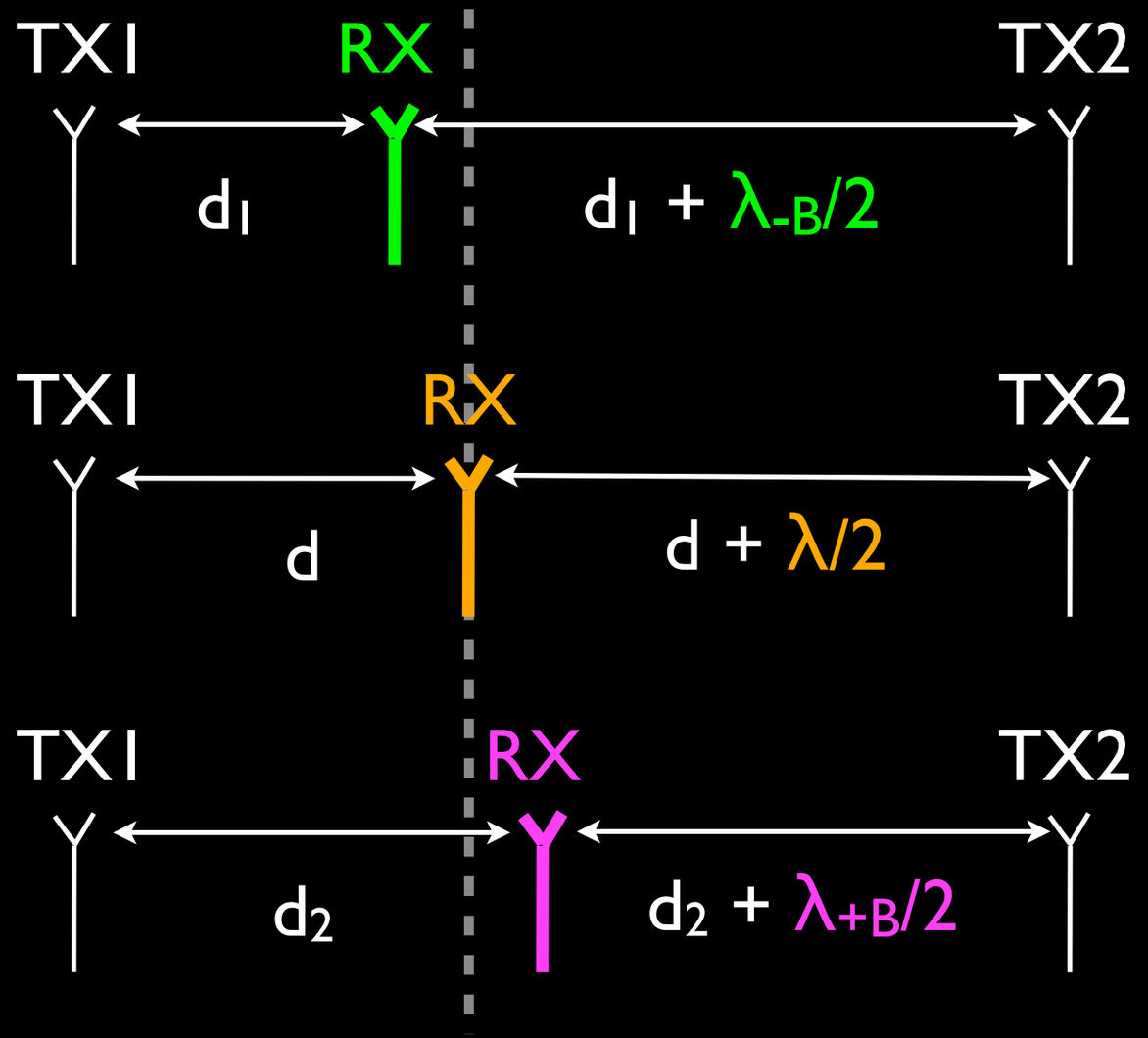

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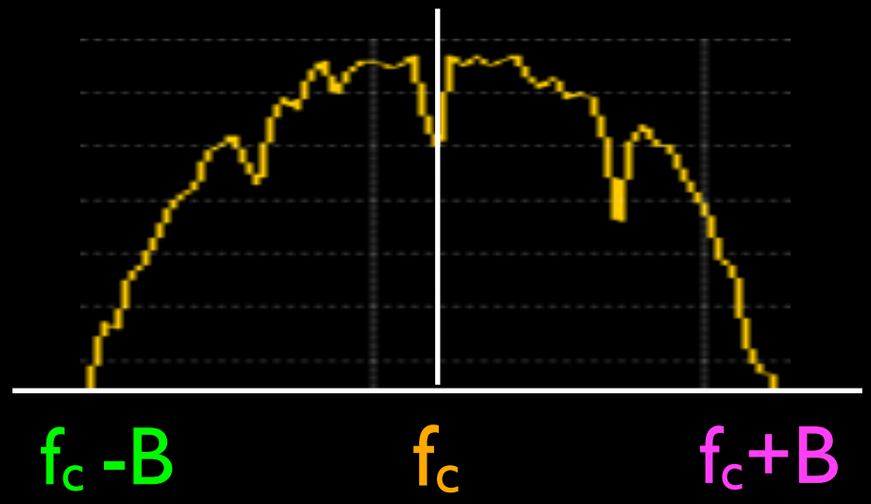
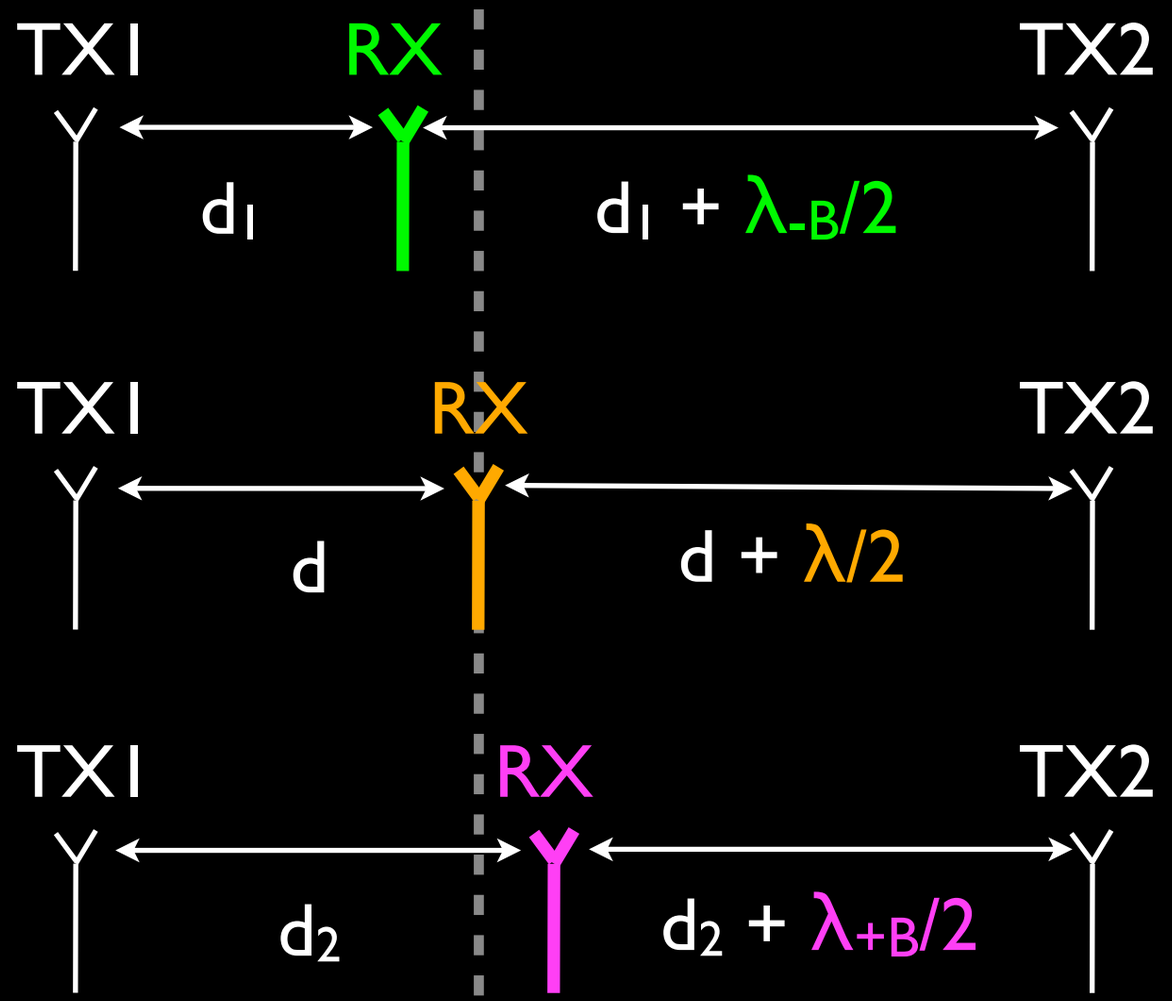
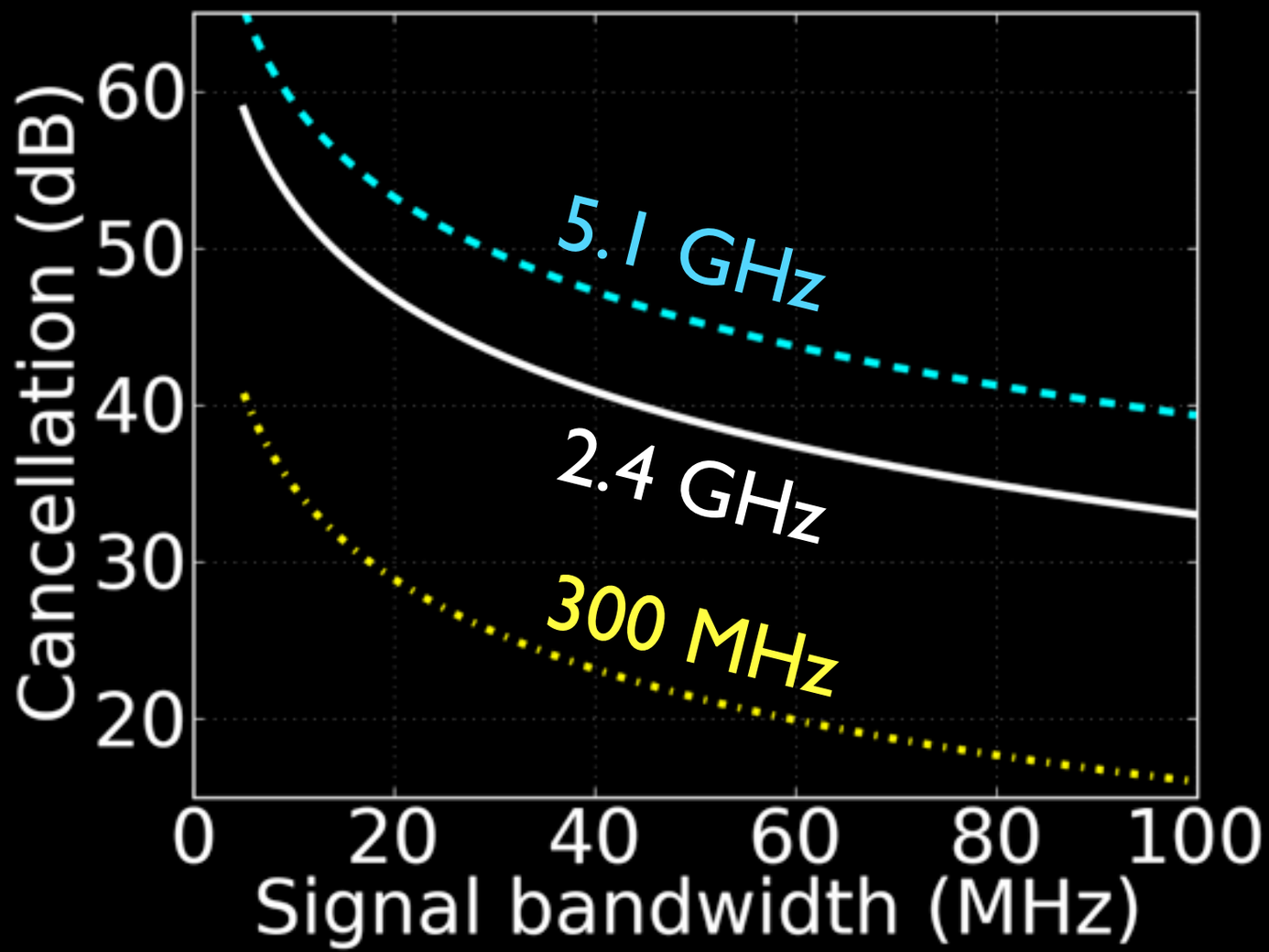


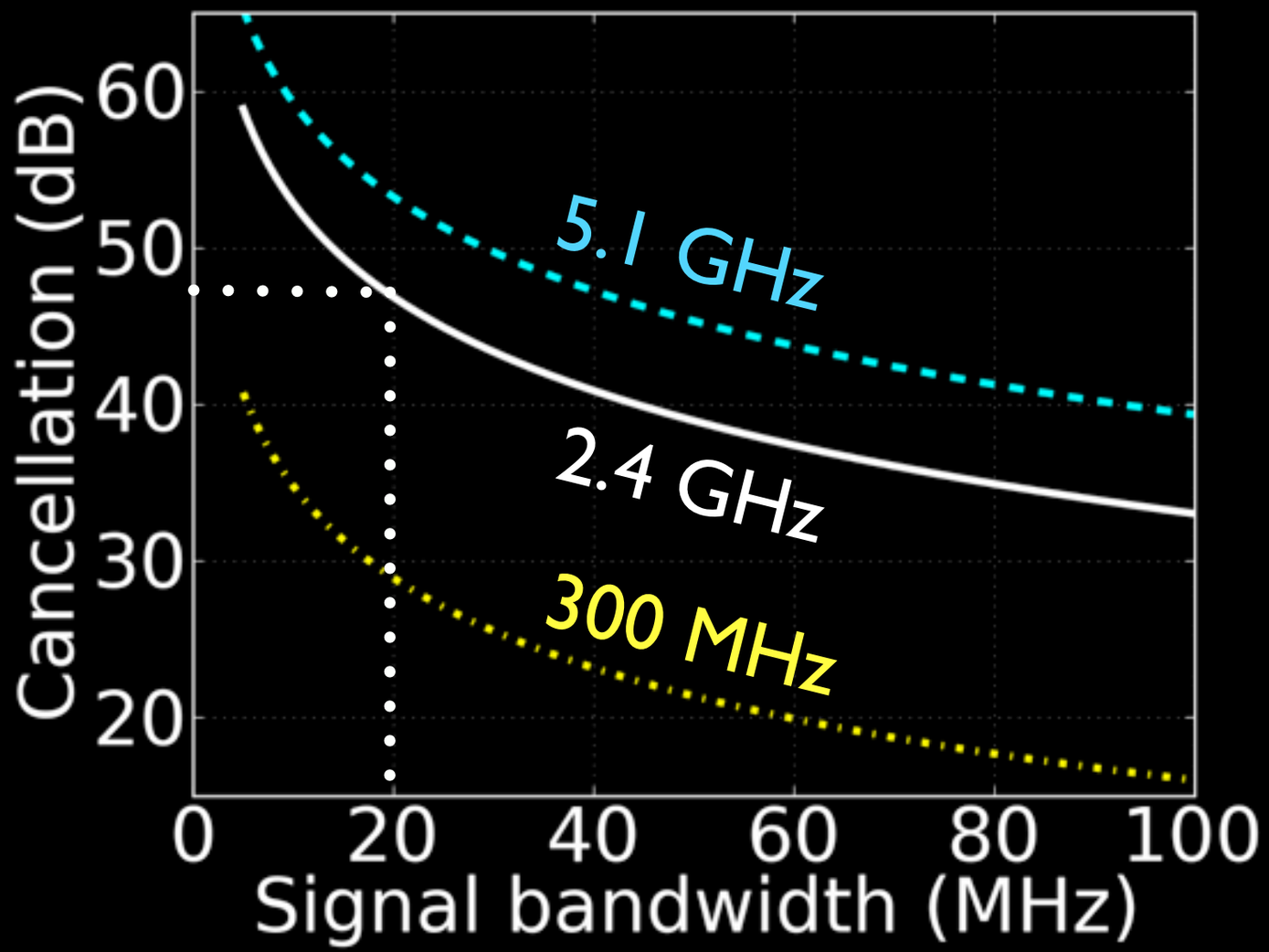


WiFi (2.4G, 20MHz) => ~0.26mm precision error

Bandwidth Constraint

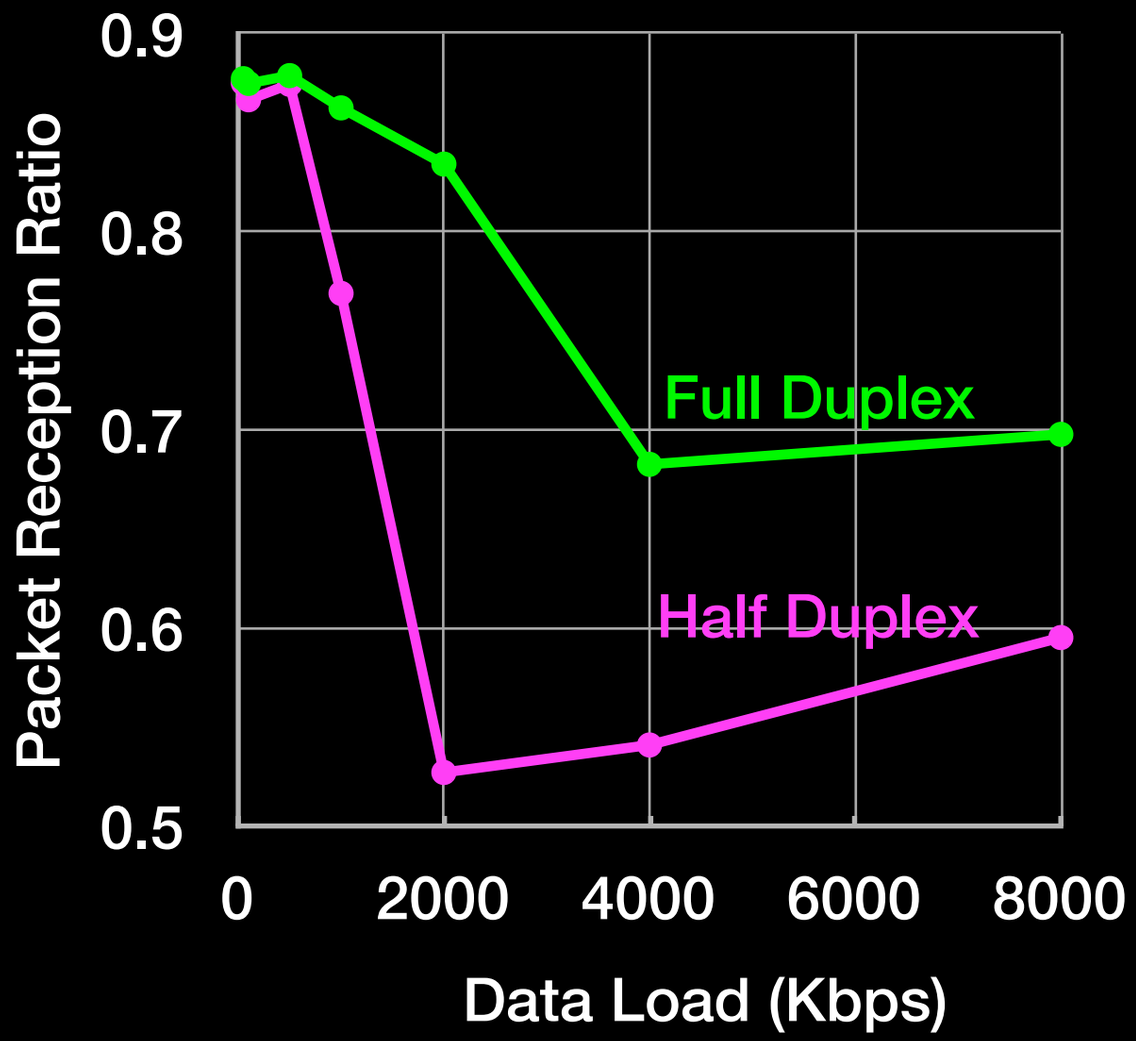


Bandwidth Constraint

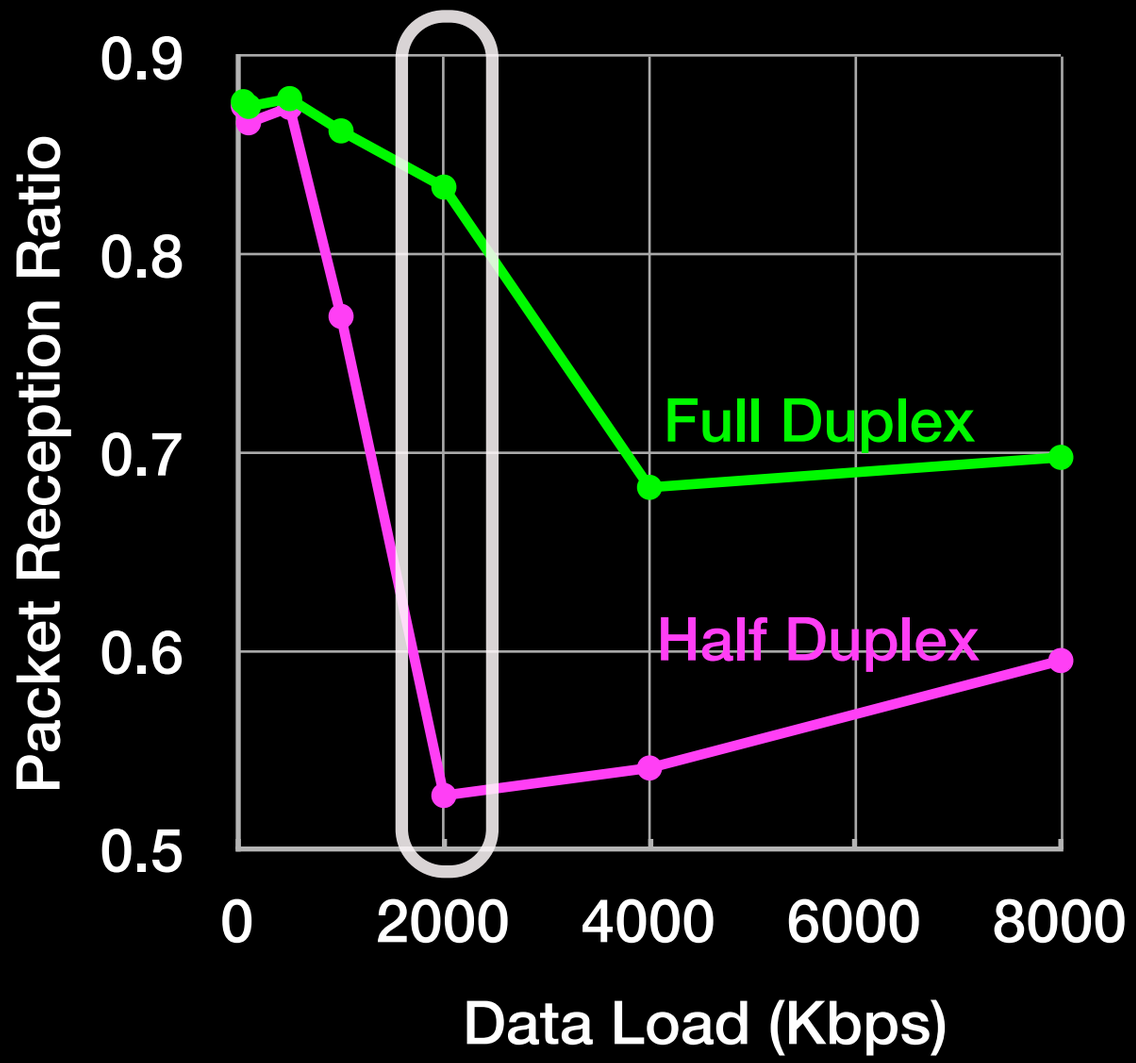


- WiFi (2.4GHz, 20MHz): Max 47dB reduction
- Bandwidth ⬆ => Cancellation ⬇
- Carrier Frequency ⬆ => Cancellation ⬆

Mitigating Hidden Terminals

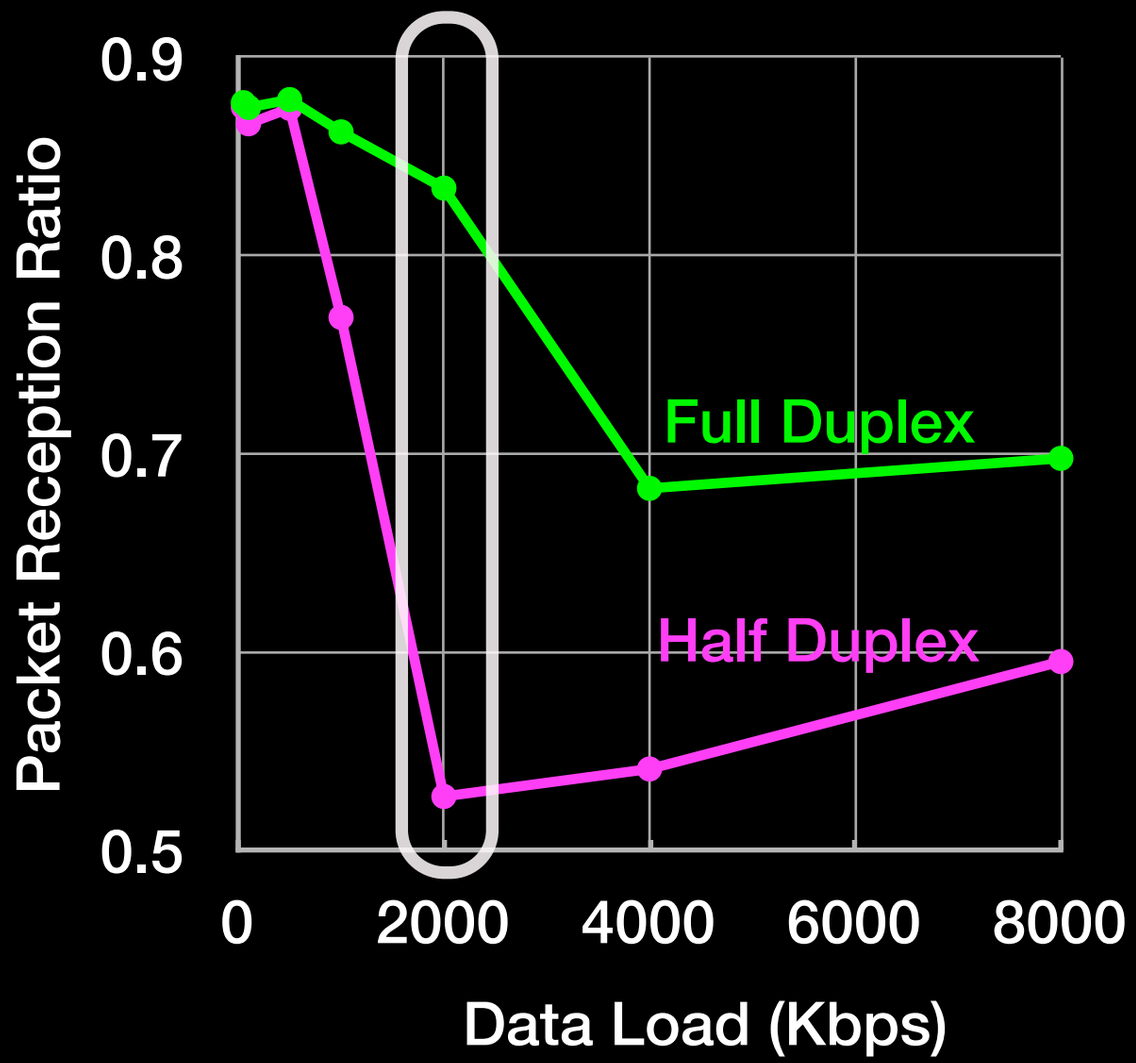


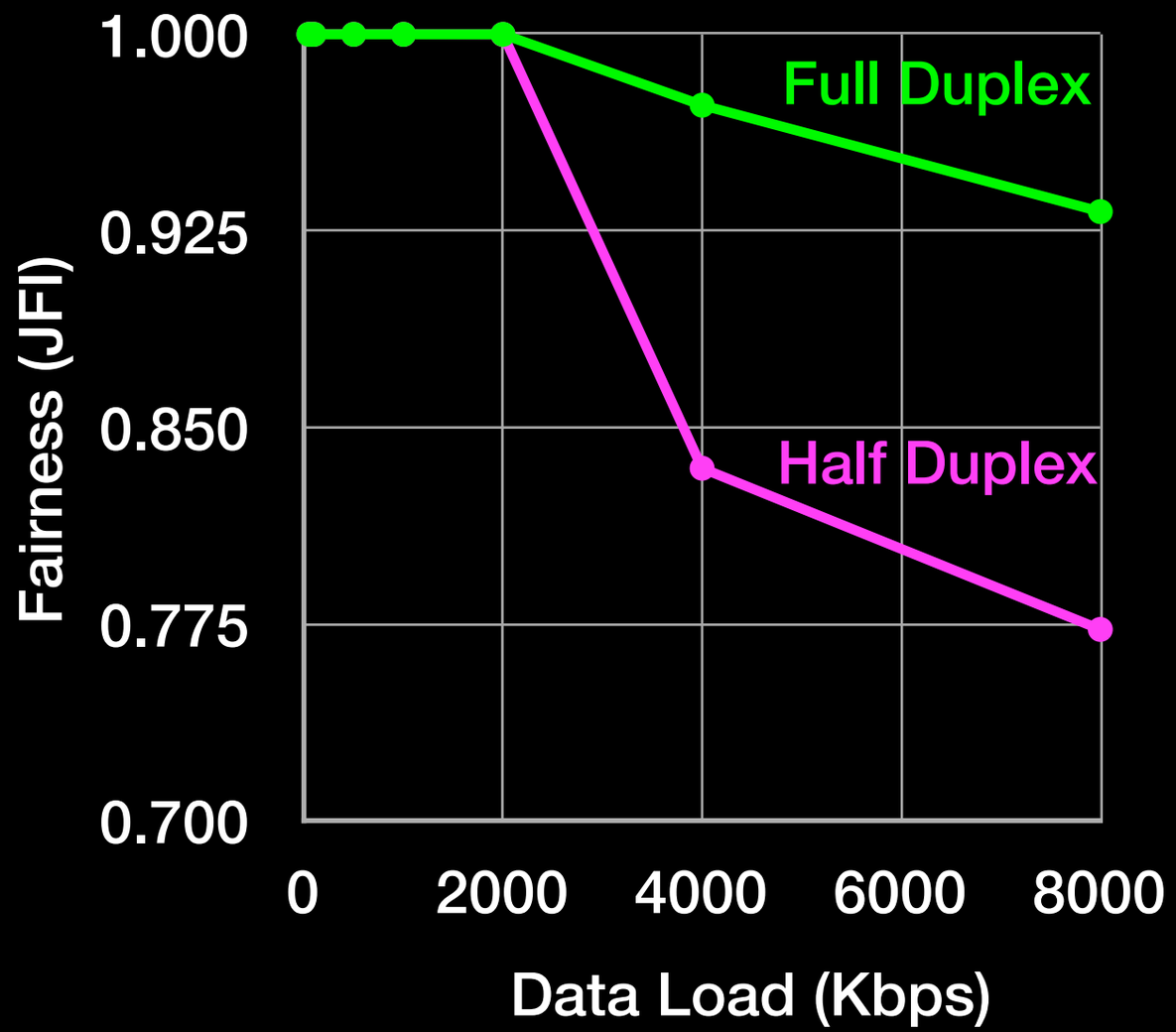
Mitigating Hidden Terminals



- 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