Course Survey

- Will be handed out after Thursday lecture
- Worth 3 extra credit points on final exam
- SCPD: email to Alexis Wing <alexisw@cs.stanford.edu>
    - She will anonymize answers, track who answered

Talk on Net Neutrality

- Barbara van Schewick on Internet Architecture, Innovation and Network Neutrality
  - Wednesday, December 1, 6-8PM
  - Stanford Law School, Room 290
  - http://cyberlaw.stanford.edu/node/6557

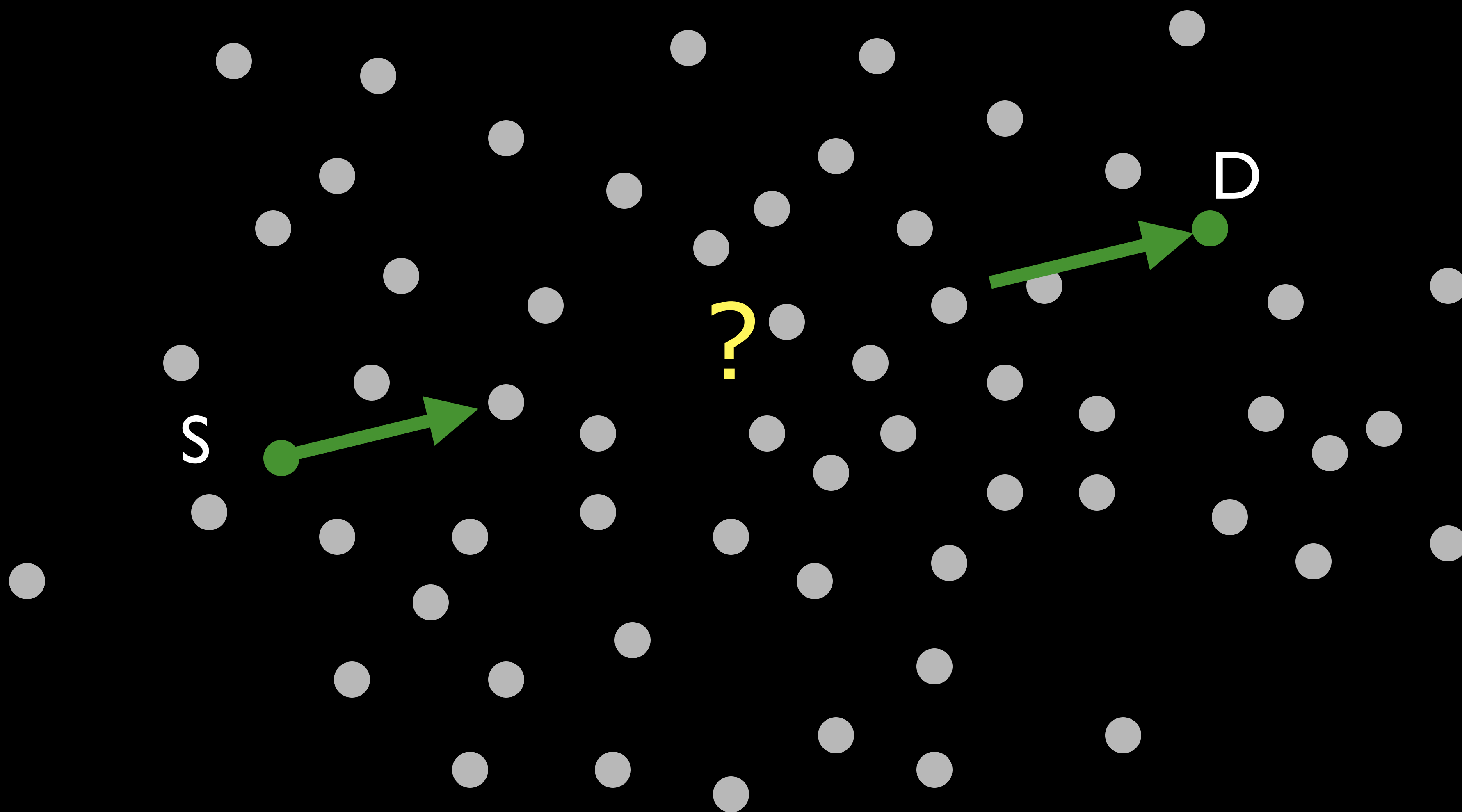
"Today – following housing bubbles, bank collapses, and high unemployment – the Internet remains the most reliable and fantastic mechanism for fostering innovation and creating new wealth. But this engine of innovation is under threat."

Wireless Routing and Full Duplex Wireless

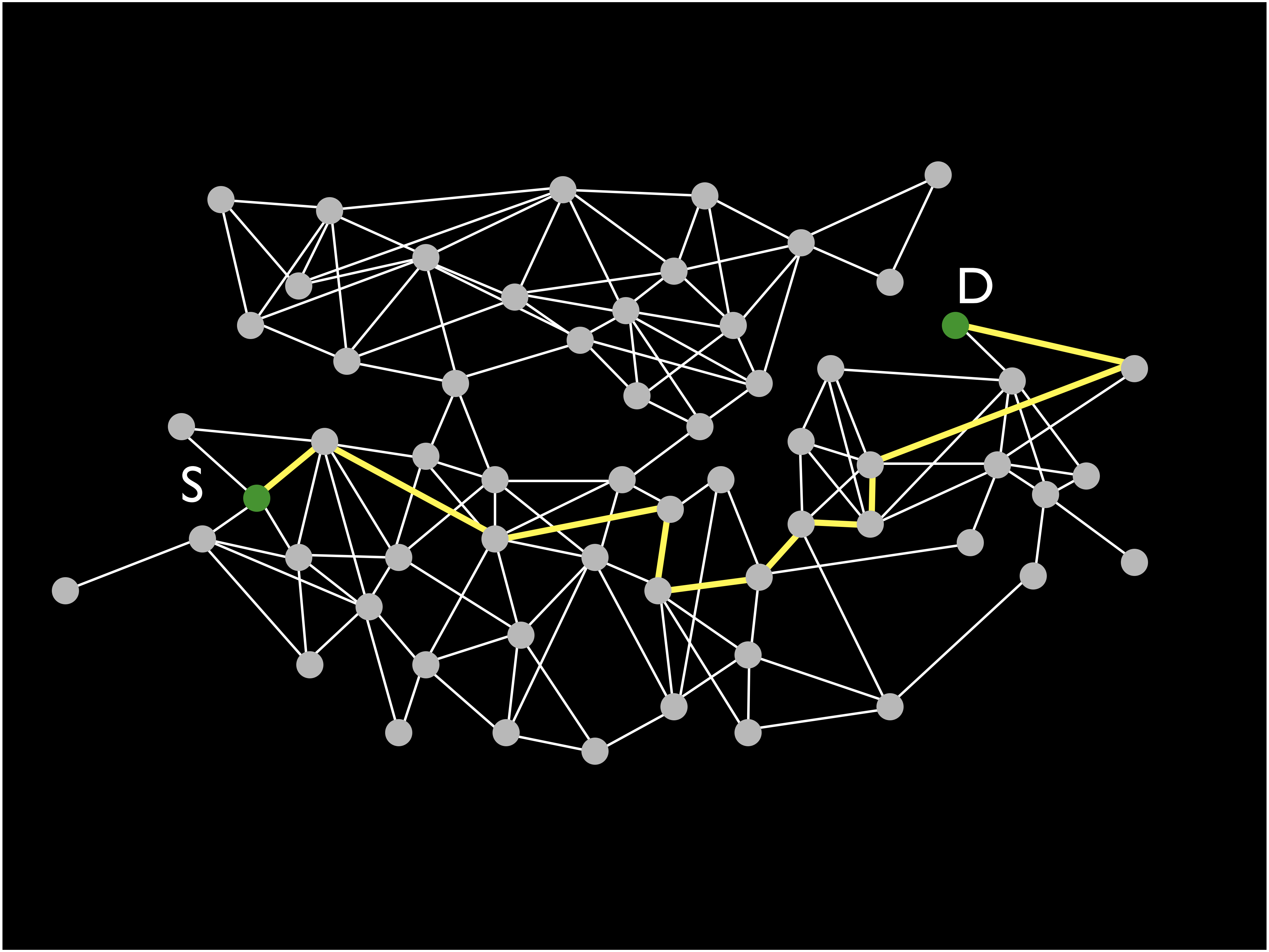
Philip Levis
Stanford University

@CS144, 30.xi.2010

also Kyle Jamieson, Rodrigo Fonseca, Omprakash Gnawali, David Moss, Kannan Srinivasan, Mayank Jain, Jung Il Choi, Maria Kazandjieva, Tal Rusak, and Sachin Katti.



Problem: deliver a packet to a destination across a multihop wireless network
Goal: minimize cost (transmissions/delivery)
Caveat: commodity wireless in unlicensed bands (802.11, 802.15.4, etc.)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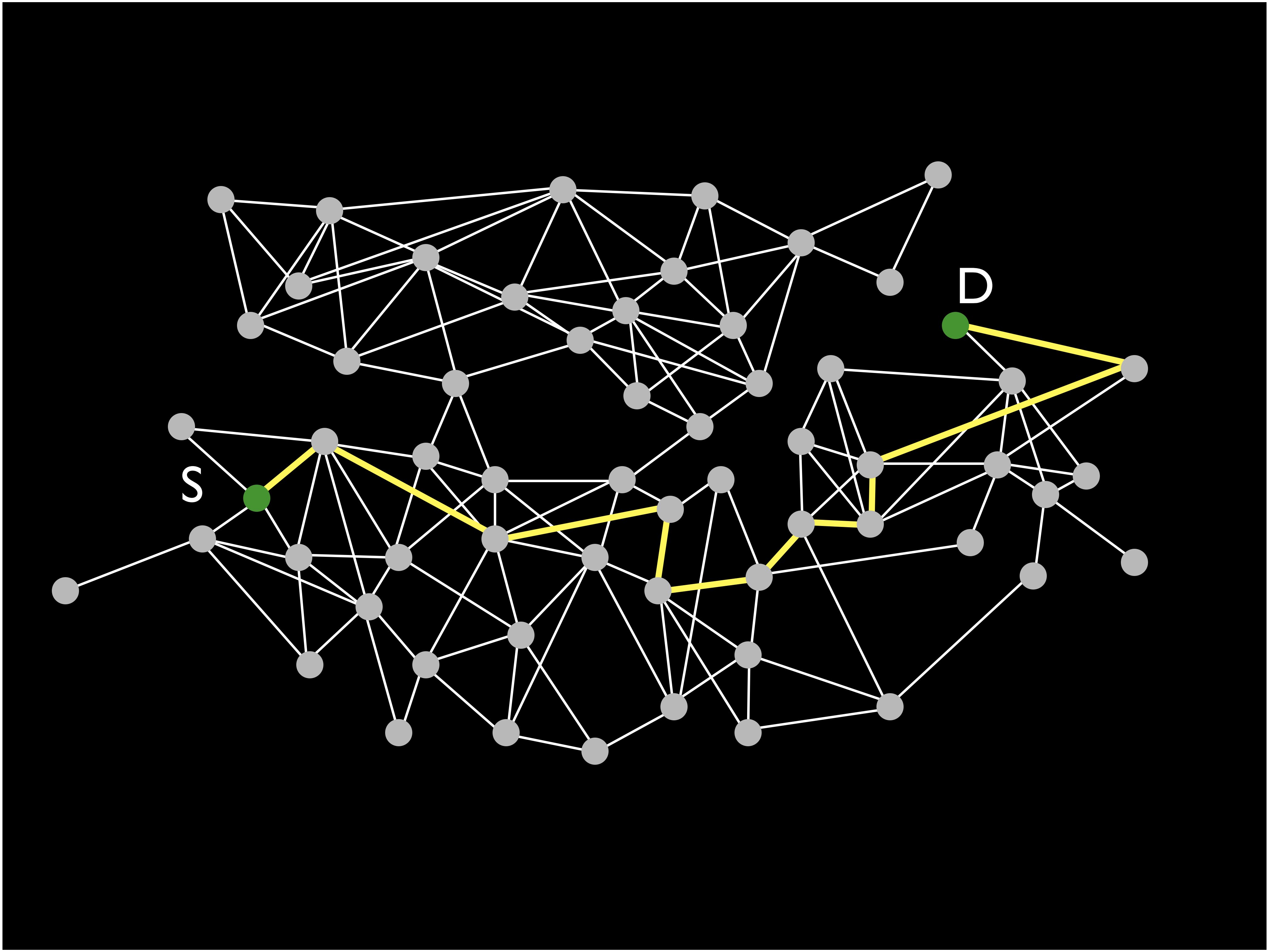
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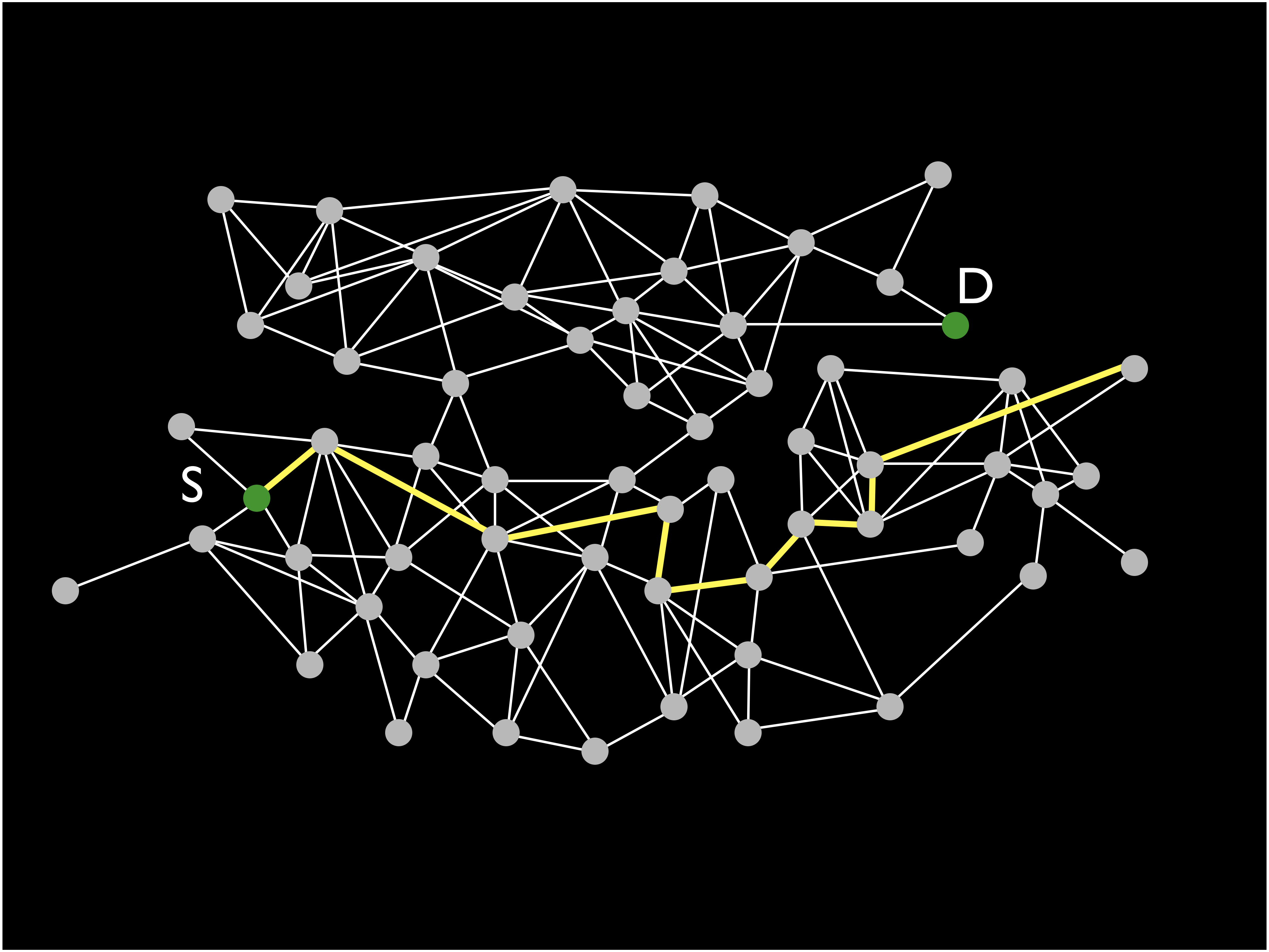
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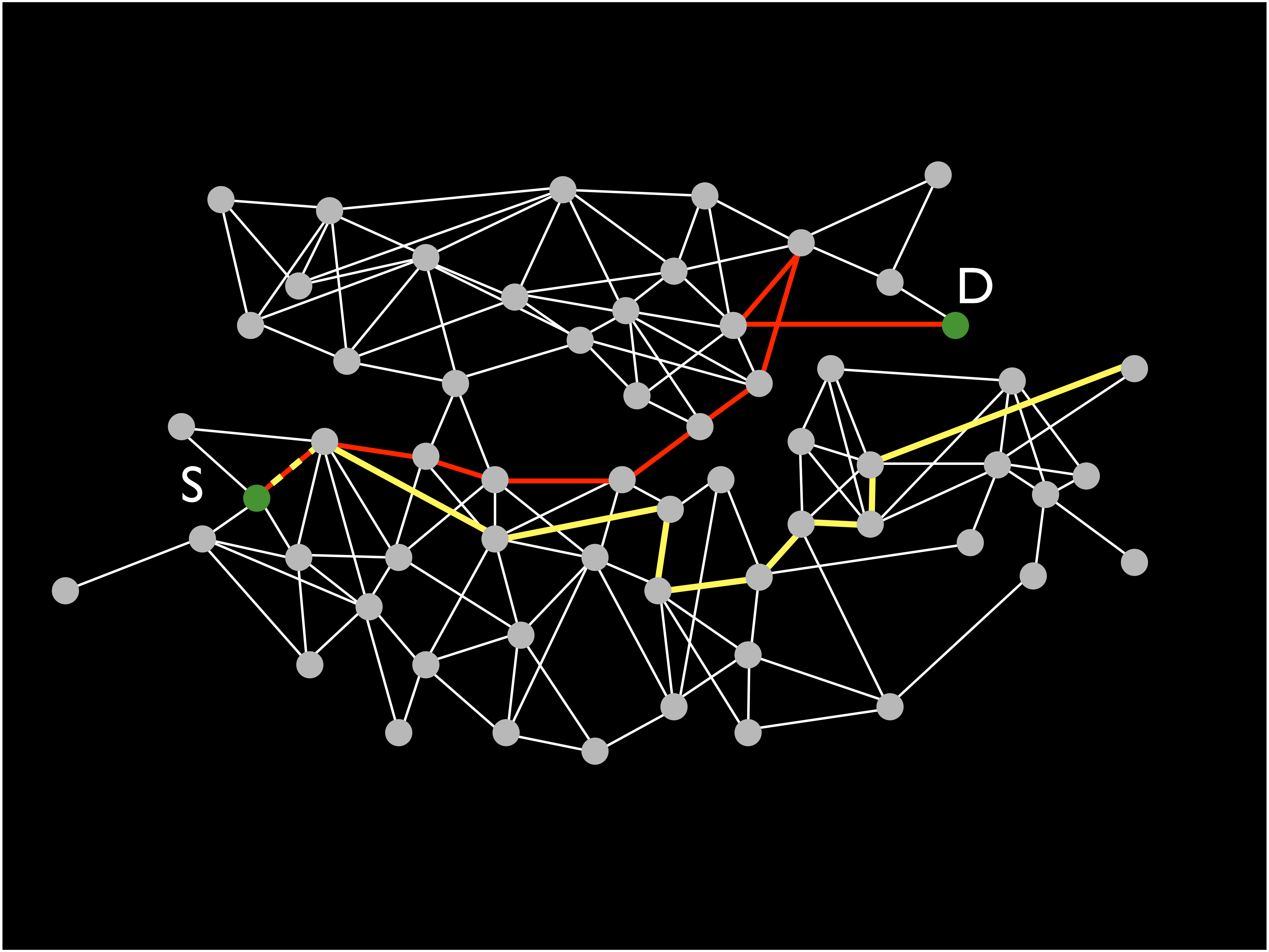

D
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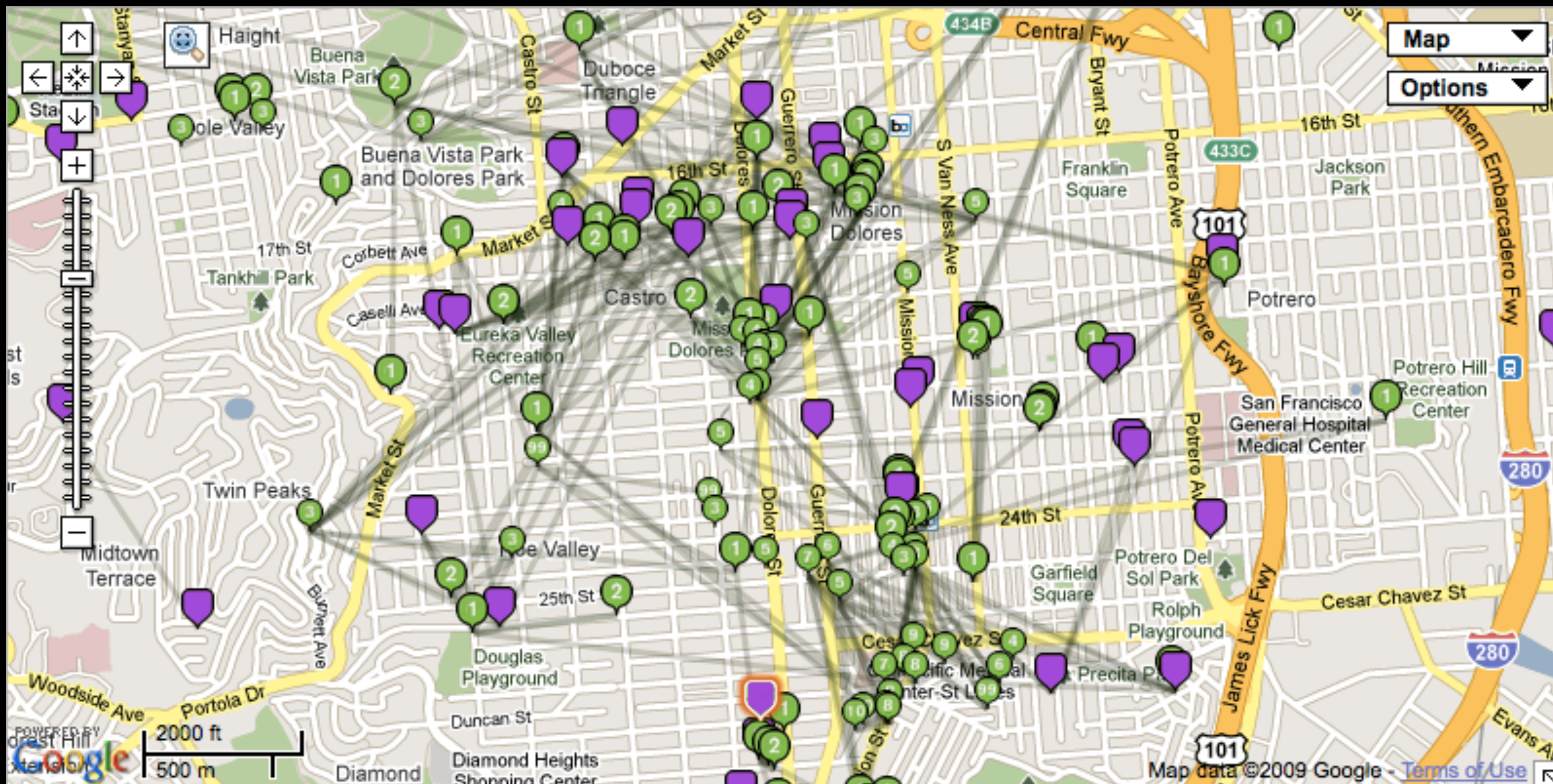
Wireless Routing Today

(e.g., srcr[1])

- Links are not binary: good, bad, etc.
- Each node sends periodic (15s) beacons
  - Measures packet reception ratio (PRR)
  - Sliding 20 packet window (5 minutes)
- Compute costs of edges using PRR
  - Expected transmissions (ETX), PRR^{-1}
- Use standard shortest path algorithms

[1] Bicket et al. "Architecture and Evaluation of an Unplanned 802.11b Mesh Network." ACM Mobicom 2005

Free the Net, San Francisco



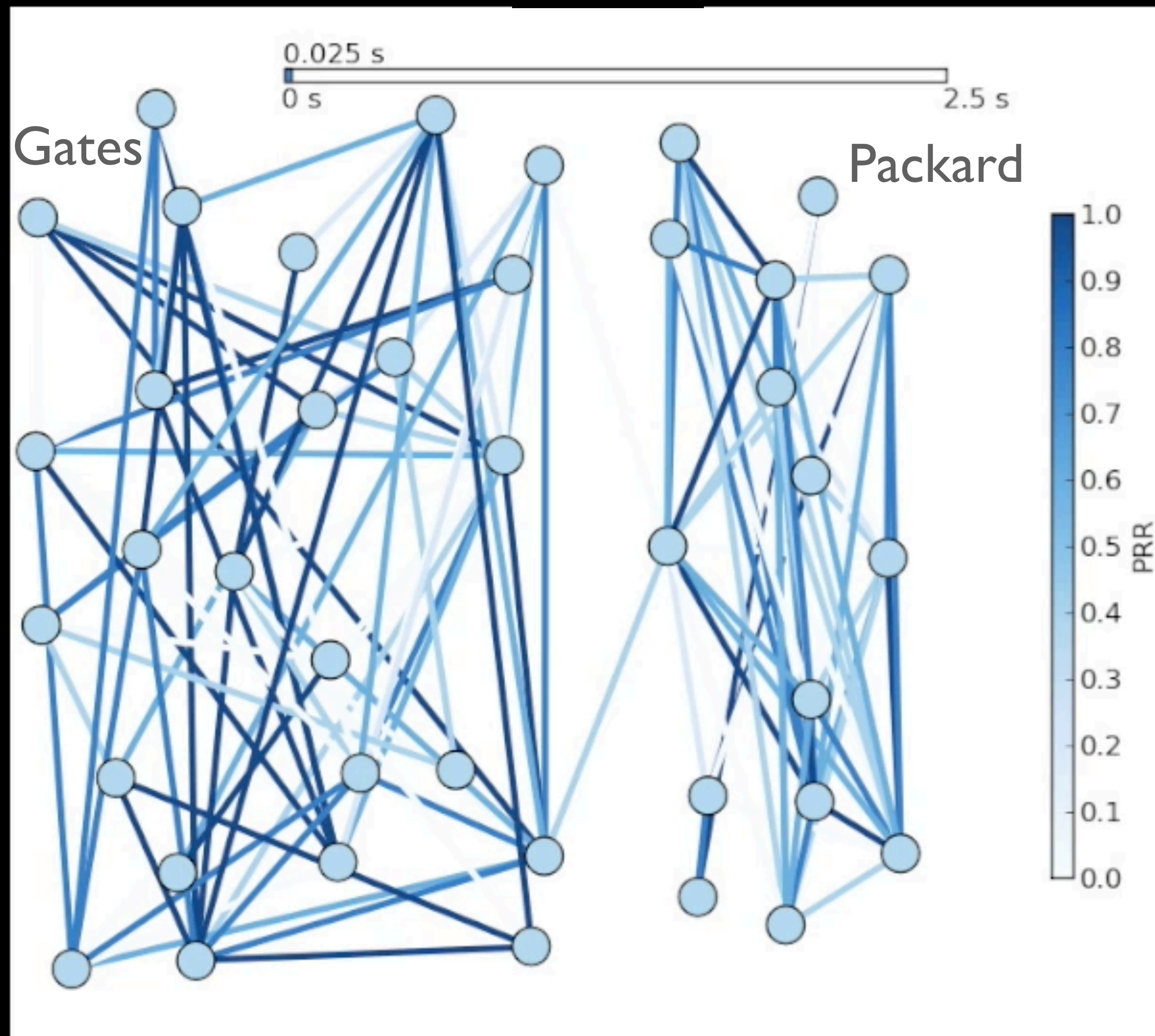
Purple tabs are wired gateways; green nodes provide multihop access
Numbers are hopcount from closest gateway
Lines show links

courtesy of Meraki.com

A Real Network: SWAN

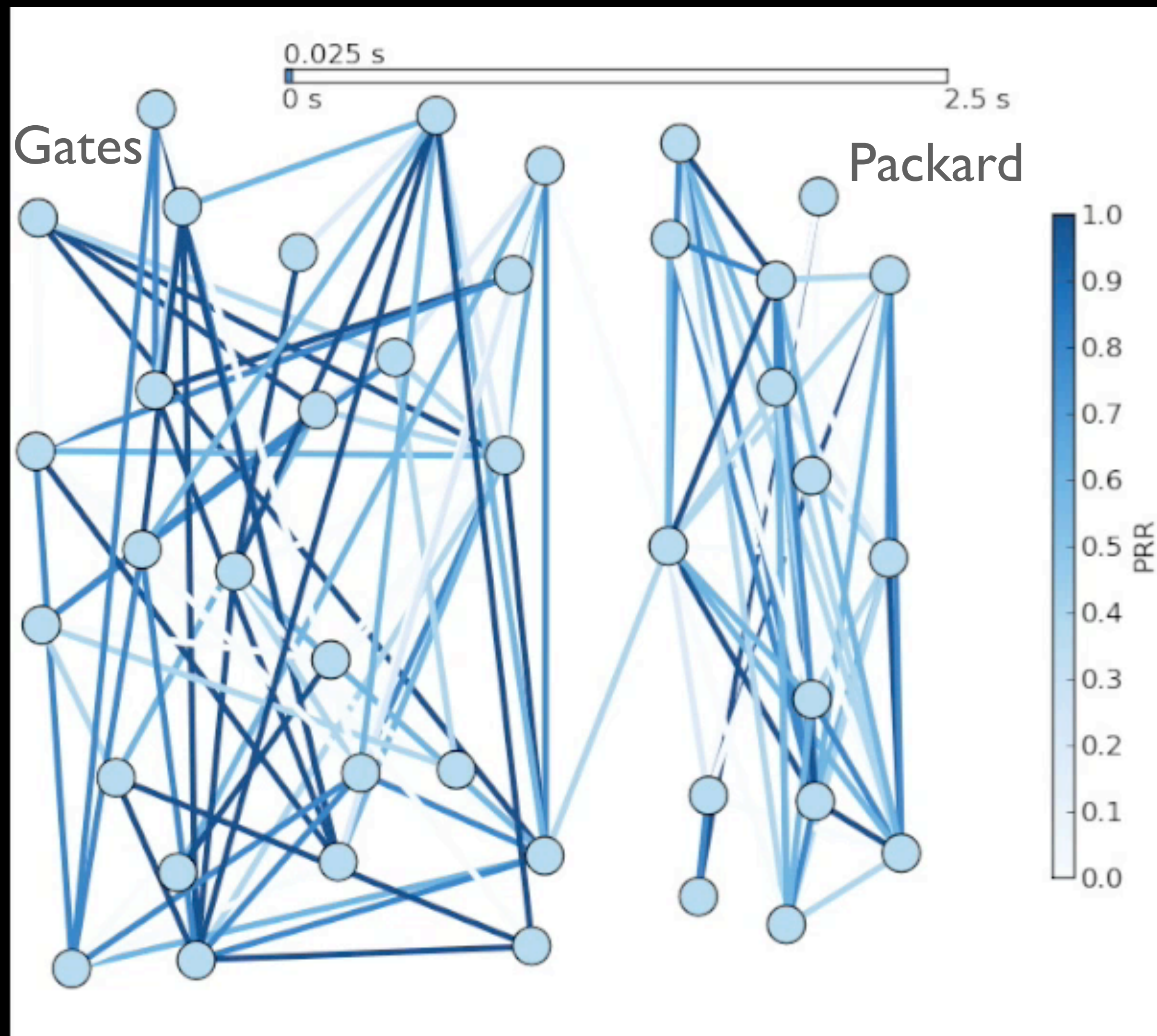
2.5 seconds

The Stanford Wireless Access Network (SWAN) is an 802.11b/g testbed at Stanford. It is part of a research collaboration with King Abdullah University of Science and Technology (KAUST).



A Real Network: SWAN

2.5 seconds



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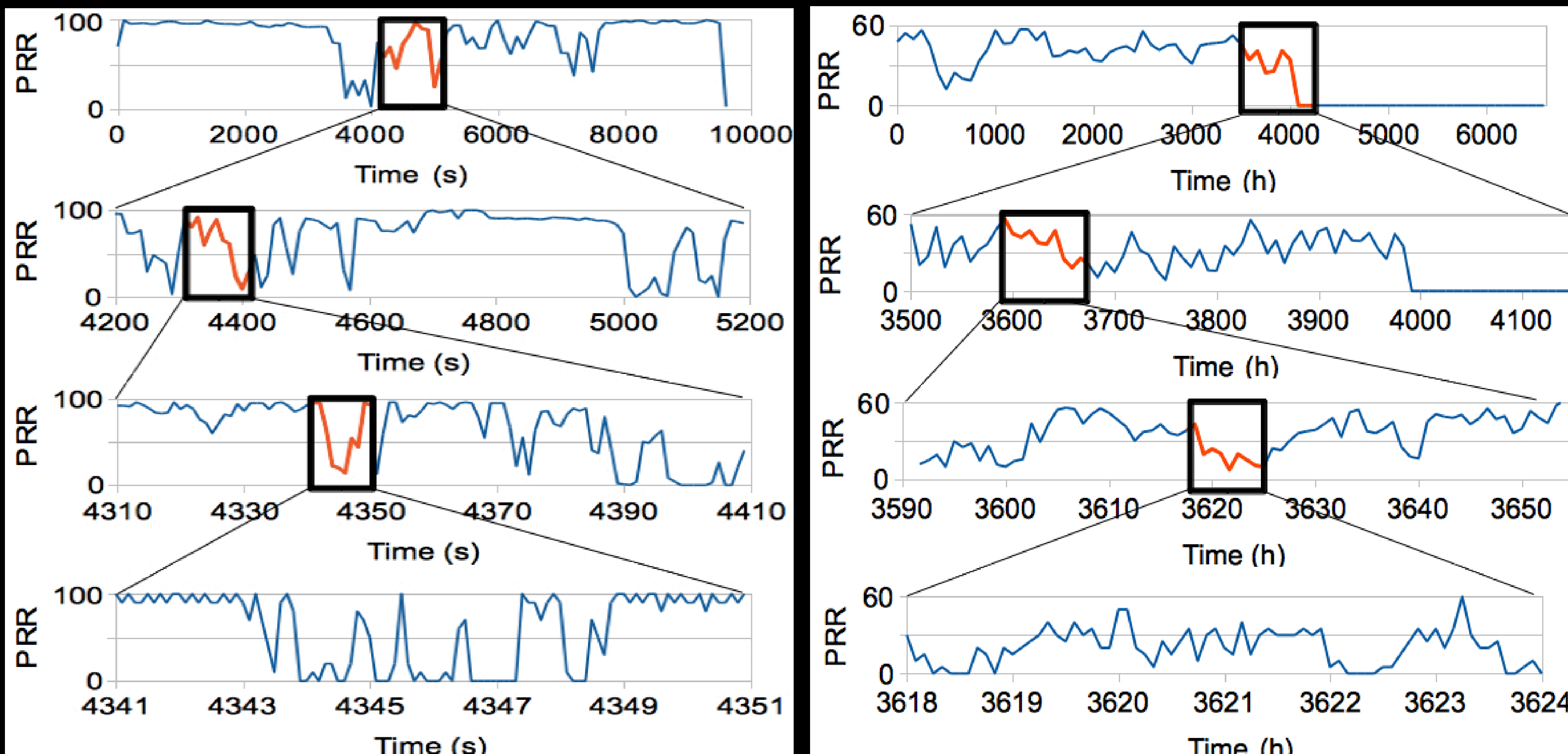
Long-term Link Behavior (scaling)



802.15.4 in Gates

802.11b in Free the Net

Bursts exist at time scales from seconds to months

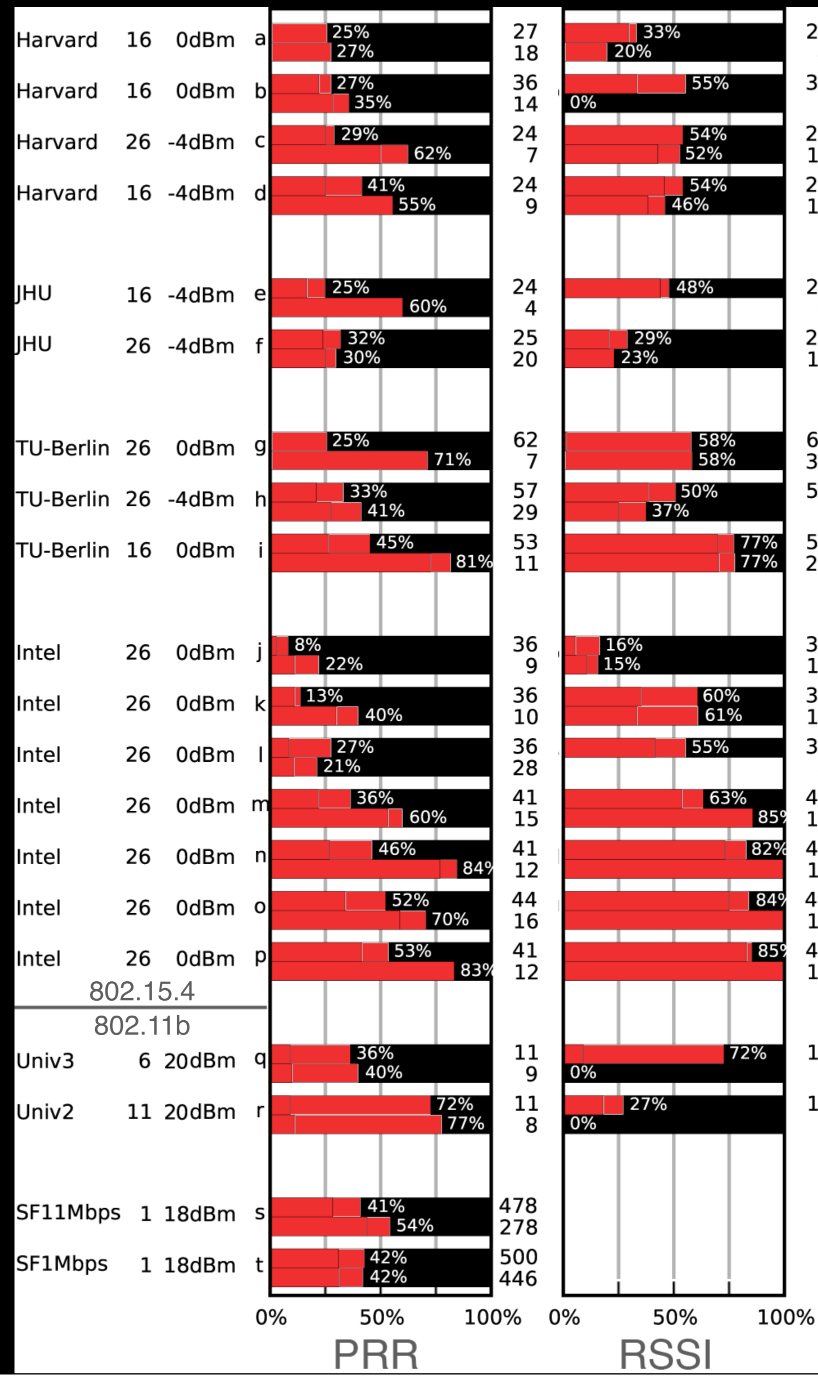
Long-term Link Behavior (scaling)

- Red shows percentage of links that exhibit behavior *consistent with* scaling
  - No characteristic burst length
  - 8-53% of links
- Common across a wide range of networks and durations

seconds to hours

minutes to days

hours to months

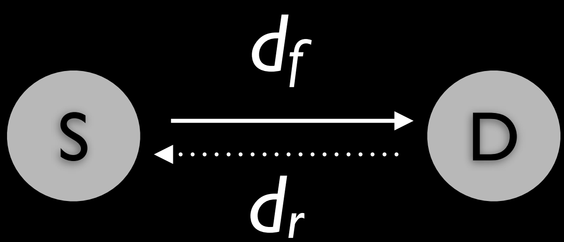


Routing Summary

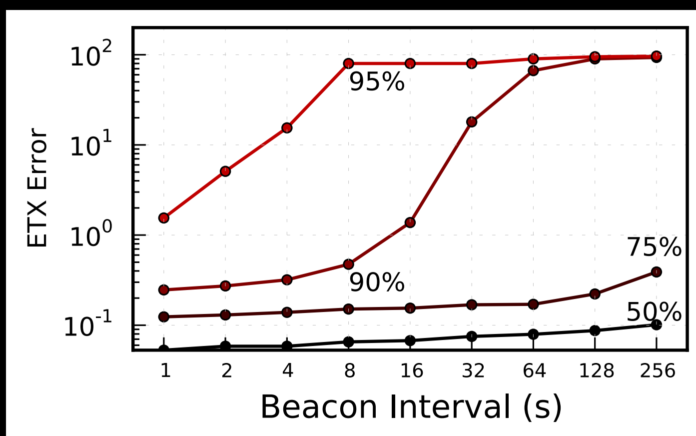
- You can't estimate link futures (scaling)
- Three mechanisms to route in this world
  - 4-bit link estimation
  - Datapath validation
  - Adaptive beaconing

Link Estimation (4B)

Common Approach



$$ETX = (d_f \times d_r)^{-1}$$

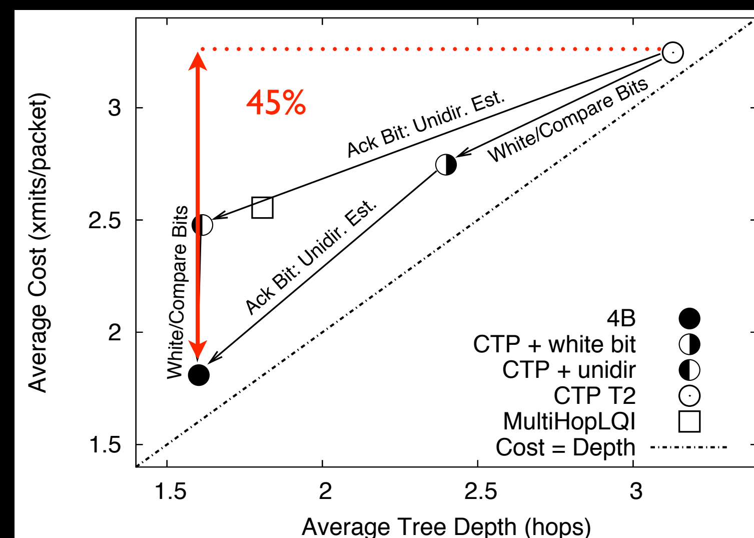


Measuring d_f and d_r with infrequent beacons can be highly inaccurate. Lines show percentile errors.

4-Bit estimator

every 5 packets, $E_t = \begin{cases} \frac{5}{acked} & acked > 0 \\ \text{consecutive unacked} & acked = 0 \end{cases}$

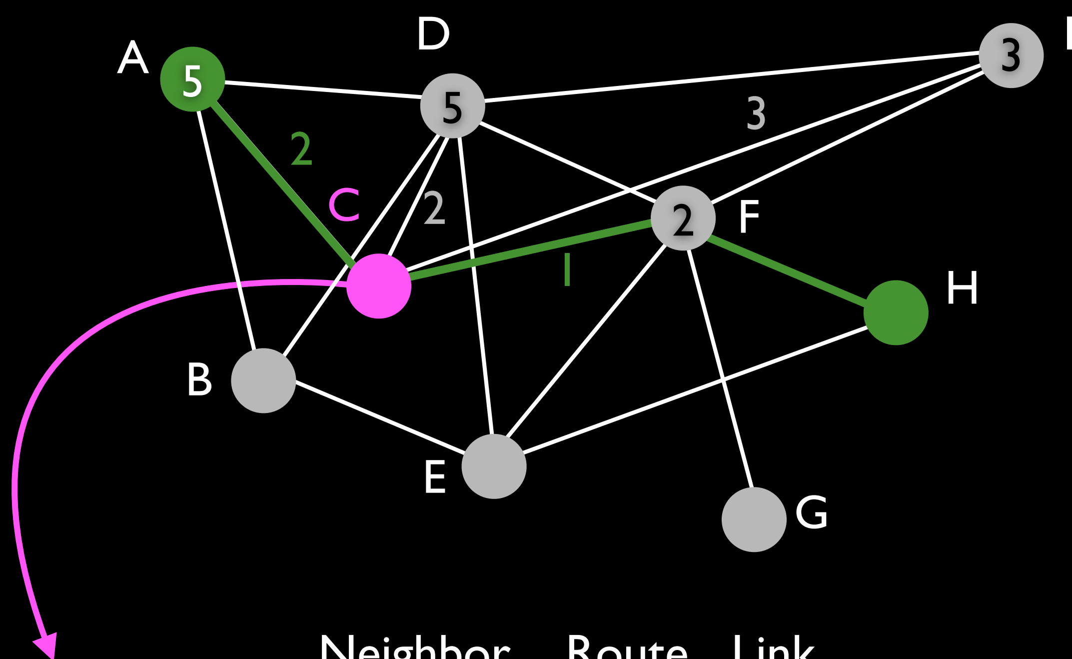
$$ETX_t = \alpha \cdot ETX_{t-1} + (1-\alpha)E_t$$



Directly measuring ETX with the data path reduces path costs by 45%.

This requires a routing protocol can adapt to such rapid edge cost changes.

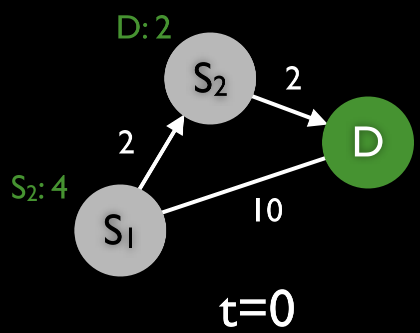
Distance Vector Routing



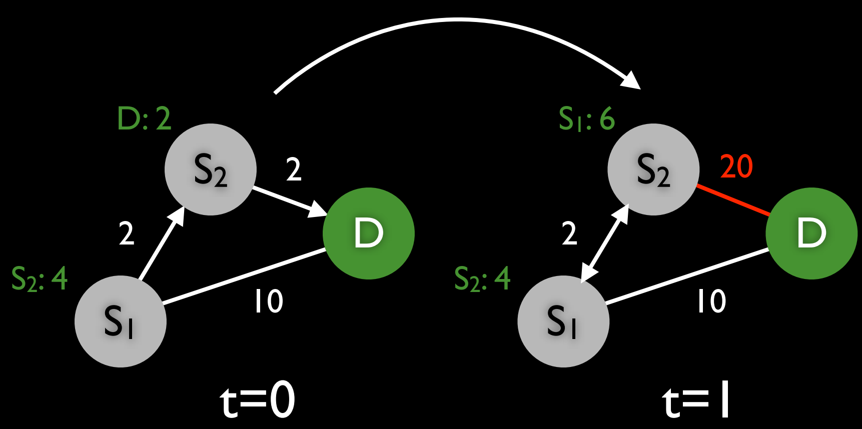
C→H:

Neighbor	Route	Link
A	5	2
D	5	2
F	2	1
J	3	3

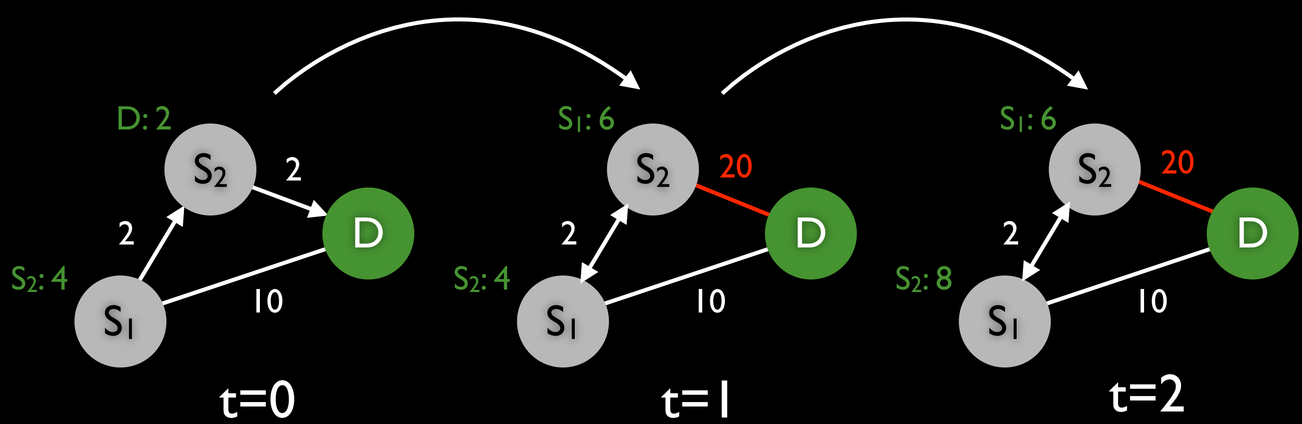
Distance Vector Challenges and Tradeoffs



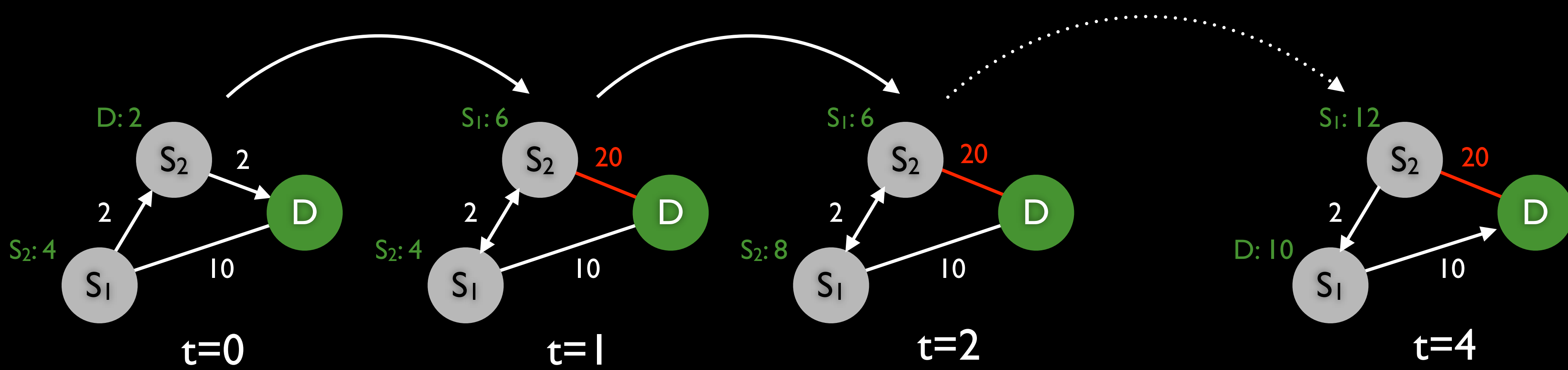
Distance Vector Challenges and Tradeoffs



Distance Vector Challenges and Tradeoffs



Distance Vector Challenges and Tradeoffs



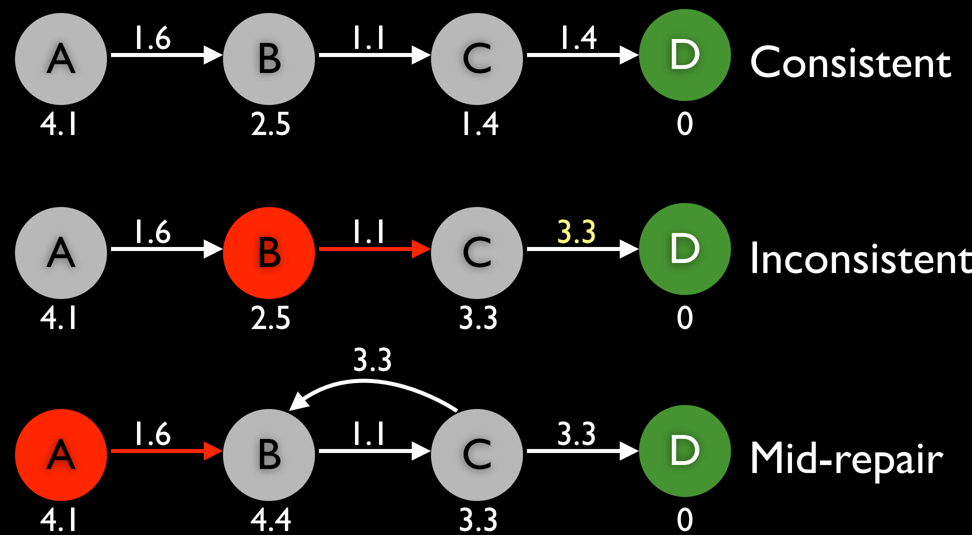
Distance vector's limited view of the network can lead to long-lasting loops.

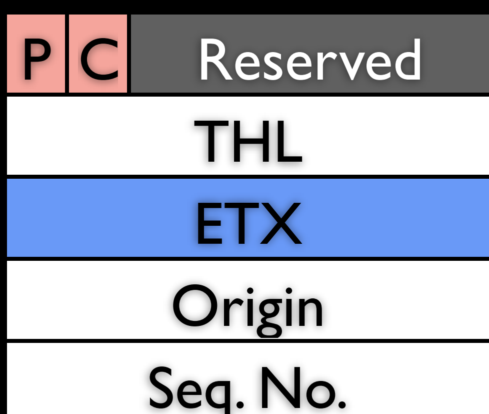
Rapid link cost changes exacerbate this problem.

Datapath Validation

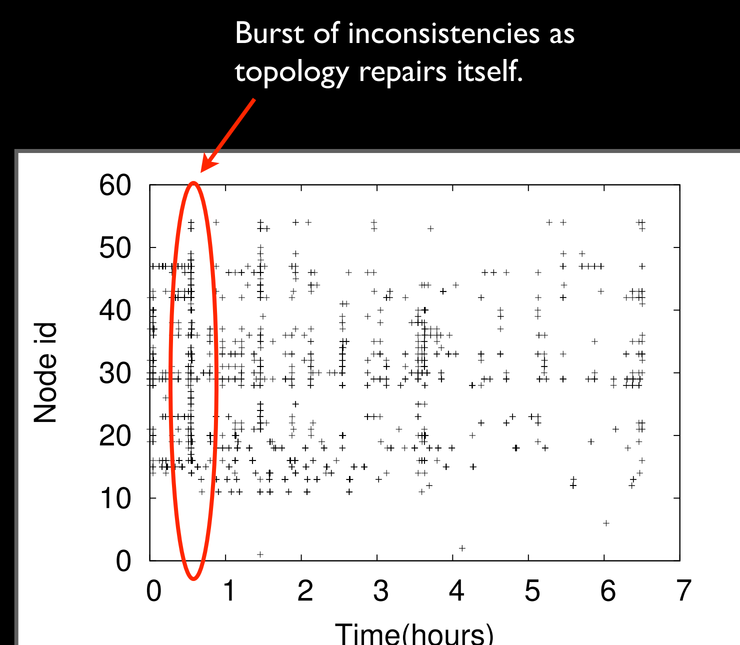
A routing topology is *consistent* if cost decreases on each hop.

Each data packet has a node's cost: the next hop checks consistency.





Data packet header

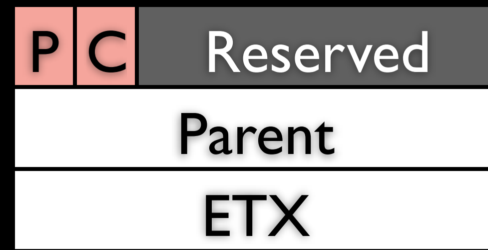


Adaptive Beaconing

Send control packets on a dynamic timer. Reset the timer to a small value τ_l on three conditions:

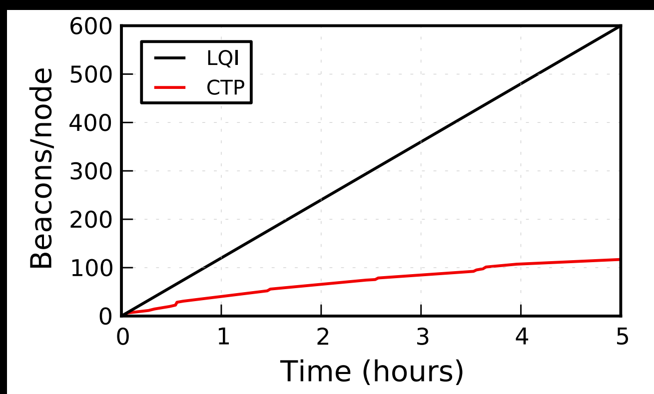
1. Datapath validation detects an inconsistency
2. Receiving a packet with the Pull bit set
3. ETX decreases significantly

Otherwise increase the beacon timer exponentially, up to a max τ_h.



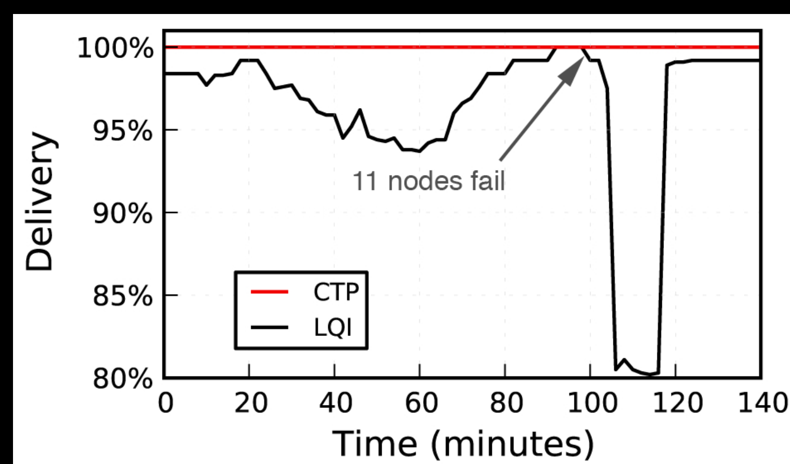
Control packet header

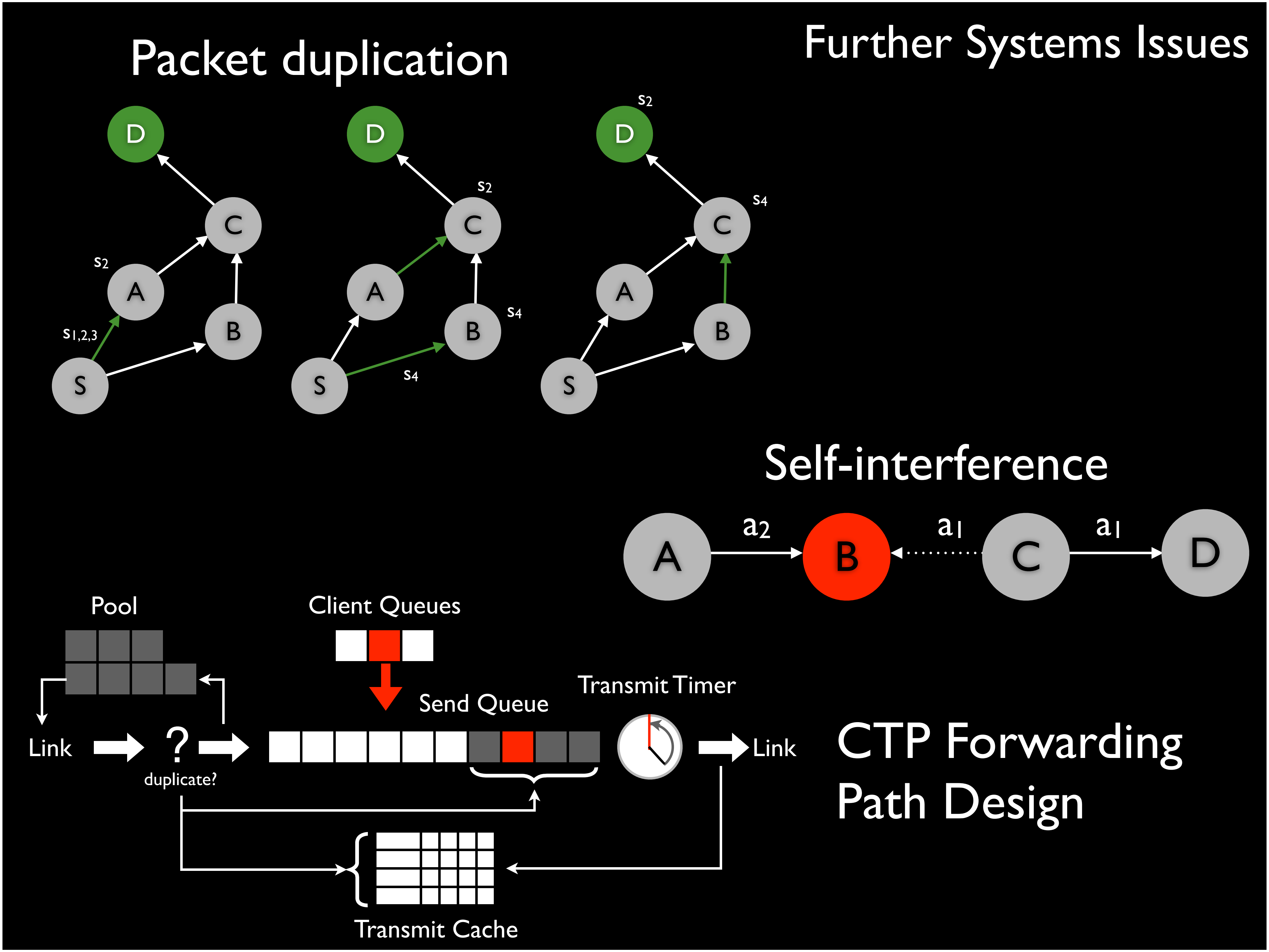
τ_l = 64ms
τ_h = 1 hour



Adaptive beaconing sends 1/4 the beacons of a 30 fixed interval, while reducing response time by 99.8%.

Adaptive beaconing quickly and seamlessly adapts to large, correlated failures.




Further Systems Issues
Packet duplication
D
C
A
B
S
s2
s1,2,3
s2
s4
s4
s2
s4
Self-interference
A
a2
B
a1
C
a1
D
Pool
Client Queues
Send Queue
Transmit Timer
Link
?
duplicate?
Link
Transmit Cache
CTP Forwarding
Path Design

CTP Noe Results Summary

Testbed	Frequency	MAC	IPI	Delivery	5% Delivery	Loss
Motelab	2.48GHz	CSMA	16s	94.7%	44.7%	Retransmit
Motelab	2.48GHz	BoX-50ms	5m	94.4%	26.9%	Retransmit
Motelab	2.48GHz	BoX-500ms	5m	96.6%	82.6%	Retransmit
Motelab	2.48GHz	BoX-1000ms	5m	95.1%	88.5%	Retransmit
Motelab	2.48GHz	LPP-500ms	5m	90.5%	47.8%	Retransmit
Tutornet (26)	2.48GHz	CSMA	16s	99.9%	100%	Queue
Tutornet (16)	2.43GHz	CSMA	16s	95.2%	92.9%	Queue
Tutornet (16)	2.43GHz	CSMA	22s	97.9%	95.4%	Queue
Tutornet (16)	2.43GHz	CSMA	30s	99.4%	98.1%	Queue
Wyman Park	2.48GHz	CSMA	16s	99.9%	100%	Retransmit
NetEye	2.48GHz	CSMA	16s	99.9%	96.4%	Retransmit
Kansei	2.48GHz	CSMA	16s	99.9%	100%	Retransmit
Vinelab	2.48GHz	CSMA	16s	99.9%	99.9%	Retransmit
Quanto	2.425GHz	CSMA	16s	99.9%	100%	Retransmit
Twist (Tmote)	2.48GHz	CSMA	16s	99.3%	100%	Retransmit
Twist (Tmote)	2.48GHz	BoX-2s	5m	98.3%	92.9%	Retransmit
Mirage (micaZ)	2.48GHz	CSMA	16s	99.9%	99.8%	Queue
Mirage (mica2dot)	916.4MHz	B-MAC	16s	98.9%	97.5%	Ack
Twist (eyesIFX)	868.3MHz	CSMA	16s	99.9%	99.9%	Retransmit
Twist (eyesIFX)	868.3MHz	SpeckMAC-183ms	30s	94.8%	44.7%	Queue
Blaze	315MHz	B-MAC-300ms	4m	99.9%		Queue

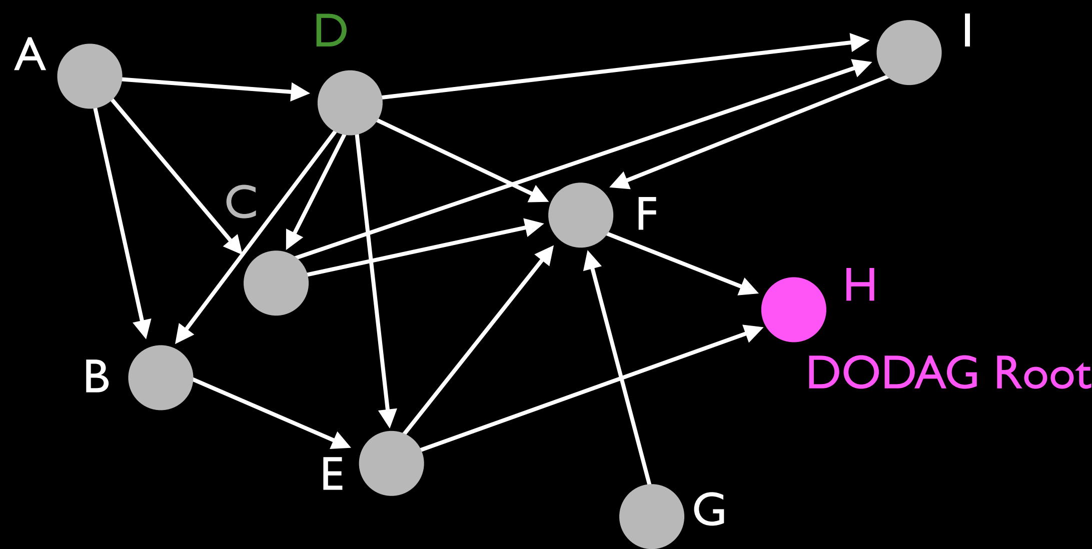
RPL

RPL

(Routing Protocol for Low power and lossy networks)

- Proposed IETF standard for low-power and lossy networks (LLNs), under IESG review
  - Smart meter networks
  - Home area networks
  - Sensor networks
  - The “Internet of Things”
- Core protocol is CTP Noe
  - Lots more details and mechanisms, of course

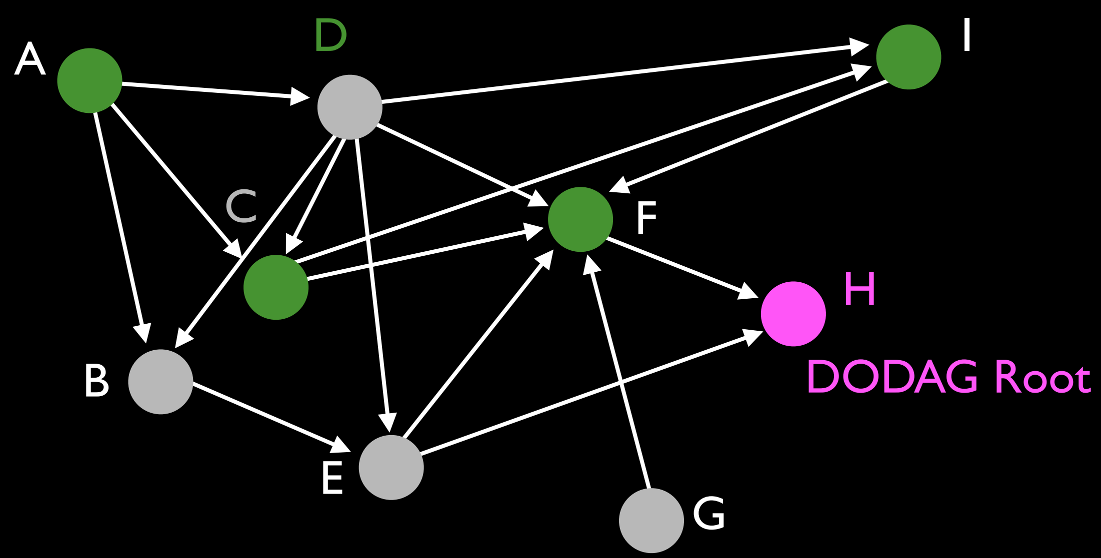
RPL Basics



DODAG: Destination Oriented Directed Acyclic Graph
- A routing topology can have multiple DODAGs
- A node is a member of only one DODAG at any time

Neighbor set: subset of link-local neighbors
Parent set: subset of neighbors which have lower cost
Preferred parent: current next hop

RPL Basics



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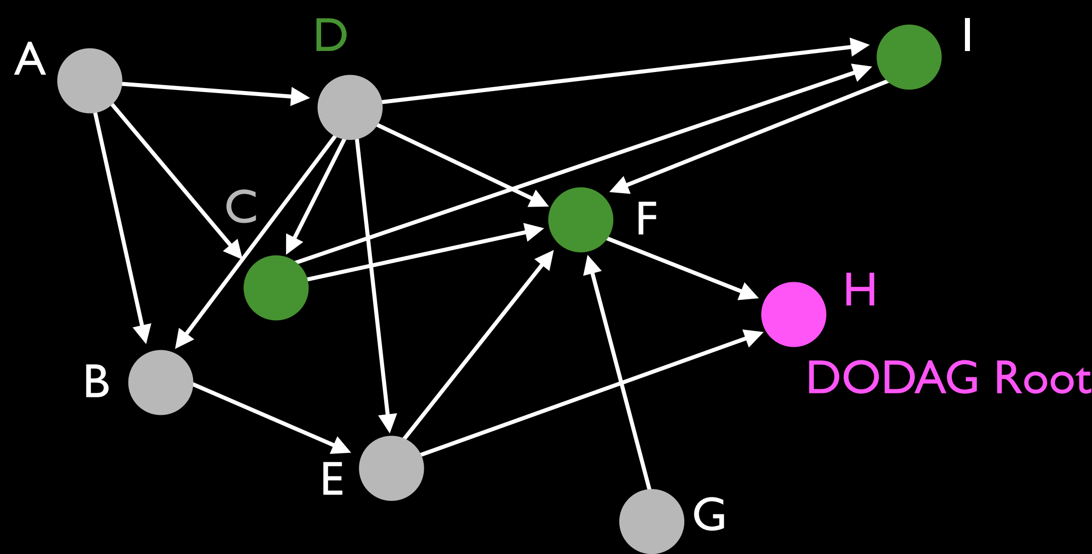

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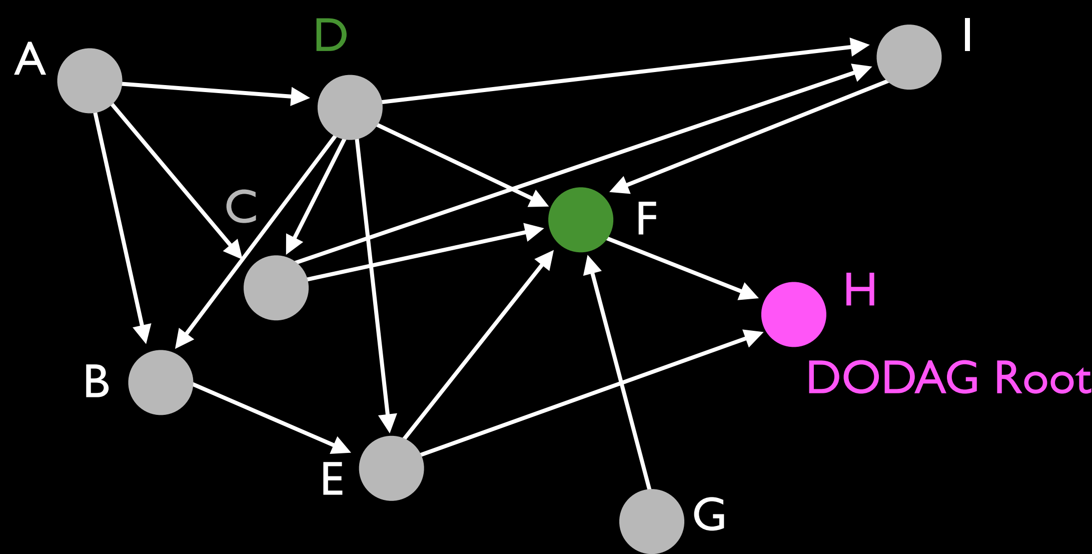

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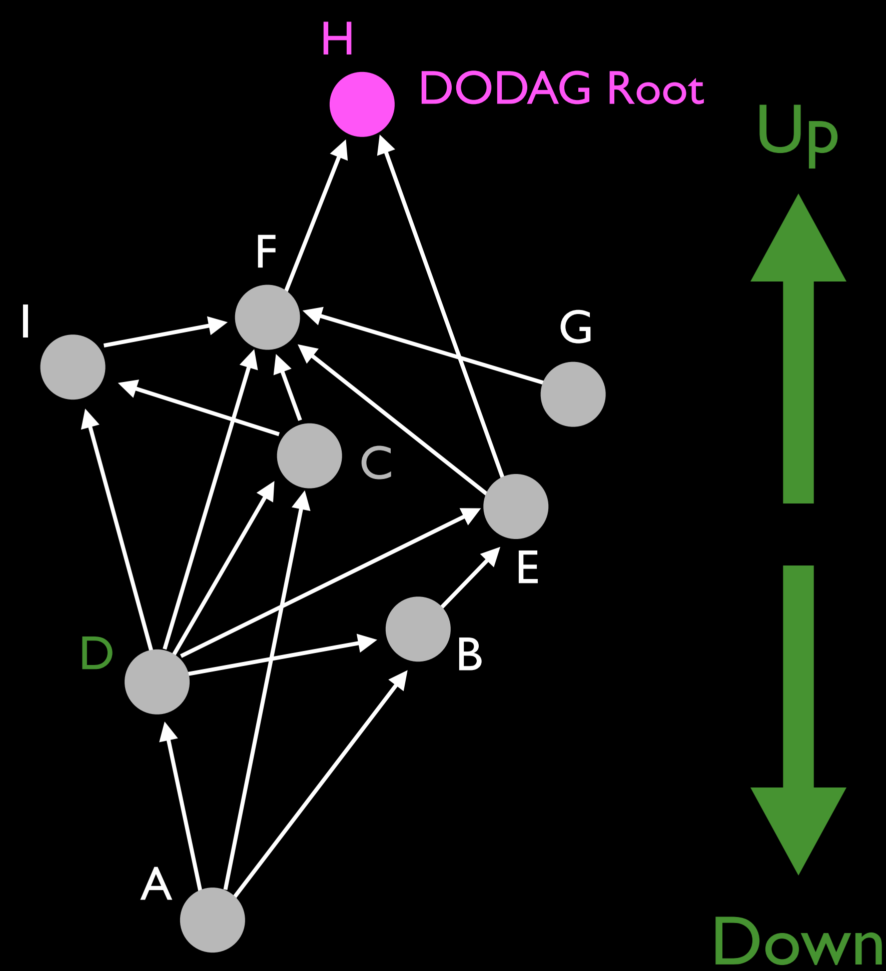
More RPL Basics

Upward routes: routes toward a DODAG root (decreasing cost)

Downward routes: routes away from a DODAG root (increasing cost)

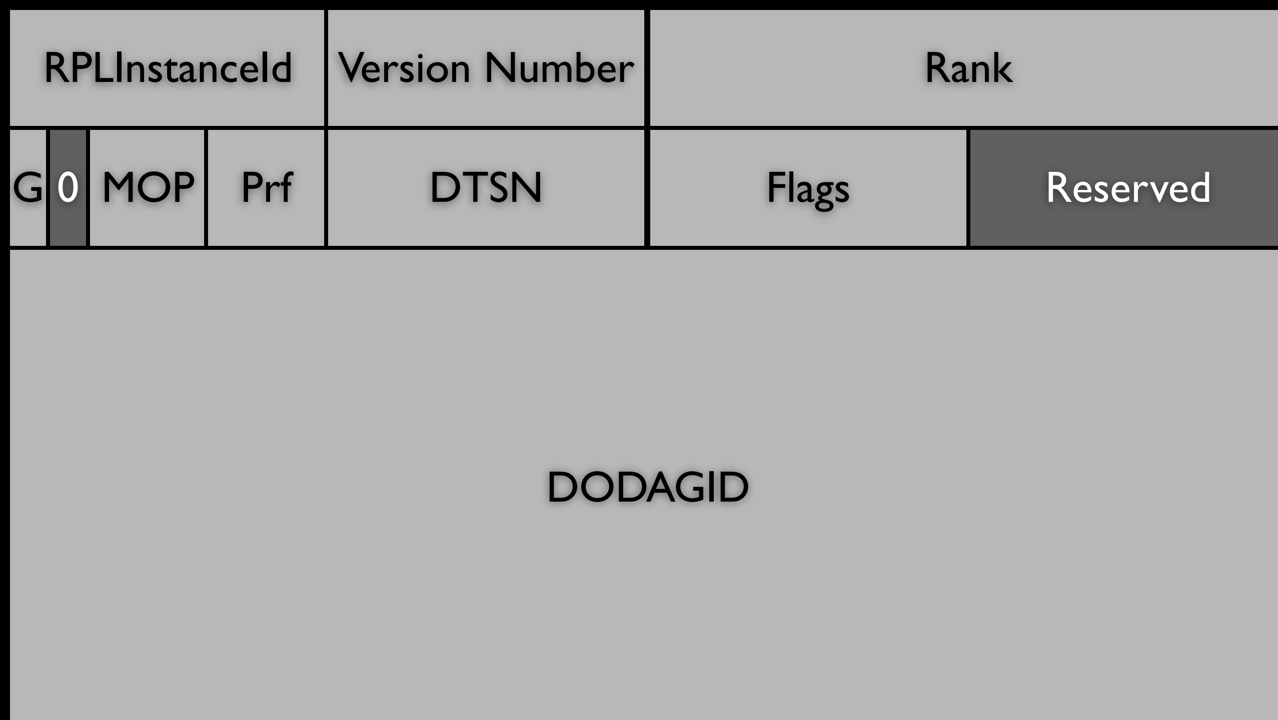
Rank: metric independent way to encode cost



RPL Messages

- Destination Information Object (DIO)
  - Upward routes
- Destination Advertisement Object (DAO), DAO Acknowledgement (DAO-ACK)
  - Downward routes
- Destination Information Solicitation (DIS)
  - Discovery, configuration
- Consistency Check (CC)
  - Security, protection against replay

DIO



DIOs spread down, establish upward routes
Sent on an exponential timer (like CTP Noe)

DIO Timer Reset

- On receiving a DIS message (like pull bit)
- On a new DODAG sequence number
- On datapath validation check failure
  - Rank encoded as an IPv6 hop-by-hop header

RPL Options

- Messages can include options
- Example: DODAG Configuration Option
  - Included in DIO sent in response to DIS

Type=4	Length=14	Flags	A	PCS	DIOIntDoubl.
DIOIntMin.	DIORedun.	MaxRankIncrease			
MinHopRankIncrease		OCP			
Reserved	Def. Lifetime	Lifetime Unit			

Wireless Routing Summary

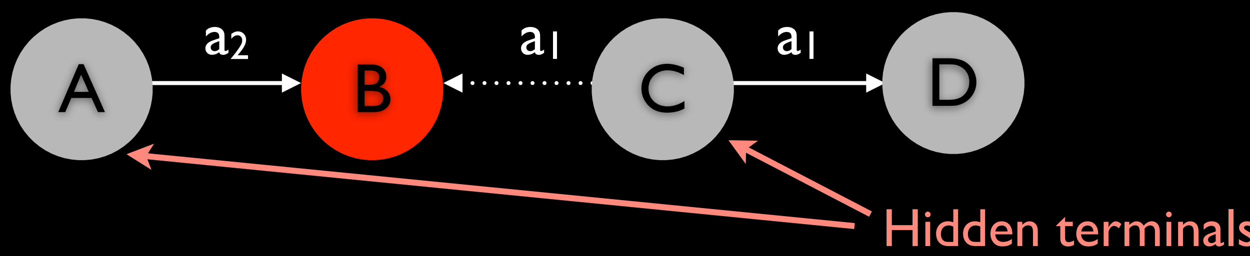
- Wireless links are bursty and many exhibit scaling
  - *Fast link estimation critical: reduces costs by 45%*
- Fast link estimators complicate routing
  - *CTP Noe: datapath validation and adaptive beacons*
  - *Basis for proposed Internet standard RPL*

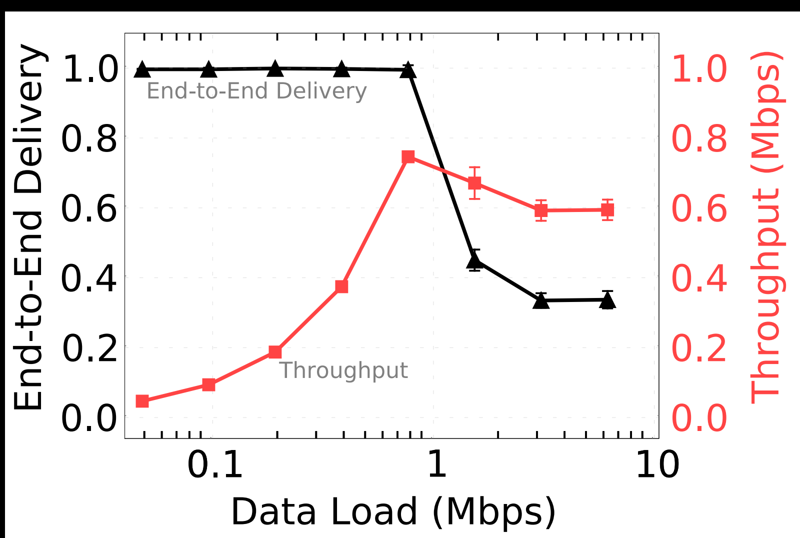
Full Duplex Wireless

Problem with CTP Noe

(not designed for high throughput)

Self-interference





Low power networks have light load.

But as load along a route increases, self-interference increases link costs. These changes follow the route: the topology can become unstable and, sometimes, collapse.

“It is generally not possible for radios to receive and transmit on the same frequency band because of the interference that results. Thus, bidirectional systems must separate the uplink and downlink channels into orthogonal signaling dimensions, typically using time or frequency dimensions.”

- Andrea Goldsmith, “Wireless Communications,” Cambridge Press, 2005.

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?

Status quo: NO

Chuck Thacker Interview

Communications of the ACM, July 2010

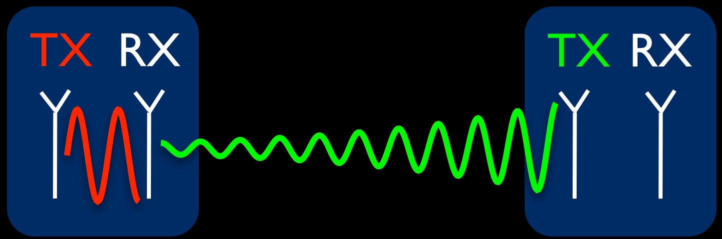
You were also involved in the invention of the Ethernet.

The Ethernet grew out of the realization I had of how to provide a network for the Alto. We had been studying the ALOHA network, a radio network that was used to connect the various Hawaiian Islands. The limitation was that when a transmitter started to transmit, it could no longer receive anything. One night I was lying in bed thinking about the problem when I had this sudden realization that if you used a more limited media, say, the coaxial cables used in cable television, the transmitter could not only hear what it transmitted, it could also tell whether what it thought it put on the wire was the same as what actually got put on the wire.

Why only half-duplex on a single band?

Why only half-duplex on a single 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
[2] Katti et al. "Embracing Wireless Interference: Analog Network Coding", ACM SIGCOMM 2007
[3] Radunovic et al. , "Rethinking Indoor Wireless: Lower Power, Low Frequency, Full-duplex", WiMesh (SECON Workshop),, 2010

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  Ineffective if ADC saturates

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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

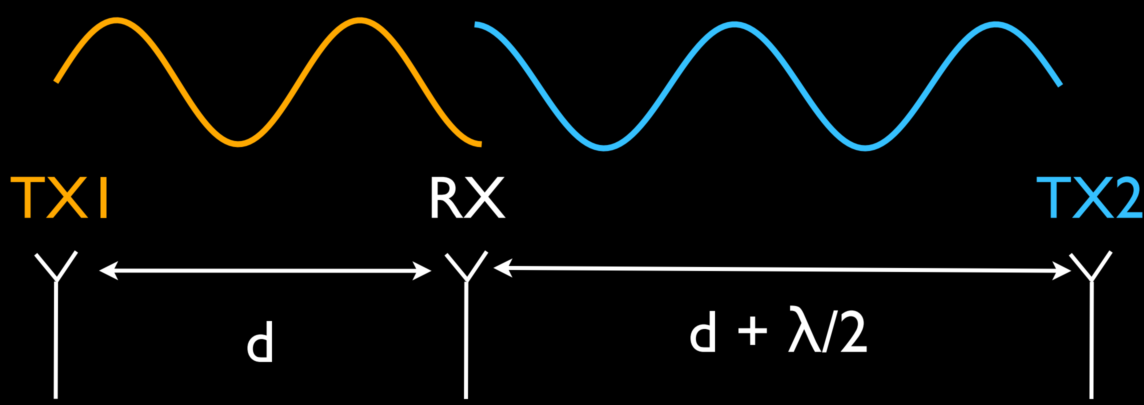
  Ineffective if ADC saturates

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

  Radunovic et al.[3] ~25dB

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

Innovation: Antenna Cancellation



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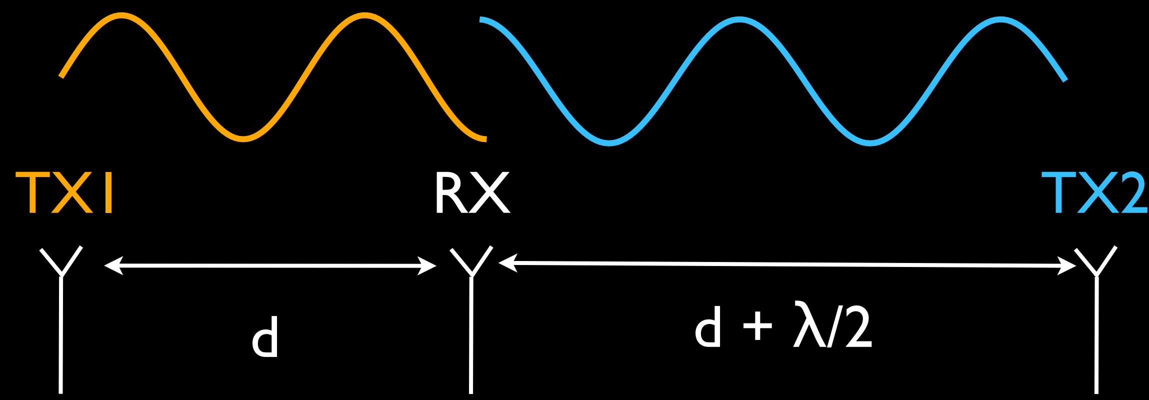


~30dB self-interference cancellation

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?

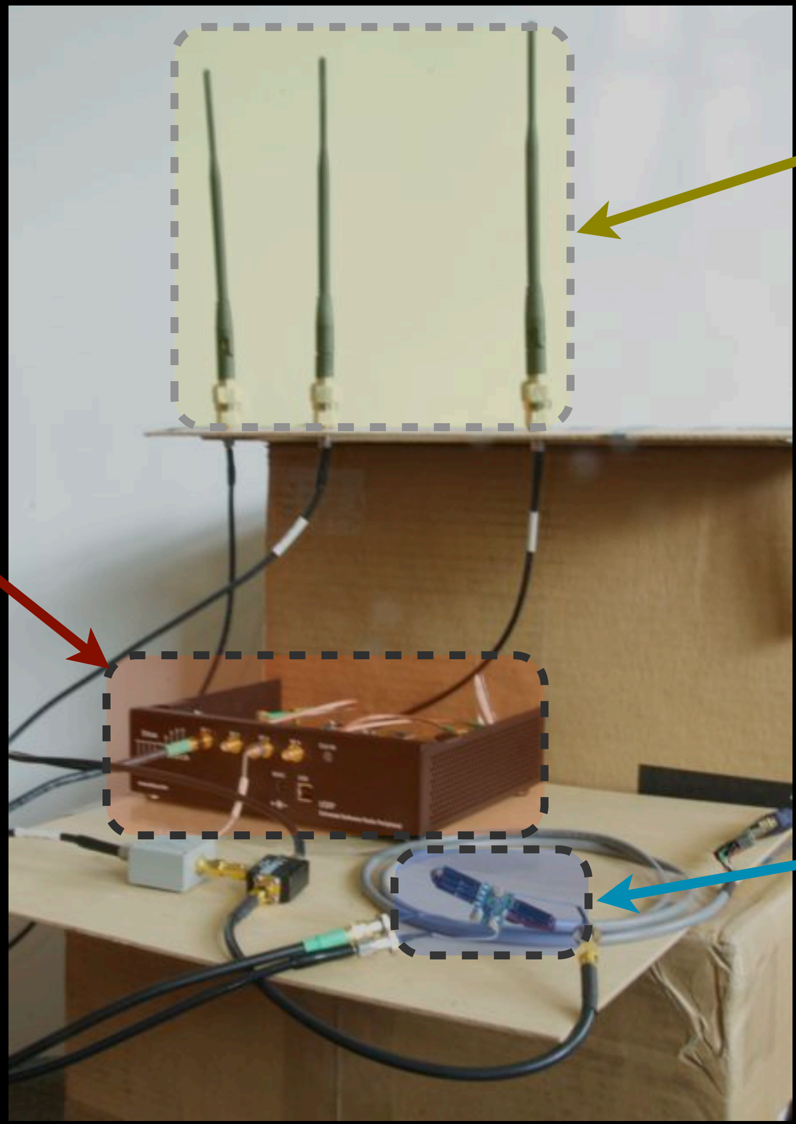
YES, IT CAN!

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

Three techniques give ~70dB cancellation

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

Our Prototype

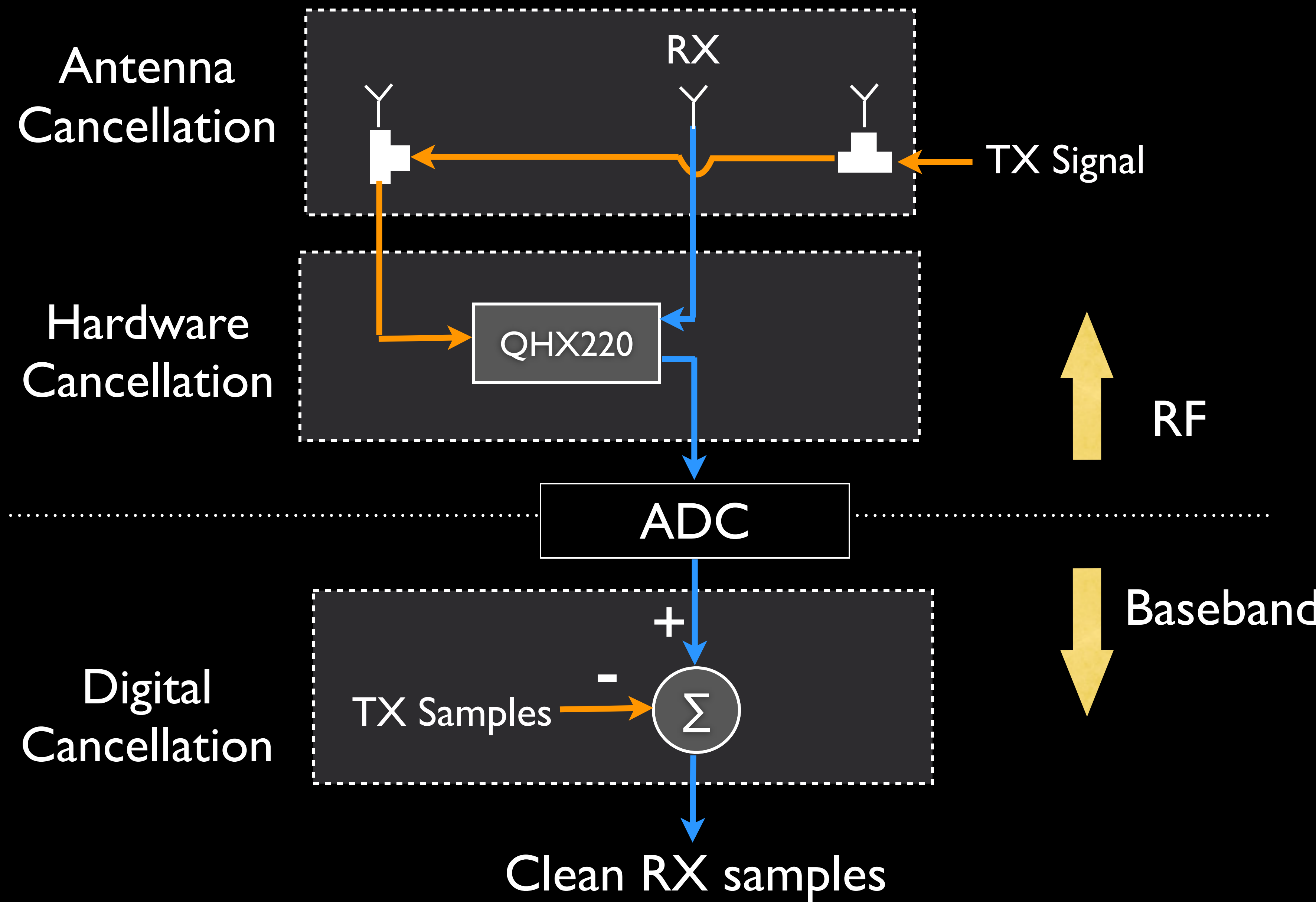


Antenna Cancellation

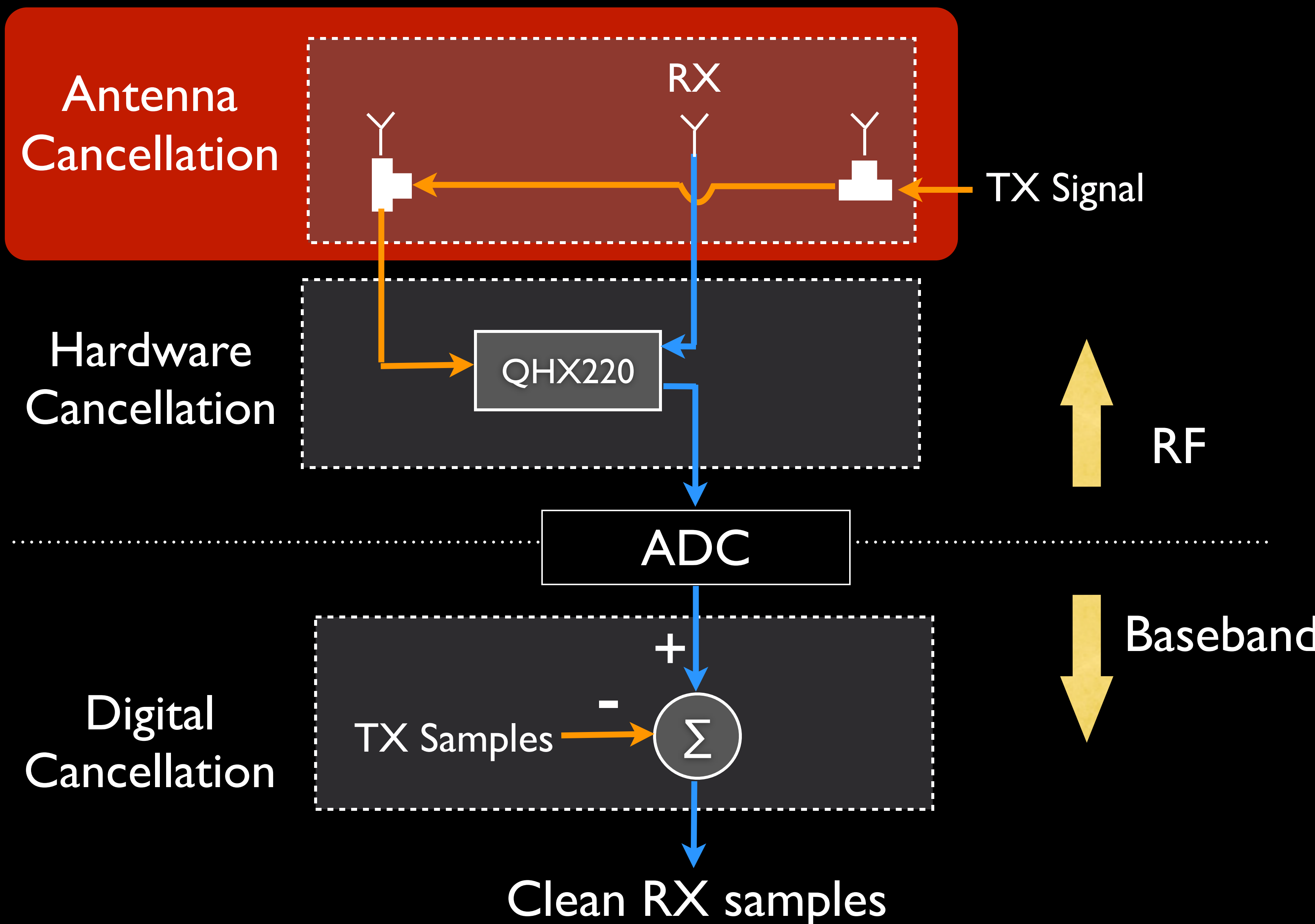
Digital Interference Cancellation

Hardware Cancellation

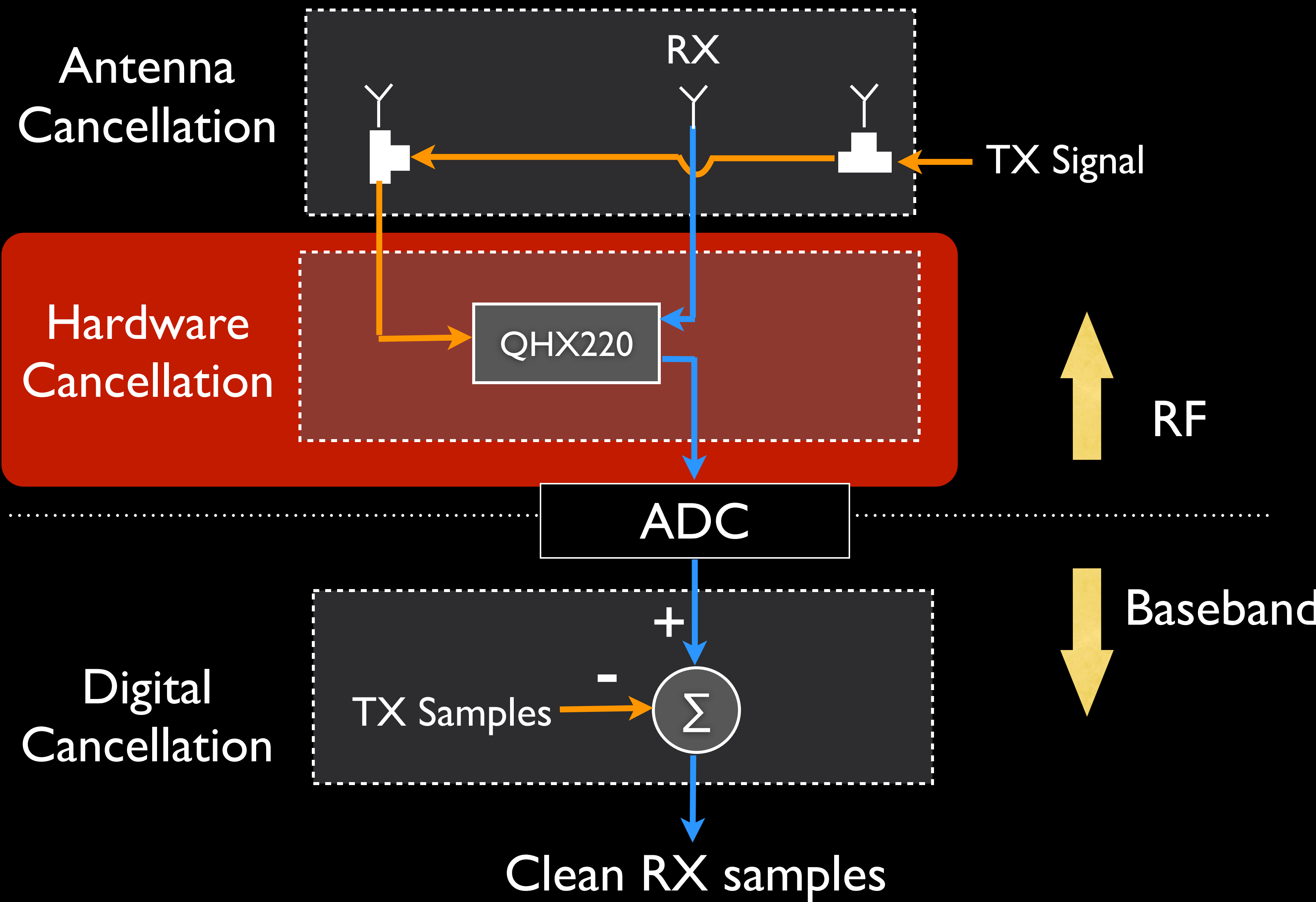
Bringing It Together



Bringing It Together



Bringing It Together



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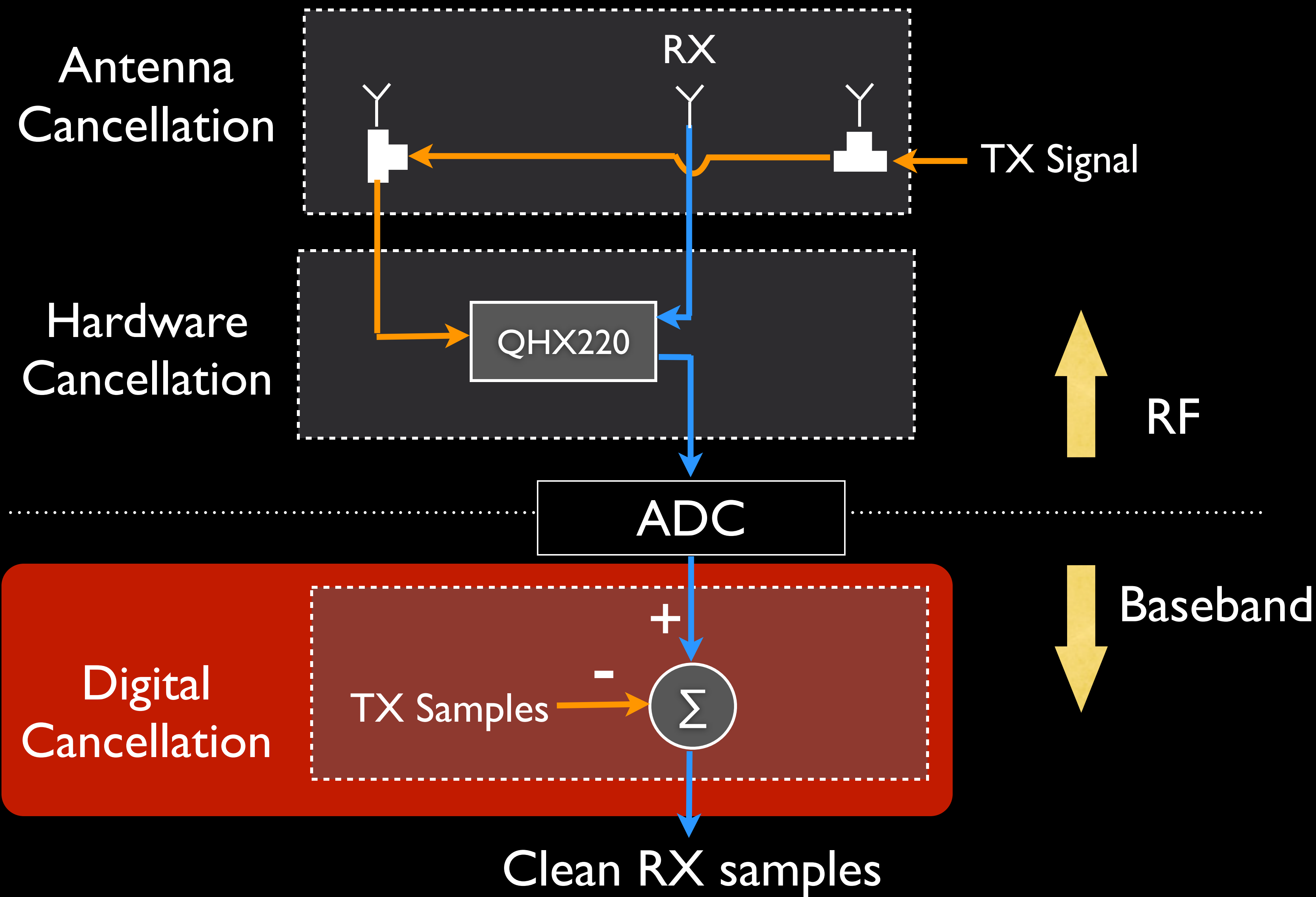
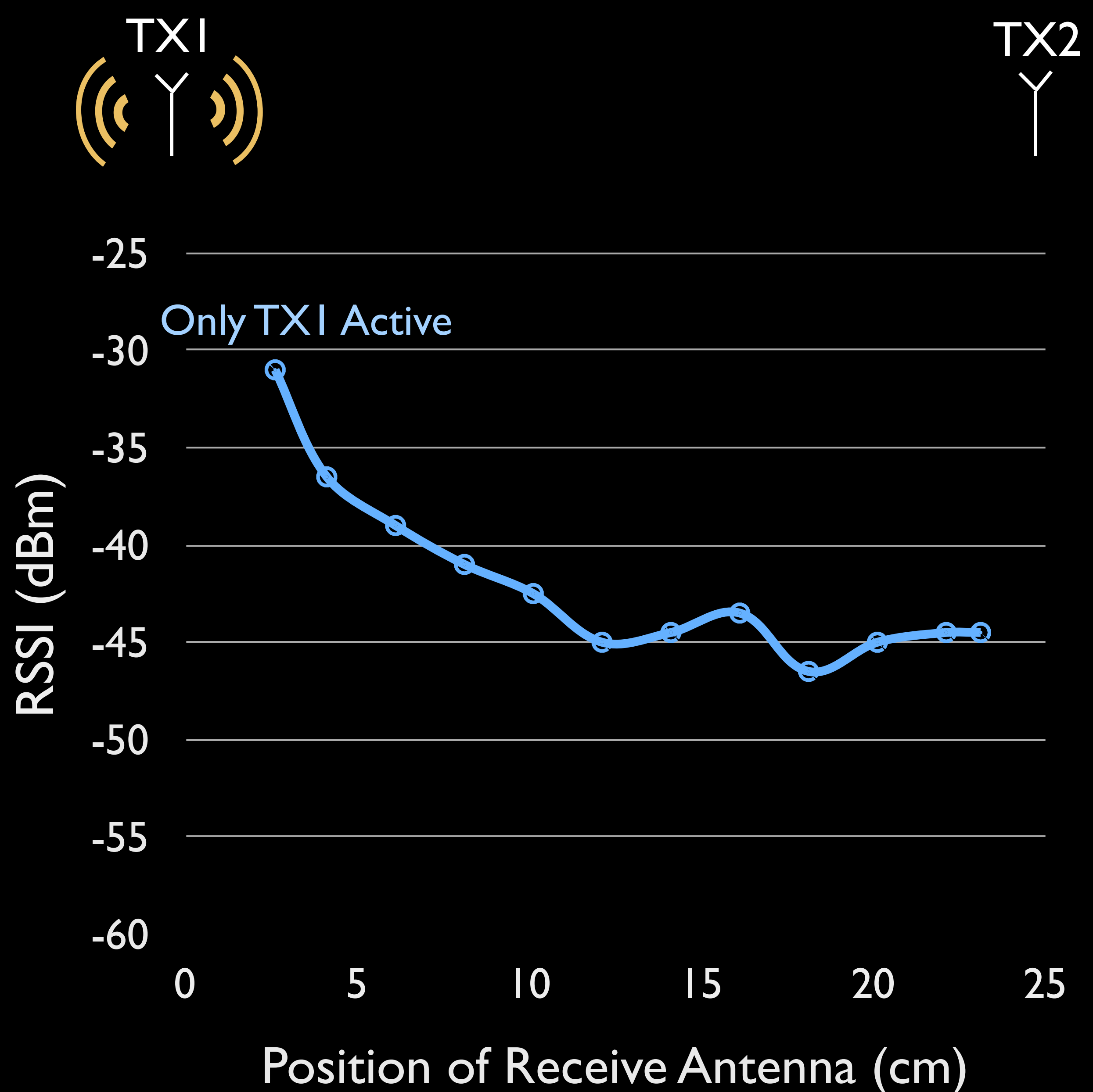


Antenna Cancellation: Performance



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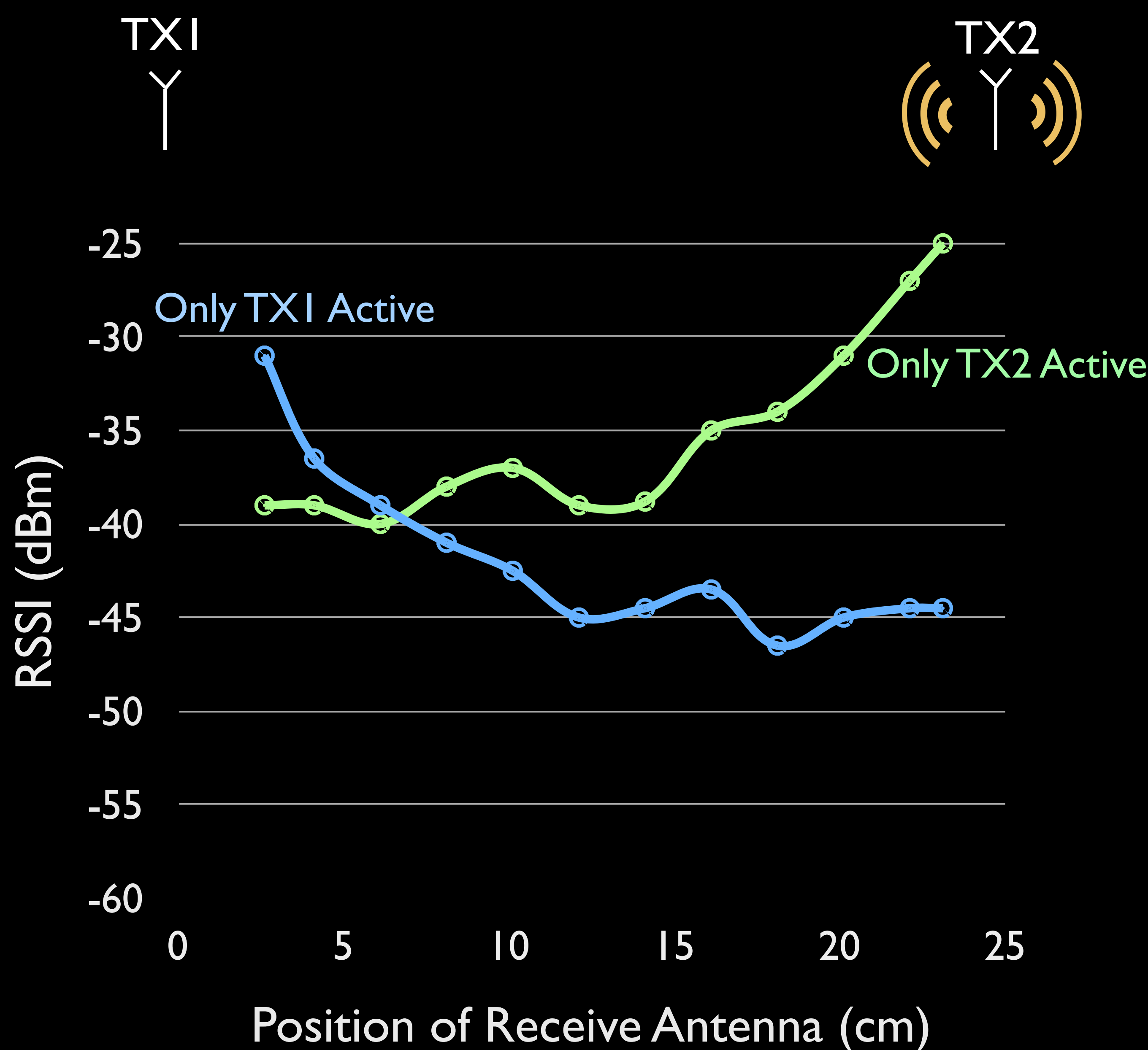

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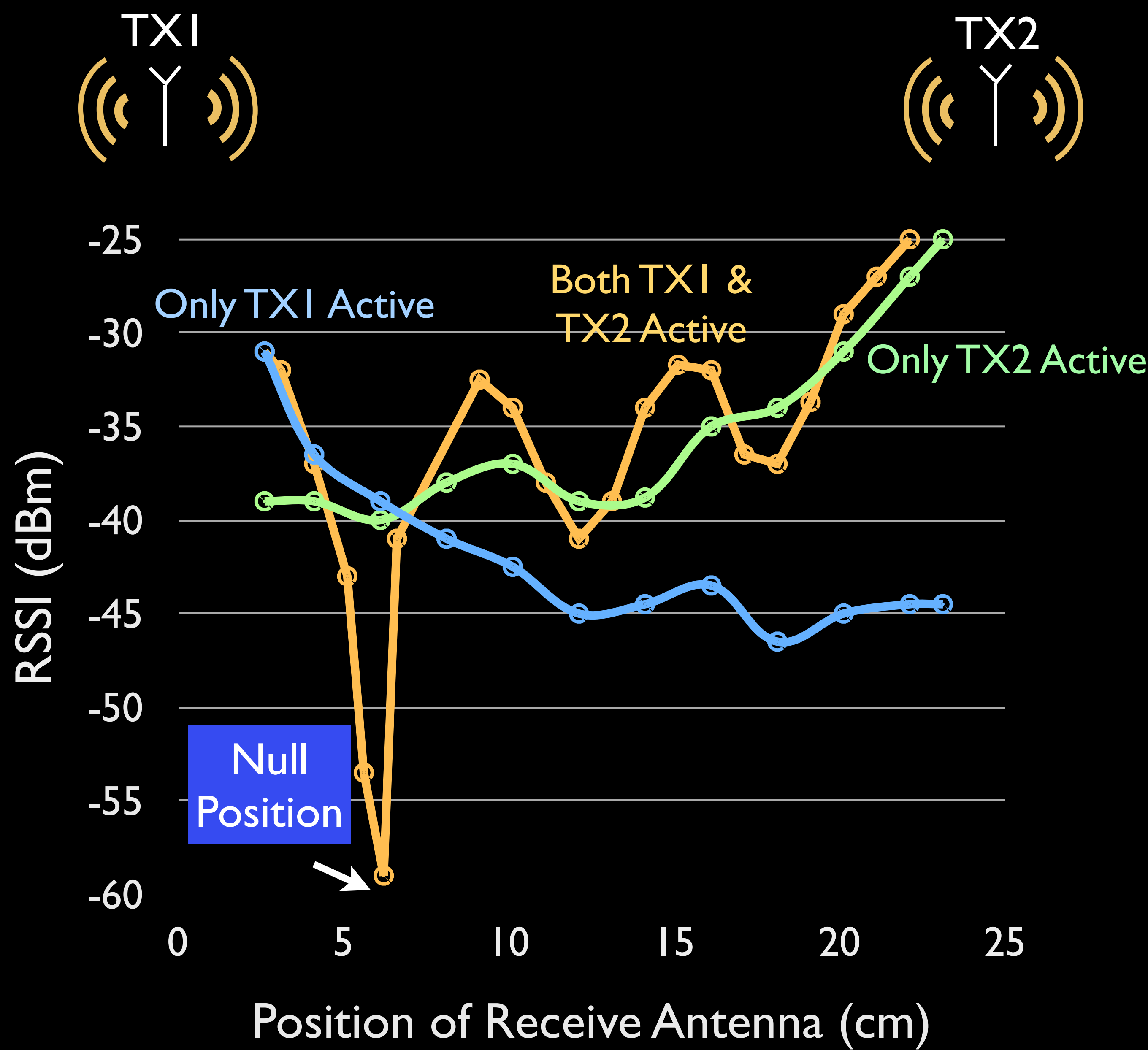

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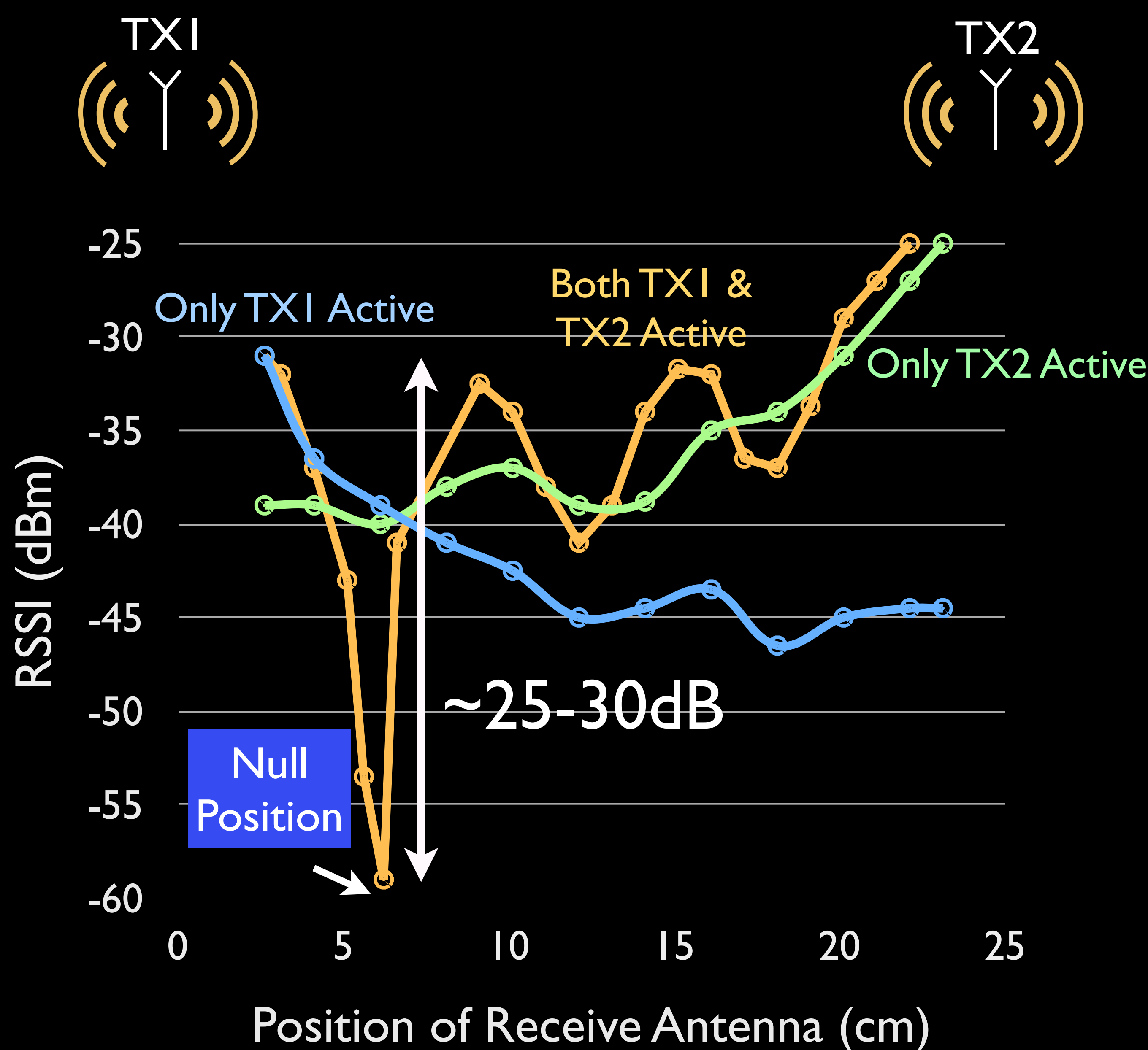
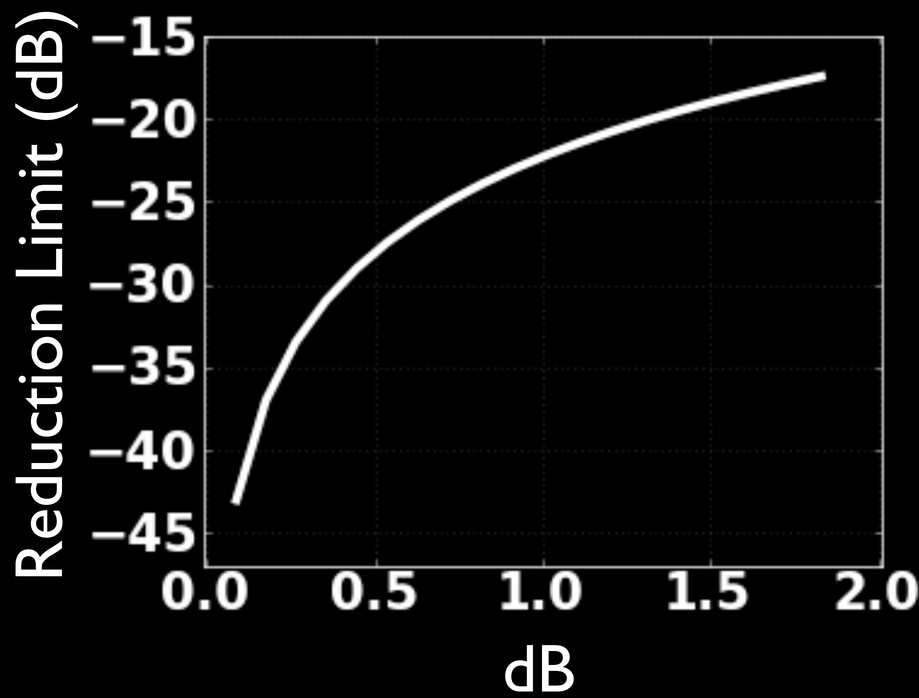
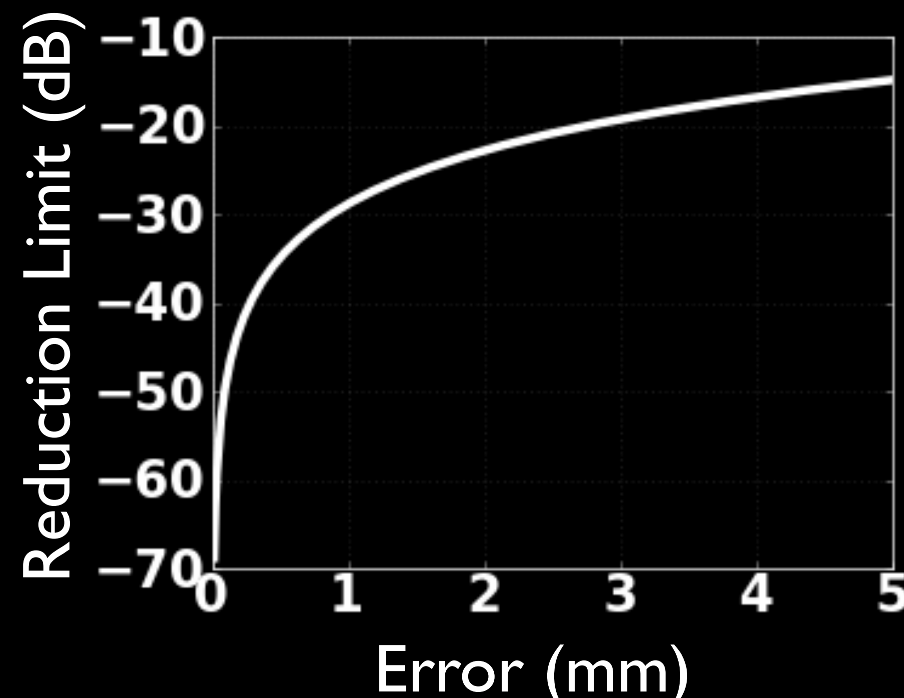


Sensitivity of Antenna Cancellation



Amplitude Mismatch
between TX1 and TX2



Placement Error
for RX

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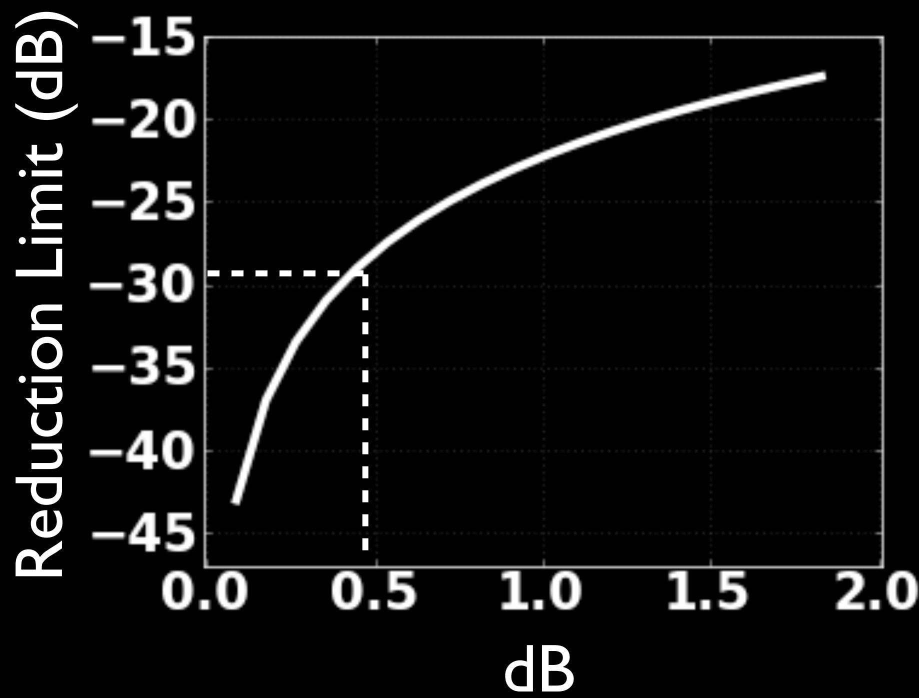

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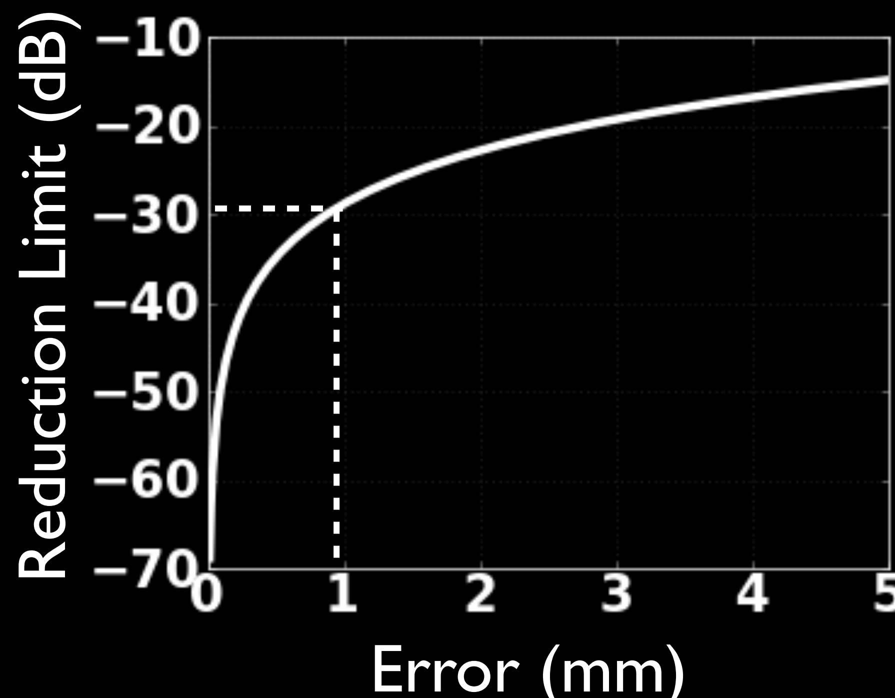
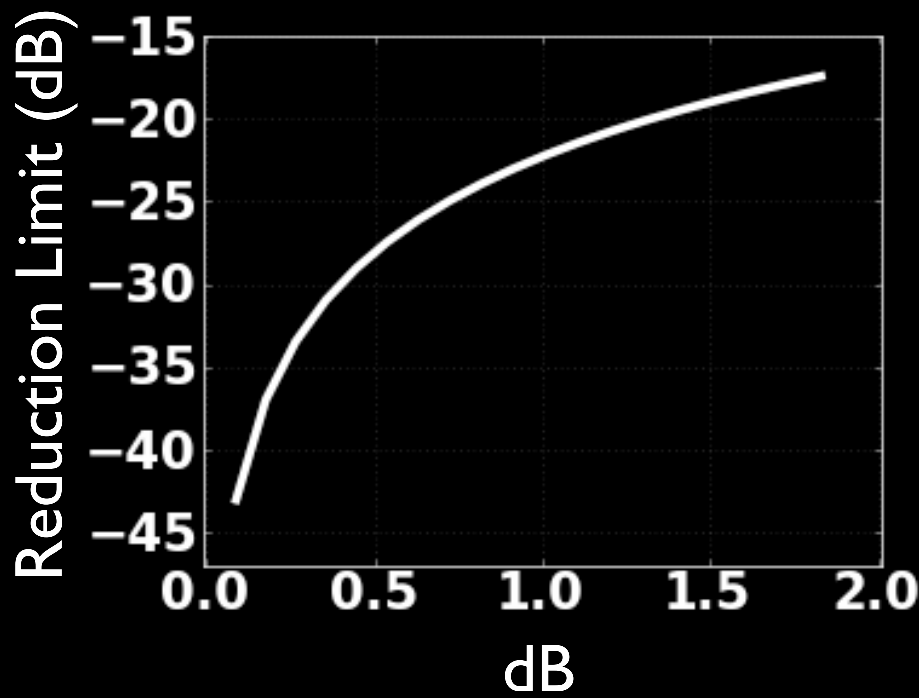


Placement Error
for RX

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

Sensitivity of Antenna Cancellation



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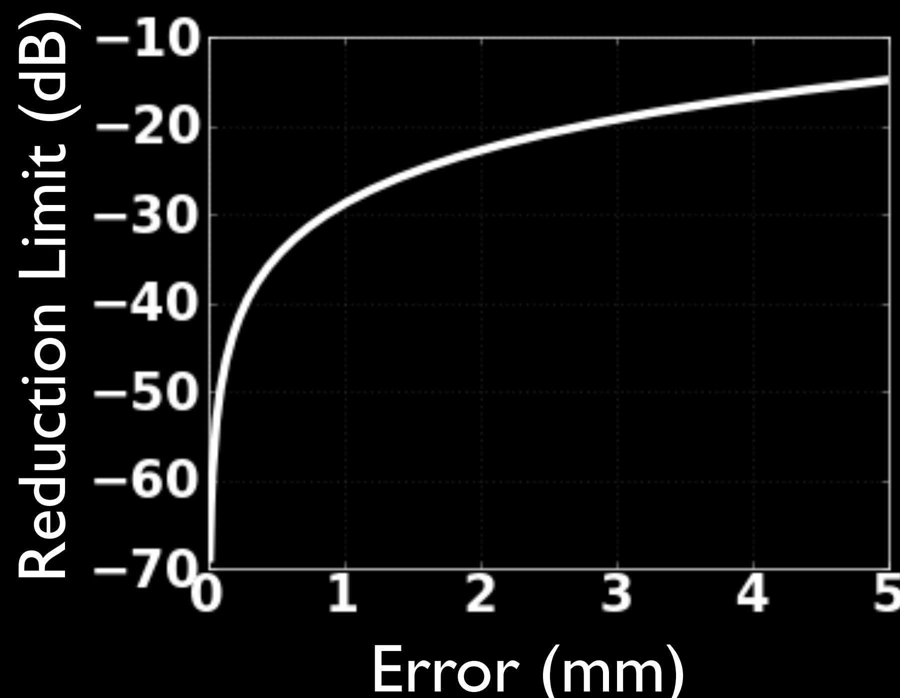
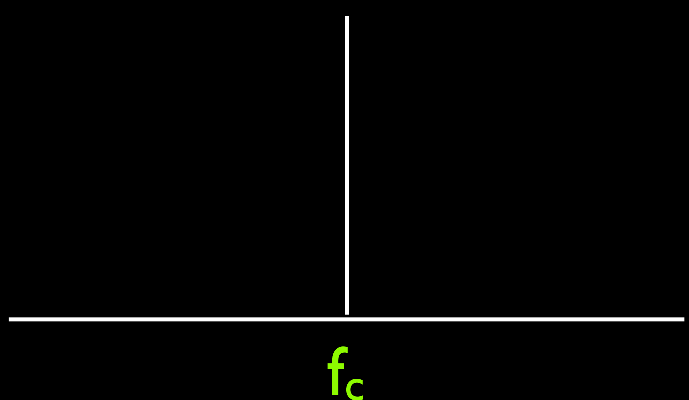


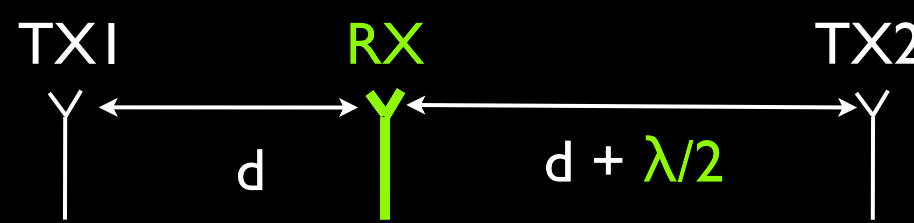
Placement Error
for RX

- 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
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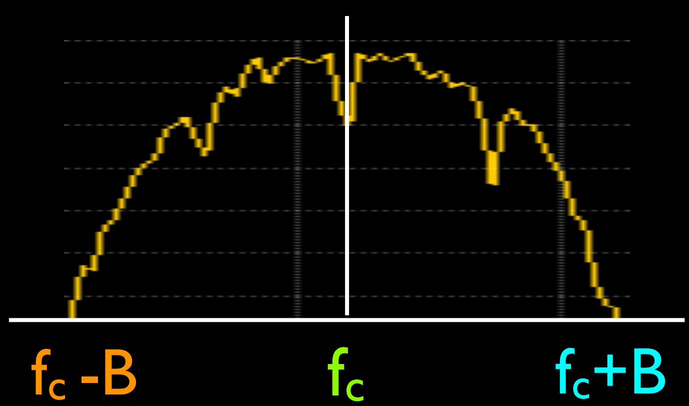

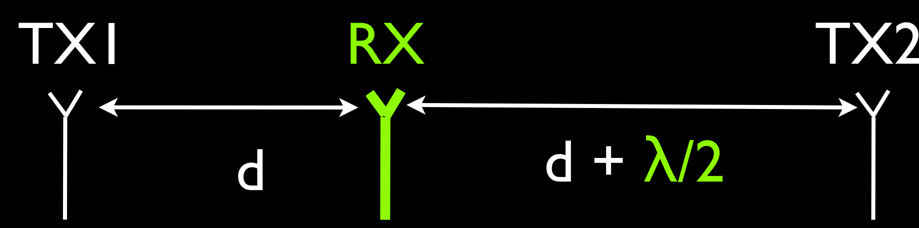

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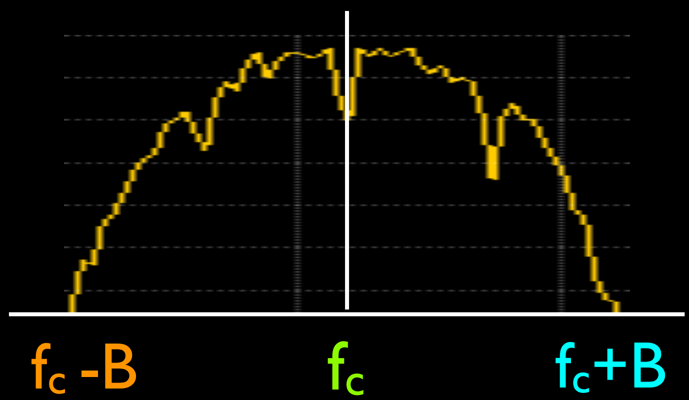

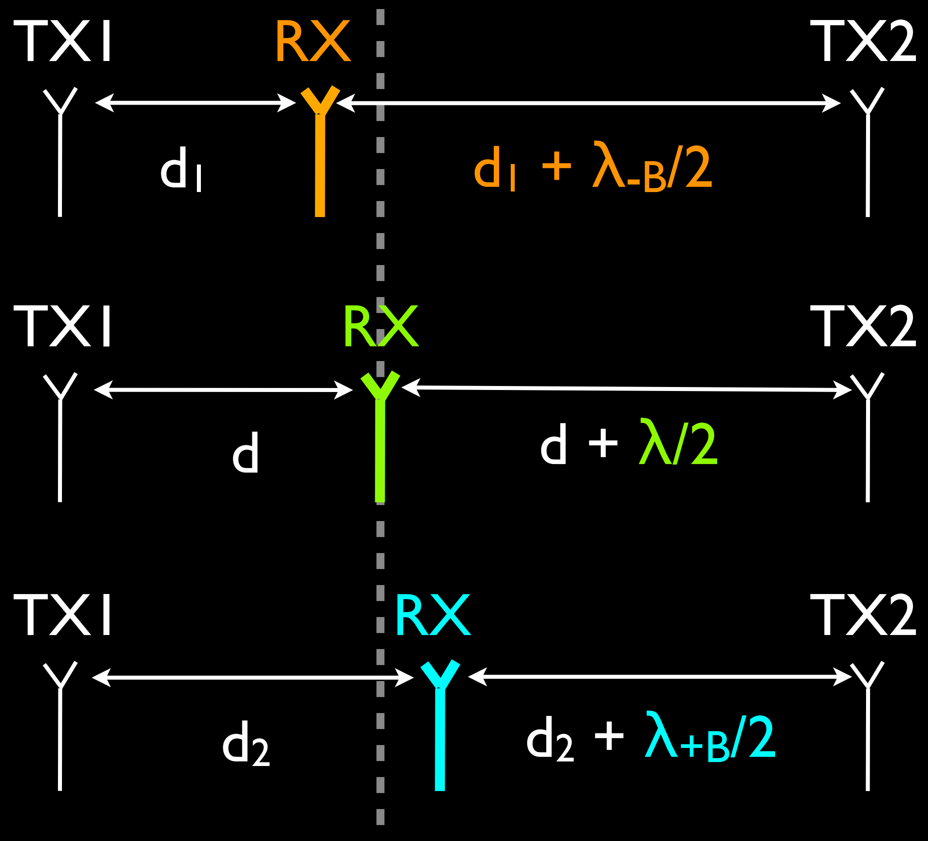

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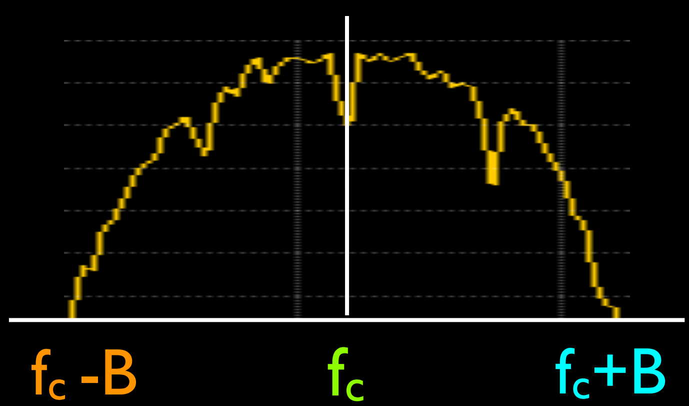
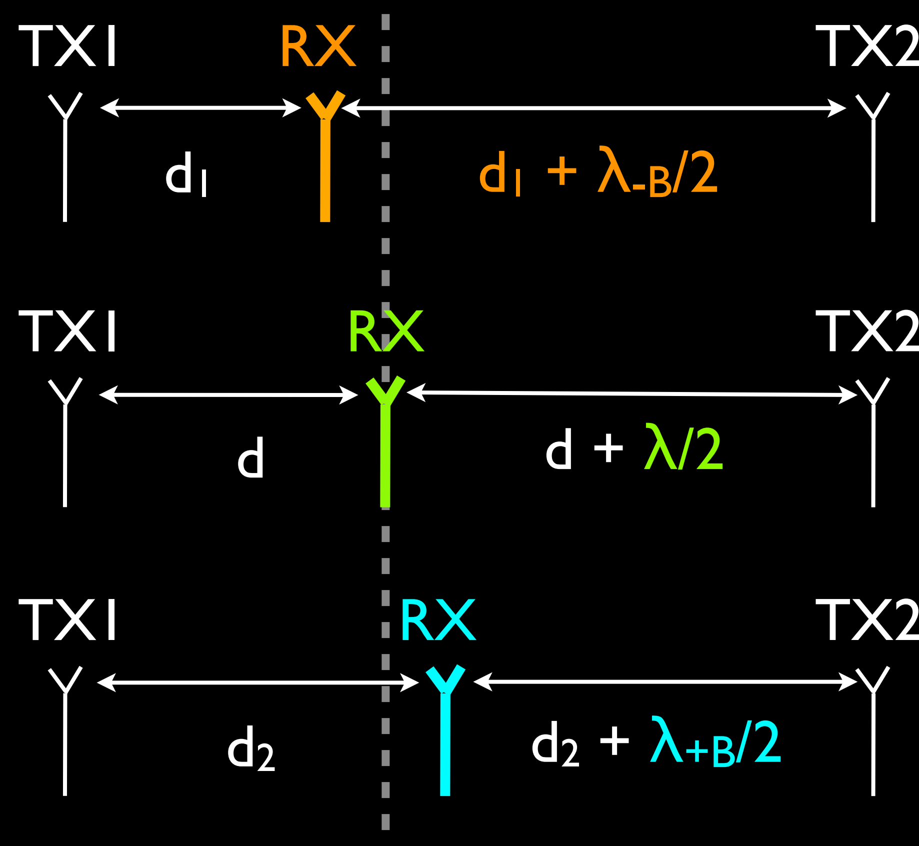
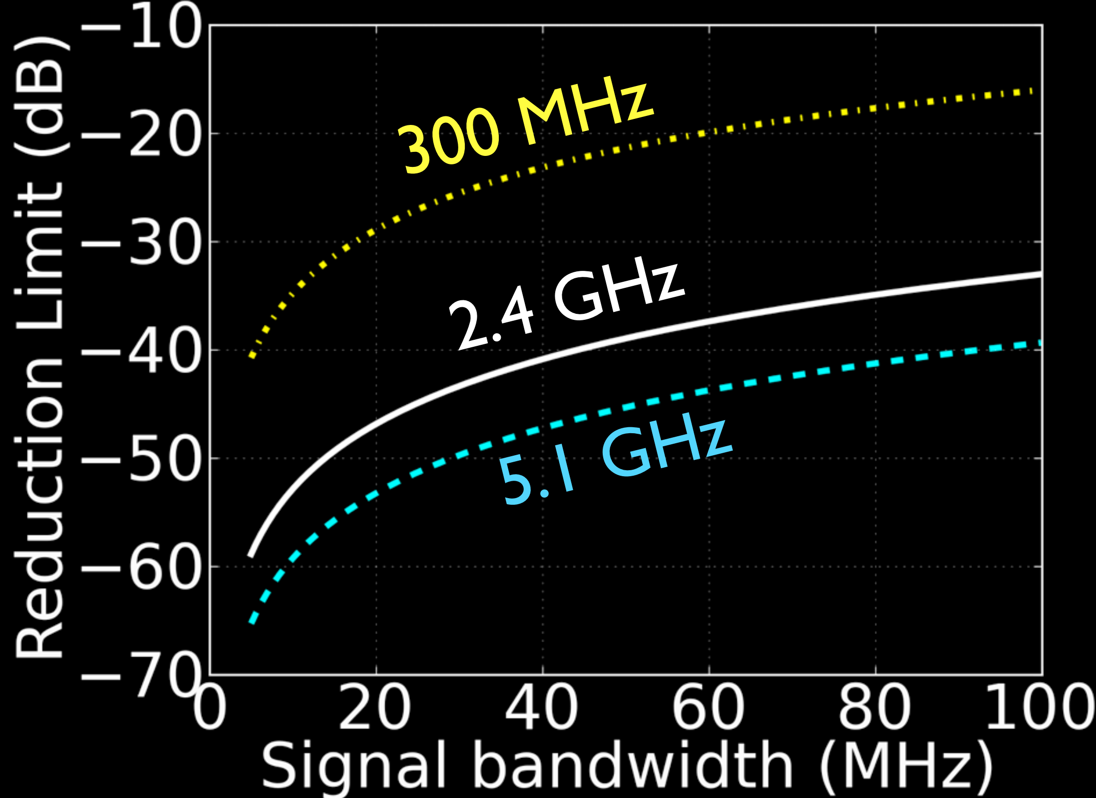




WiFi (2.4G, 20MHz) => ~0.26mm precision error

Bandwidth Constraint



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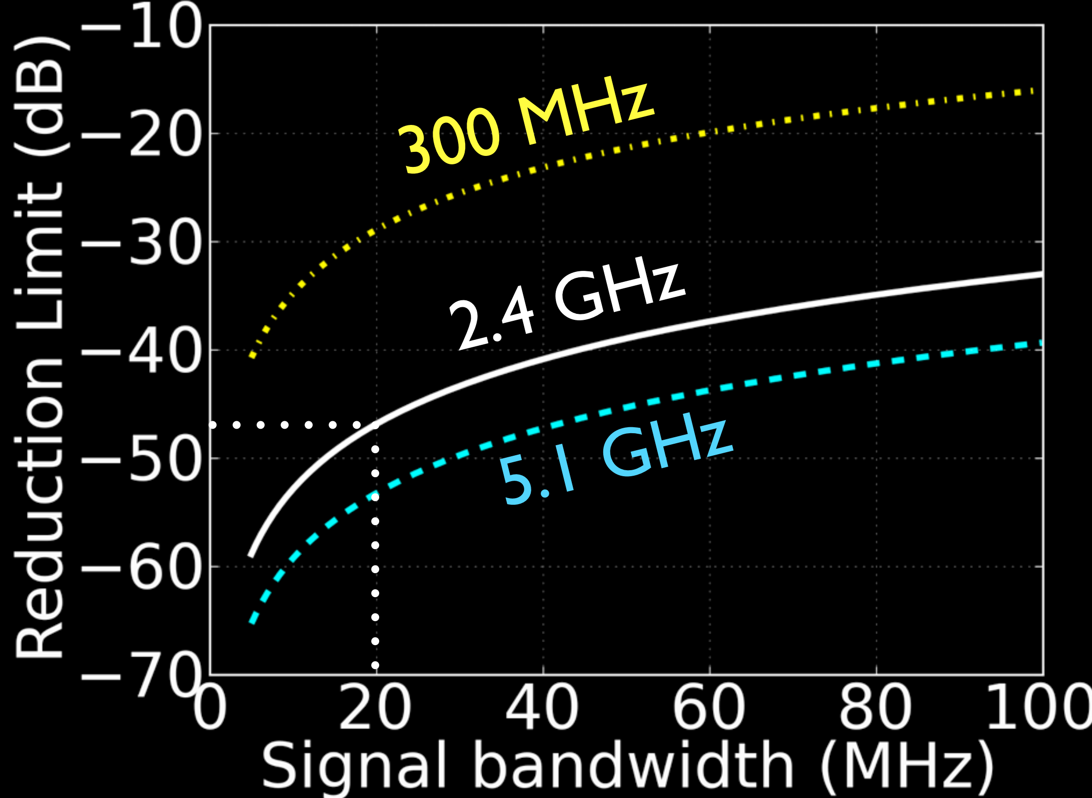
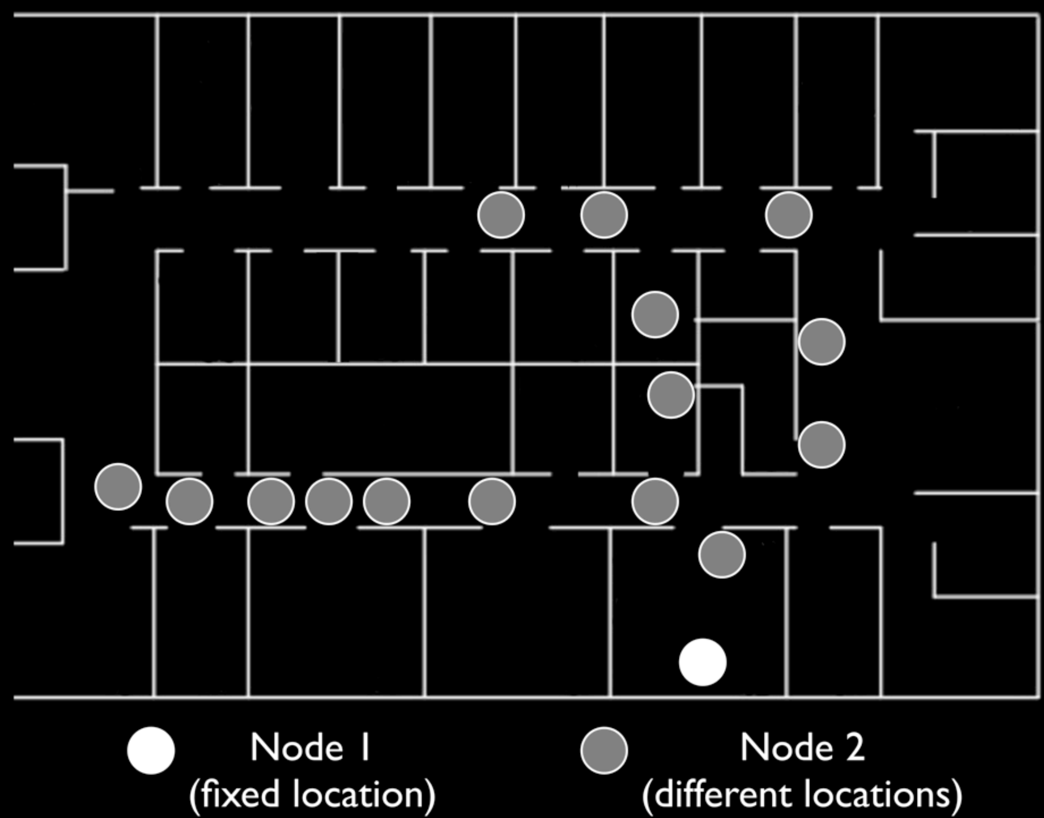


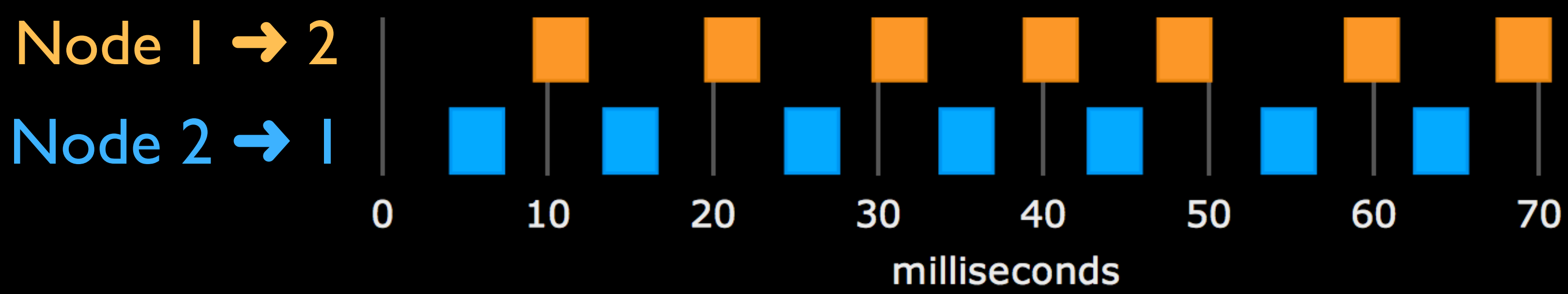
- WiFi (2.4GHz, 20MHz): Max 47dB reduction
- Bandwidth ↑ => Cancellation ↓
- Carrier Frequency ↑ => Cancellation ↑

Experimental Setup

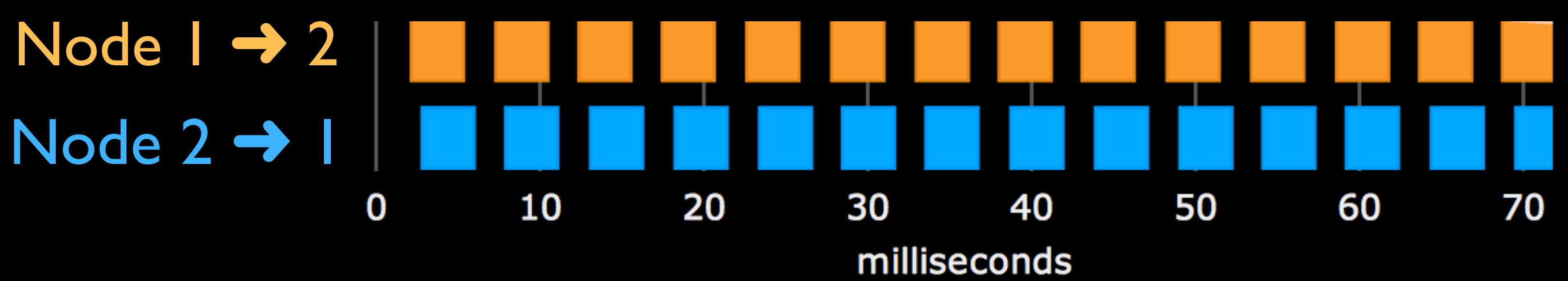
- 802.15.4 based signaling on USRP nodes
- Two nodes at varying distances placed in an office building room and corridor



Half-Duplex :- Nodes interleave transmissions

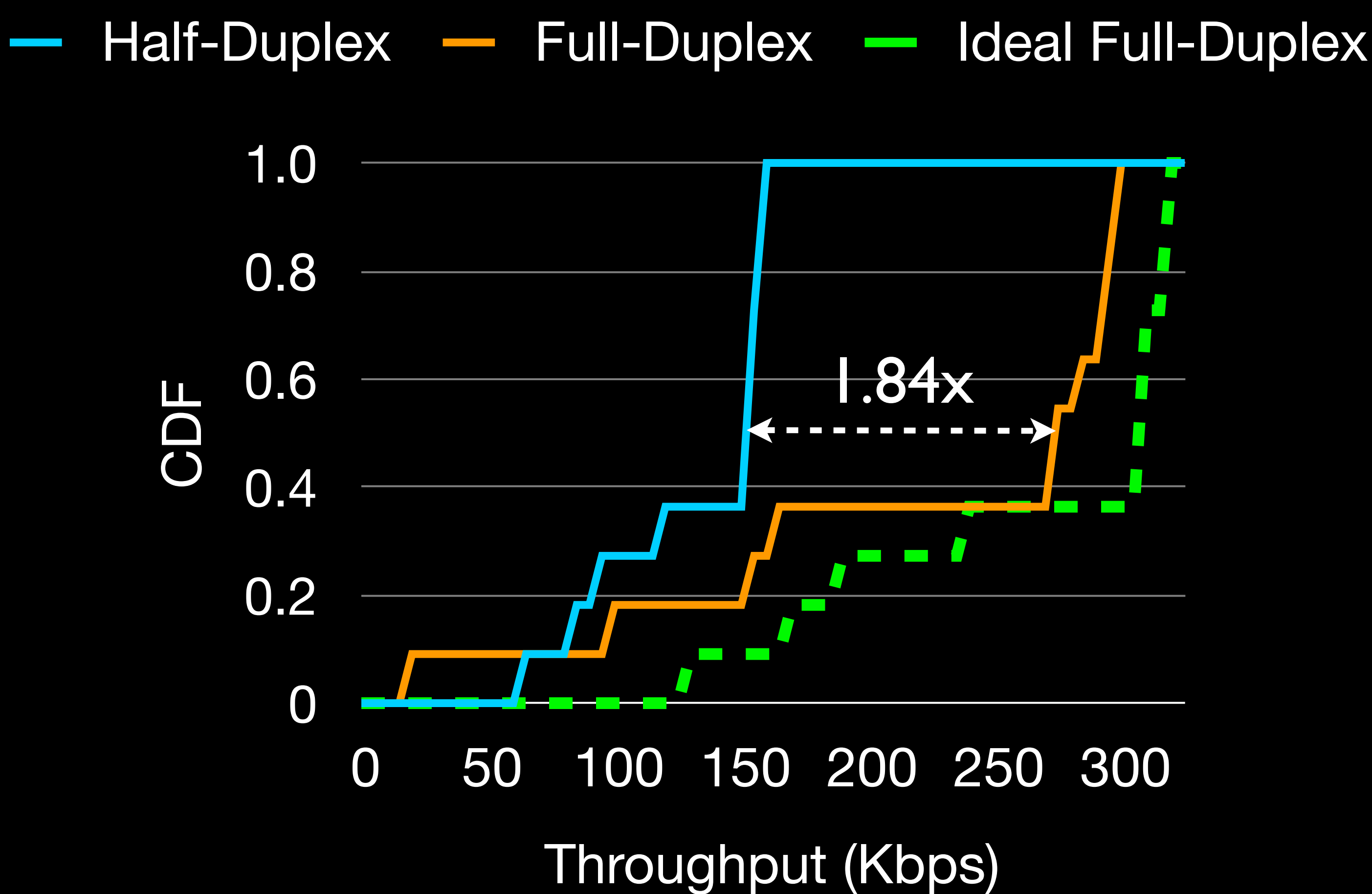


Full-Duplex :- Nodes transmit concurrently



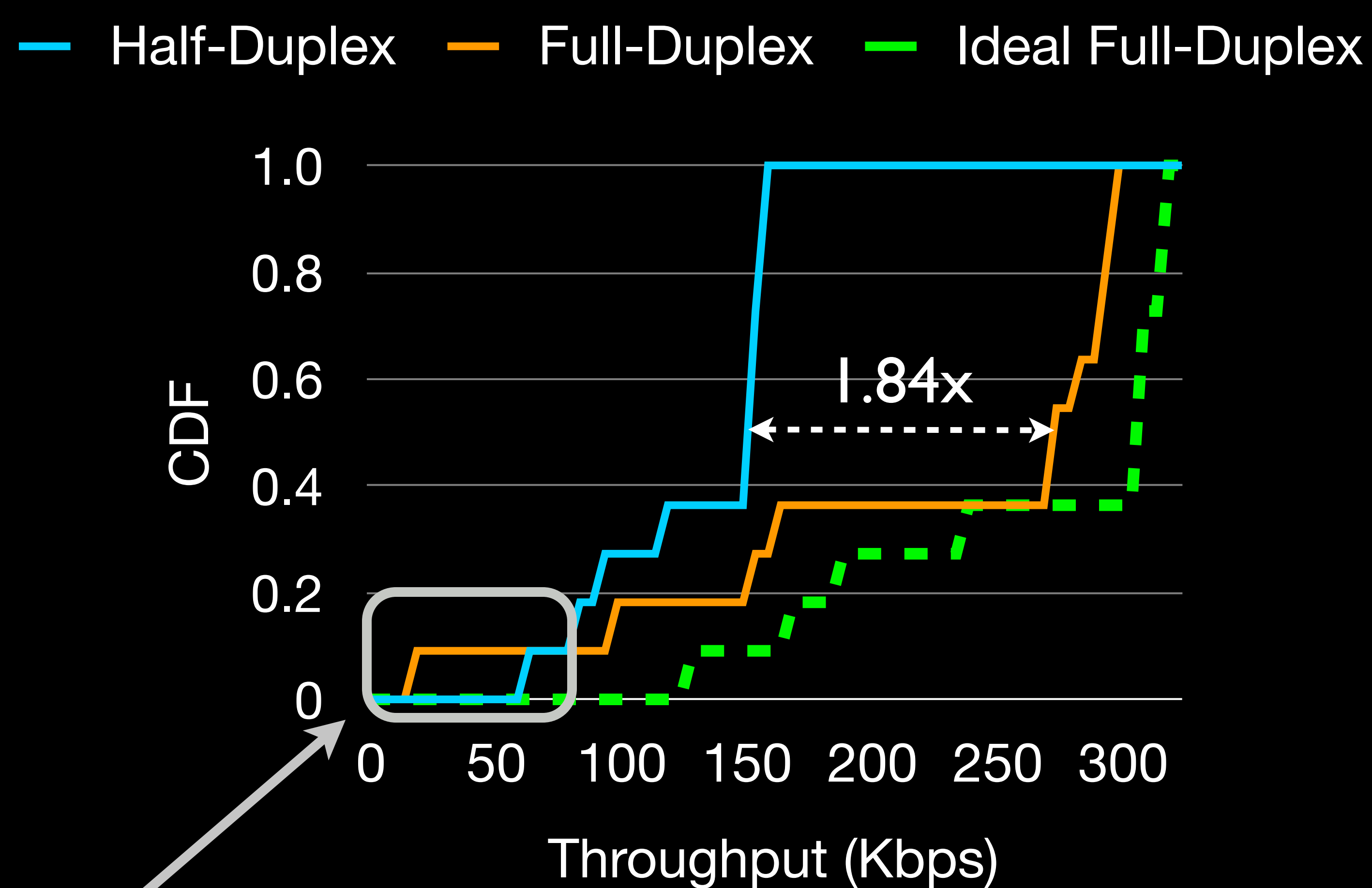
- Full-duplex should double aggregate throughput

Throughput



Median throughput 92% of ideal full-duplex

Throughput



Performance loss at low SNR

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

(and we need 3 antennas)

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

(and we need 3 antennas)

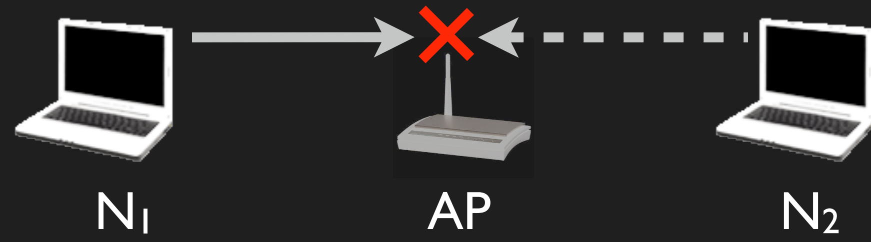
True benefit lies beyond the physical layer

Implications to Wireless Networks

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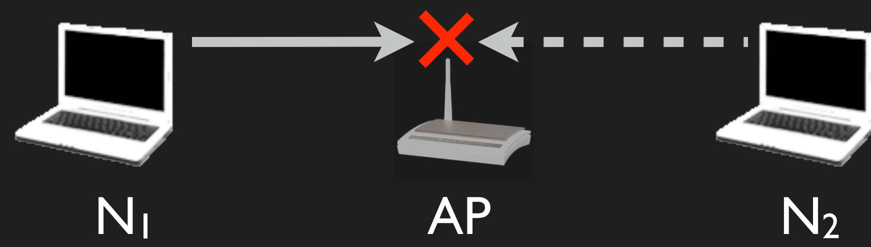

- CSMA/CA can't solve this
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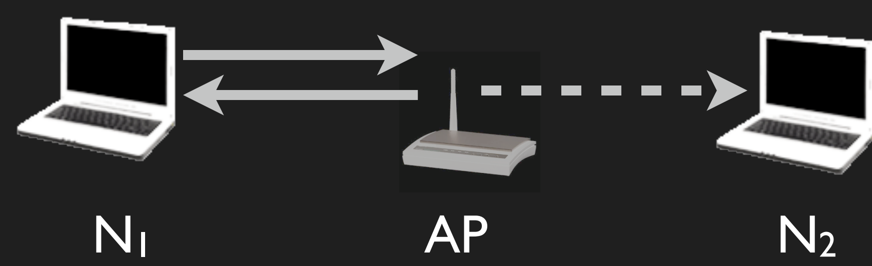
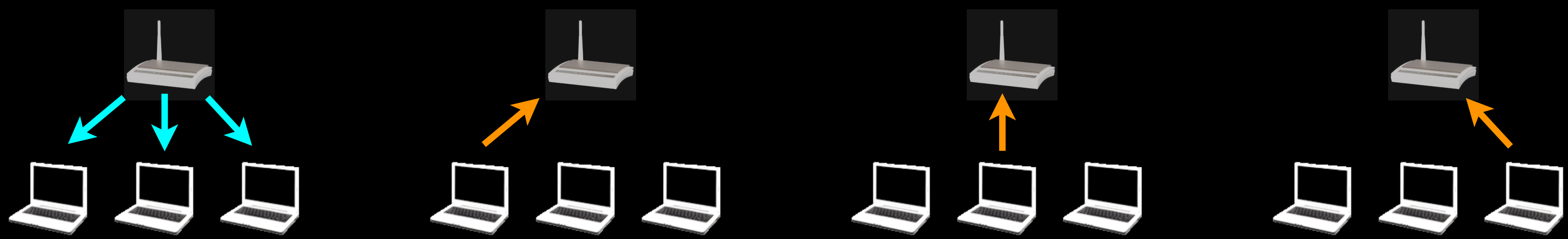
Full Duplex solves hidden terminals



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

Network Congestion and WLAN Fairness

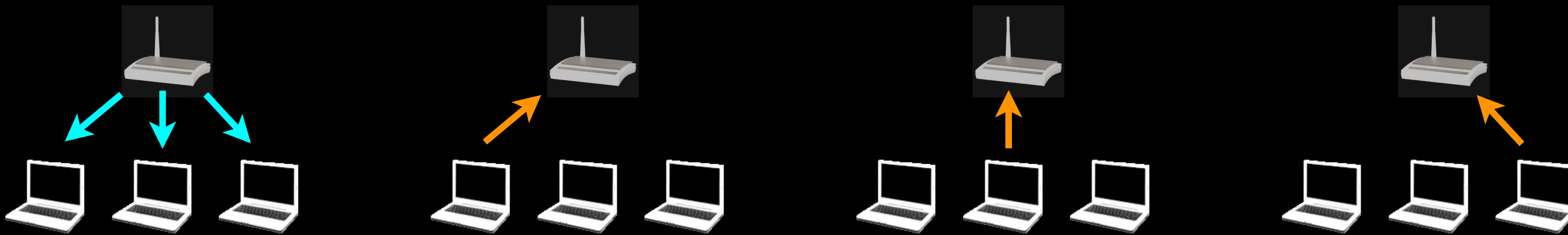


Without full-duplex:

- 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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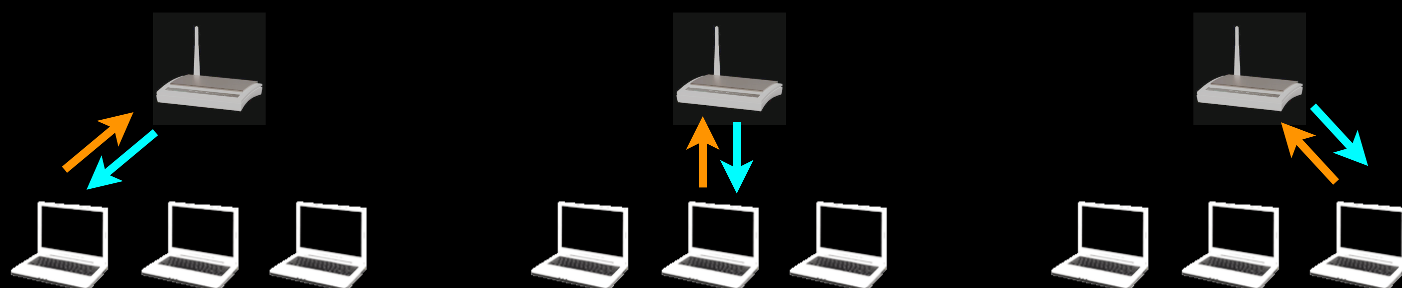


With full-duplex:

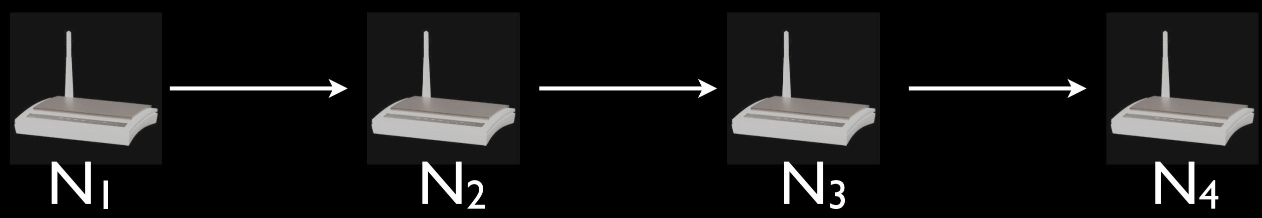
- AP sends and receives at the same time

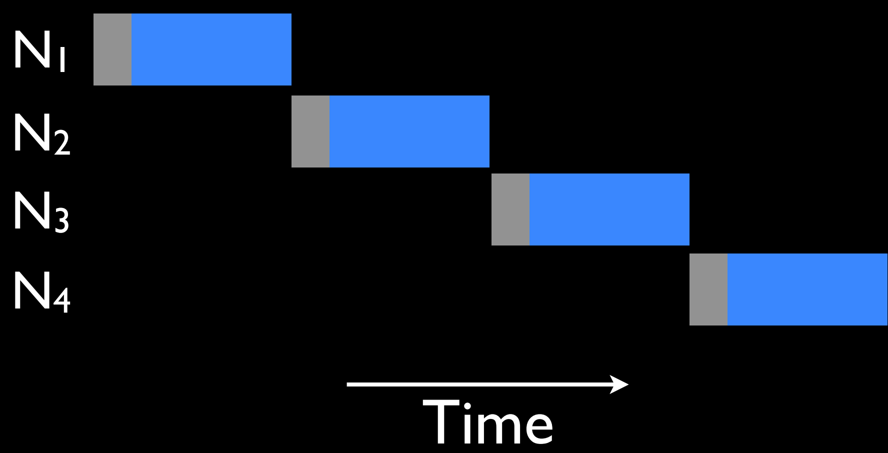
Downlink Throughput = 1   Uplink Throughput = 1

Reducing Round-Trip Times

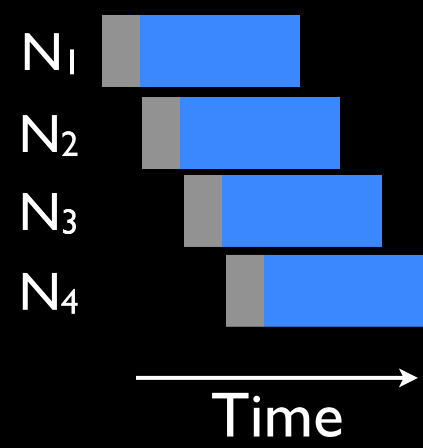
Long delivery and round-trip times in multi-hop networks

Solution: wireless cut-through routing!





Half-duplex



Full-duplex

Questions

Internet Today


Internet movies drowning out the DVD - The Changing World - NZ Herald News

http://www.nzherald.co.nz/

The Changing World — Next Article: 25 skills every man should know

Internet movies drowning out the DVD

5:30 AM Monday Nov 29, 2010

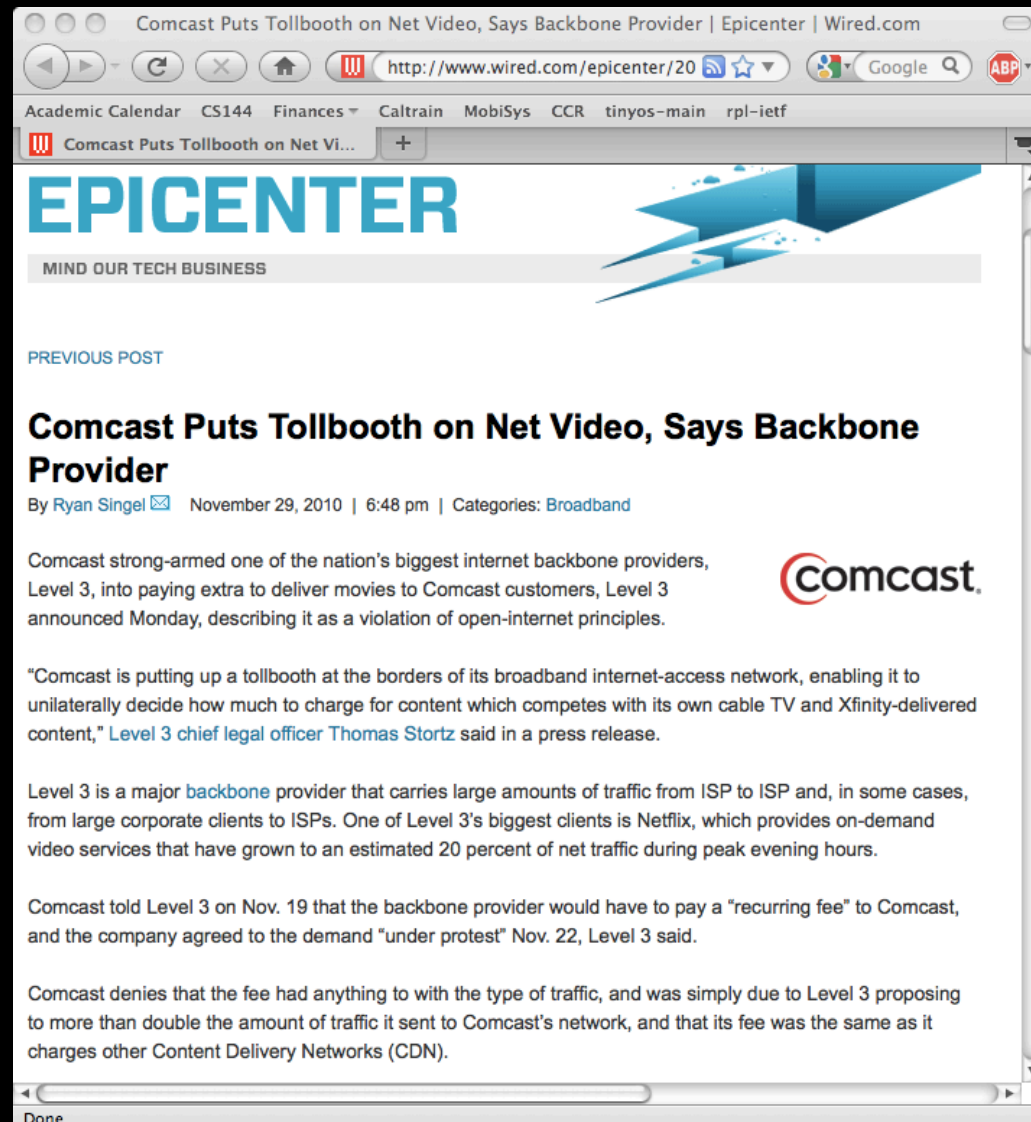
Netflix, the United States company that rents out movies and TV shows, is preparing for the day when getting DVDs by mail is as old-fashioned as going to the video store.

It's hoping to wean people from DVDs with a cheap plan that offers movies and old TV episodes exclusively through online streaming, at a cost of US$8 ($10.50) per month.

Online streaming of movies will radically change the way the video rental industry operates. Photo / Thinkstock

Blockbuster US declares bankruptcy

Susan Easton: Movie giant's fall fable for net age


Comcast Puts Tollbooth on Net Video, Says Backbone Provider | Epicenter | Wired.com

http://www.wired.com/epicenter/20

EPICENTER

MIND OUR TECH BUSINESS

PREVIOUS POST

Comcast Puts Tollbooth on Net Video, Says Backbone Provider

By Ryan Singel | November 29, 2010 | 6:48 pm | Categories: Broadband

Comcast strong-armed one of the nation's biggest internet backbone providers, Level 3, into paying extra to deliver movies to Comcast customers, Level 3 announced Monday, describing it as a violation of open-internet principles.

"Comcast is putting up a tollbooth at the borders of its broadband internet-access network, enabling it to unilaterally decide how much to charge for content which competes with its own cable TV and Xfinity-delivered content," Level 3 chief legal officer Thomas Stortz said in a press release.

Level 3 is a major backbone provider that carries large amounts of traffic from ISP to ISP and, in some cases, from large corporate clients to ISPs. One of Level 3's biggest clients is Netflix, which provides on-demand video services that have grown to an estimated 20 percent of net traffic during peak evening hours.

Comcast told Level 3 on Nov. 19 that the backbone provider would have to pay a "recurring fee" to Comcast, and the company agreed to the demand "under protest" Nov. 22, Level 3 said.

Comcast denies that the fee had anything to with the type of traffic, and was simply due to Level 3 proposing to more than double the amount of traffic it sent to Comcast's network, and that its fee was the same as it charges other Content Delivery Networks (CDN).

After CS144

Systems	CS140 (w)	CS240 (s)		advanced OS
		CS244B (s)		distributed systems
Networking	CS144 (f)	CS244 (w)	CS344 (s)	general networking
		CS244E (w)	CS344E (s)	wireless networking
Web Applications	CS142 (f)	CS241		secure web programming
Security	CS155 (s)	CS255 (w)		cryptography
		CS259 (w)		protocol security

Final Lecture

- Guest lecture: Jon Peterson
  - On Internet Architecture Board (IAB)
  - Co-chair of alto working group
  - Co-author of Session Initiation Protocol (SIP)
- Will talk about alto and other issues in the Internet today -- bring questions!

Backup

- Bandwidth Constraint

  Working on a frequency independent 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

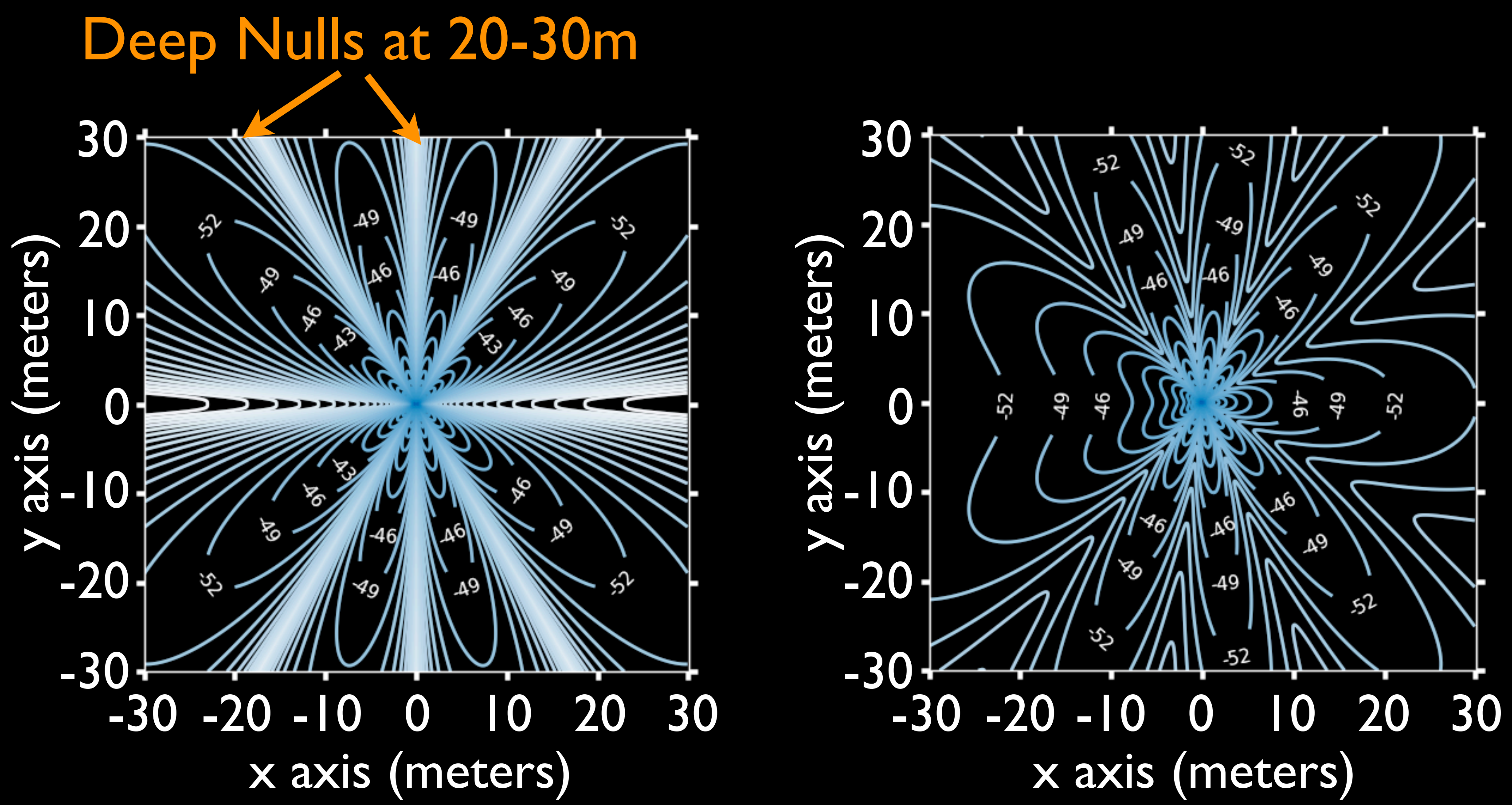
Summary

- Working prototype for achieving in-band full-duplex wireless
- Cancellation limited by engineering precision and bandwidth of channel
  - *Phase offset, amplitude, circuit noise*
- How far can full duplex go? WiFi? WiMAX/LTE?
- As we add more antennas, what degrees of freedom do we have and how should we use them?
- How does this change the rest of the stack?

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

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

- Different transmit powers for two TX helps



Equal Transmit Power

Unequal Transmit Power

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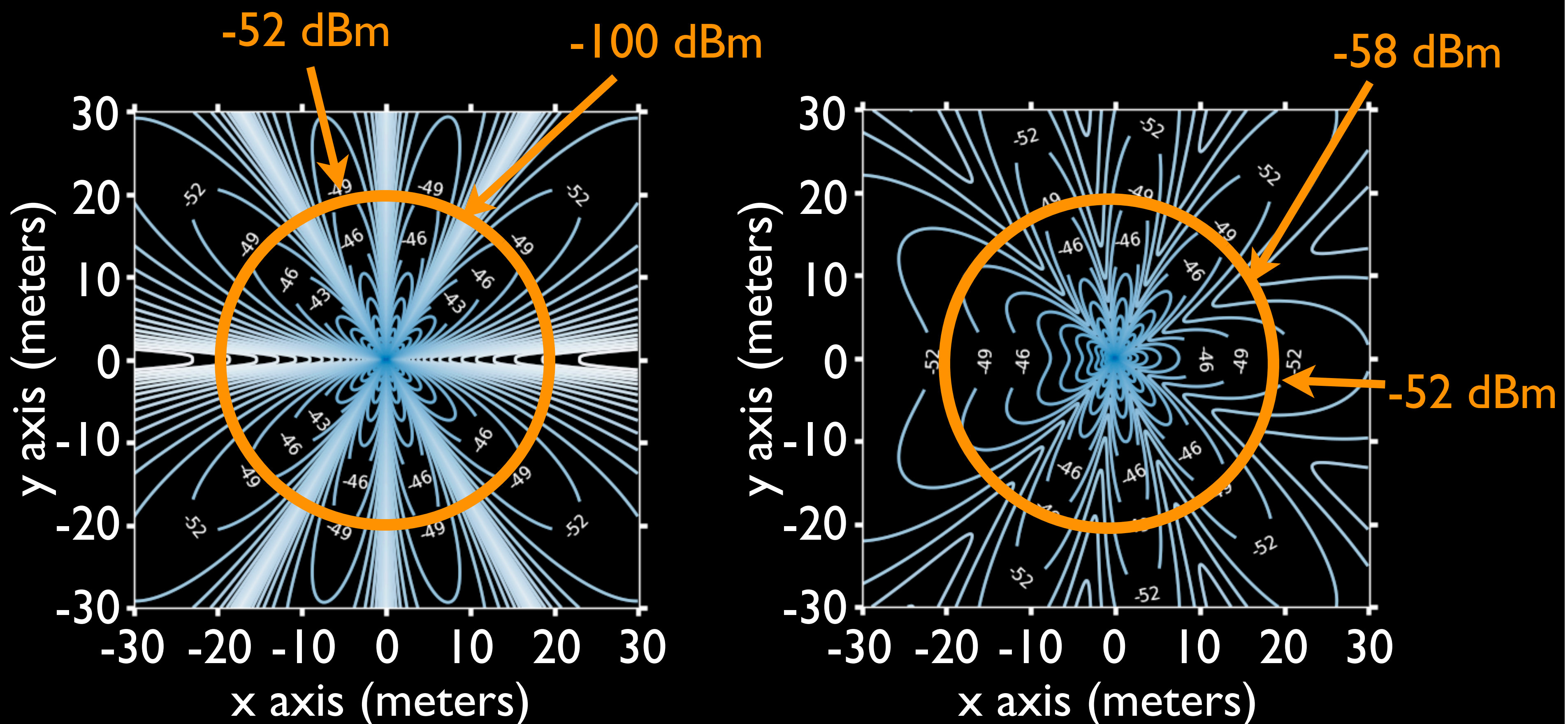

Equal Transmit Power

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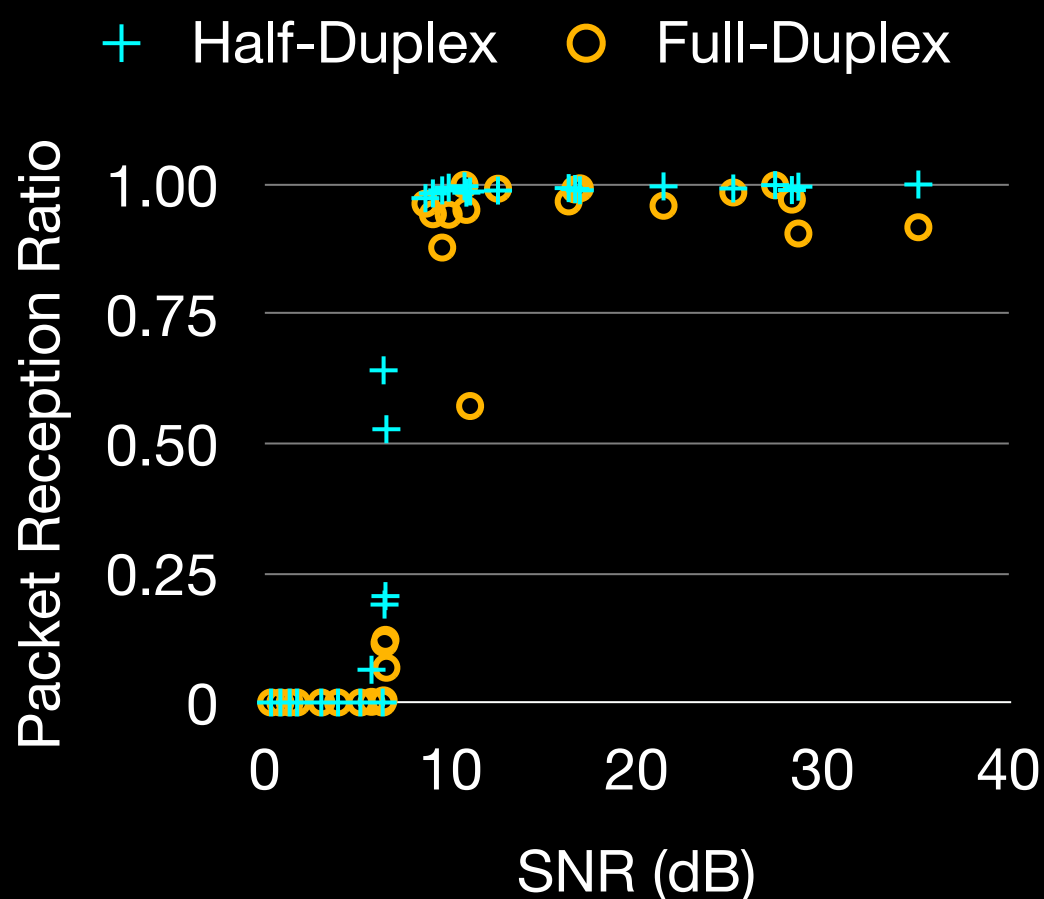
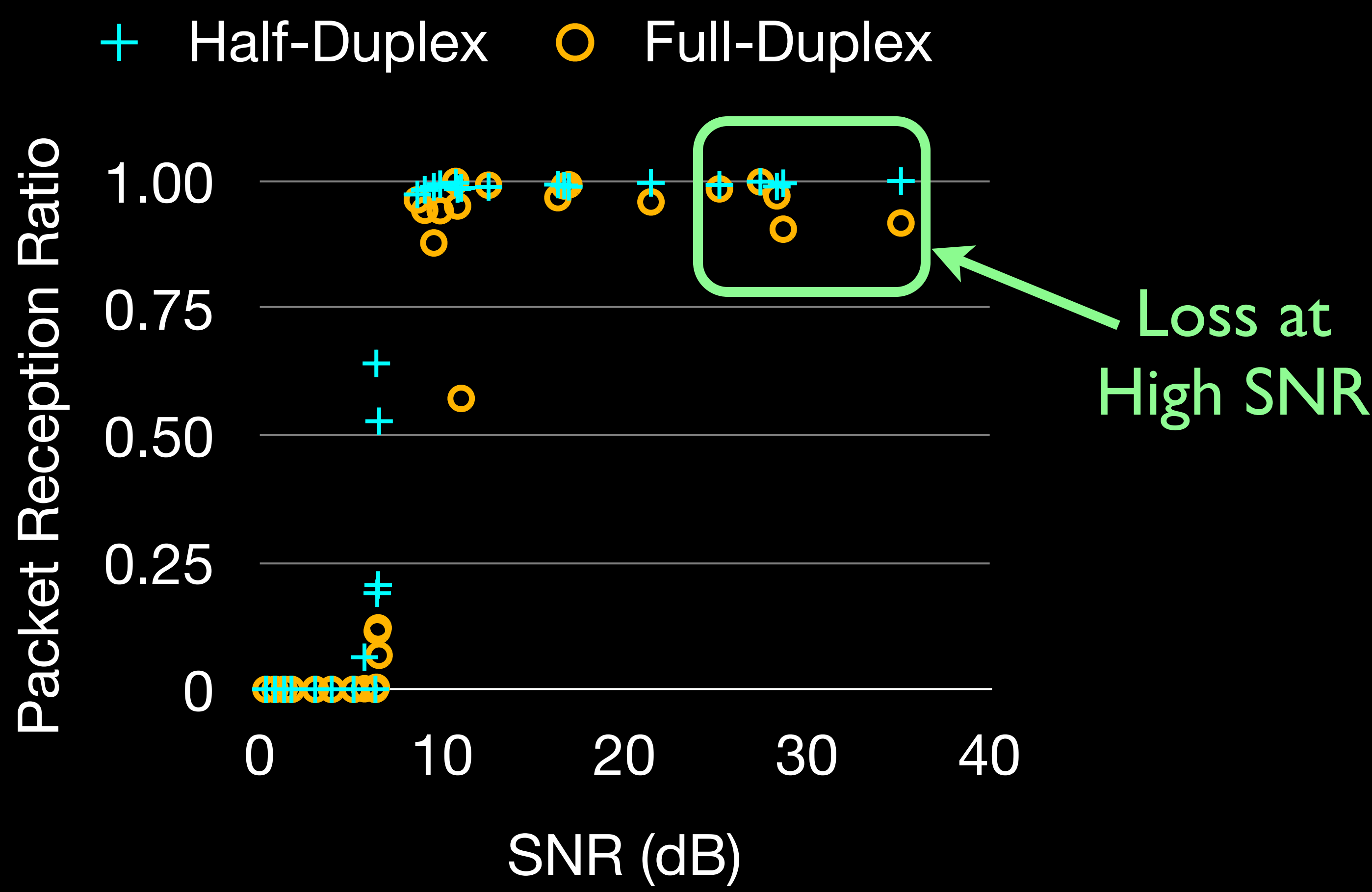
Link Reception Ratio



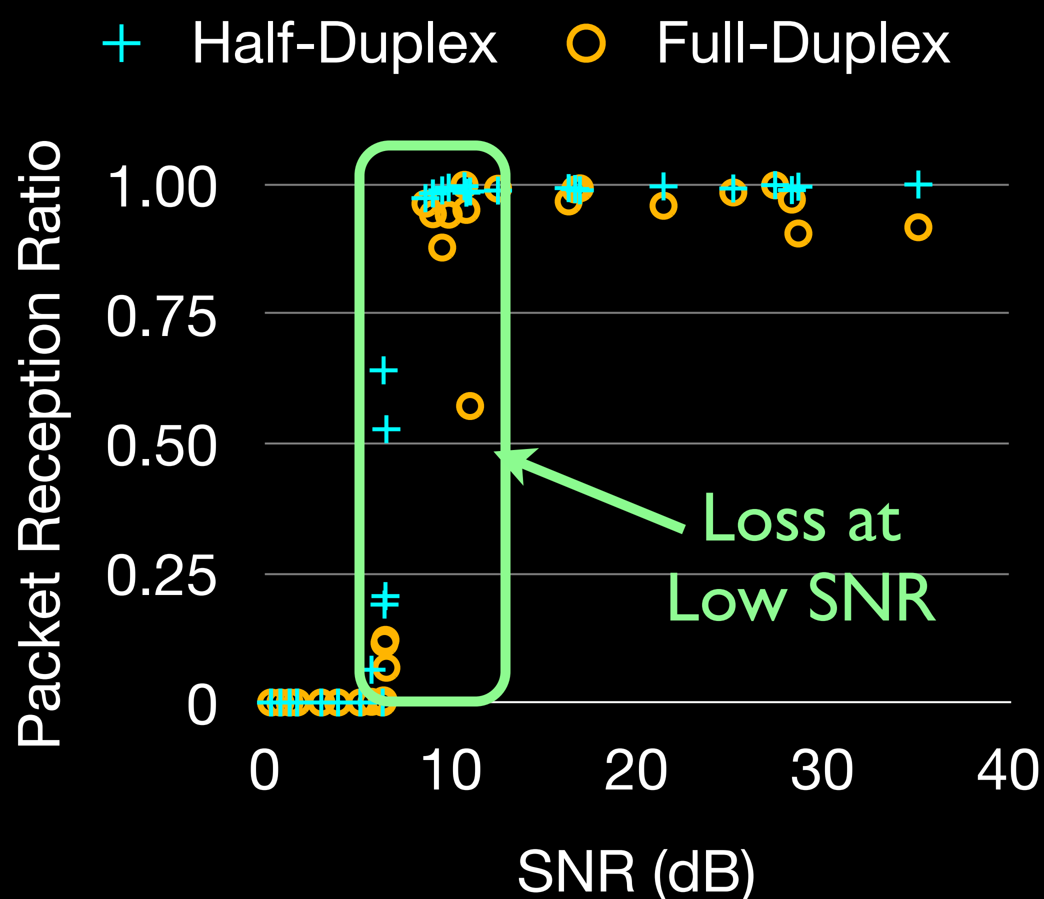
Little loss in link reliability: 88% of half-duplex on average

Link Reception Ratio



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

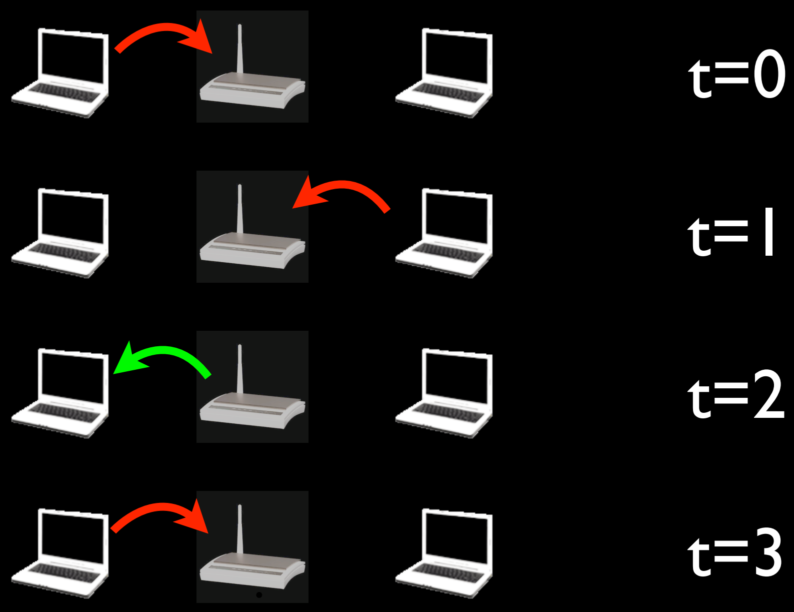
Link Reception Ratio



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

Network Congestion and WLAN Fairness

For an AP serving many clients



Without full-duplex

- APs contend with clients for wireless access
- Downlink throughput = 1/n
- Bottleneck at AP

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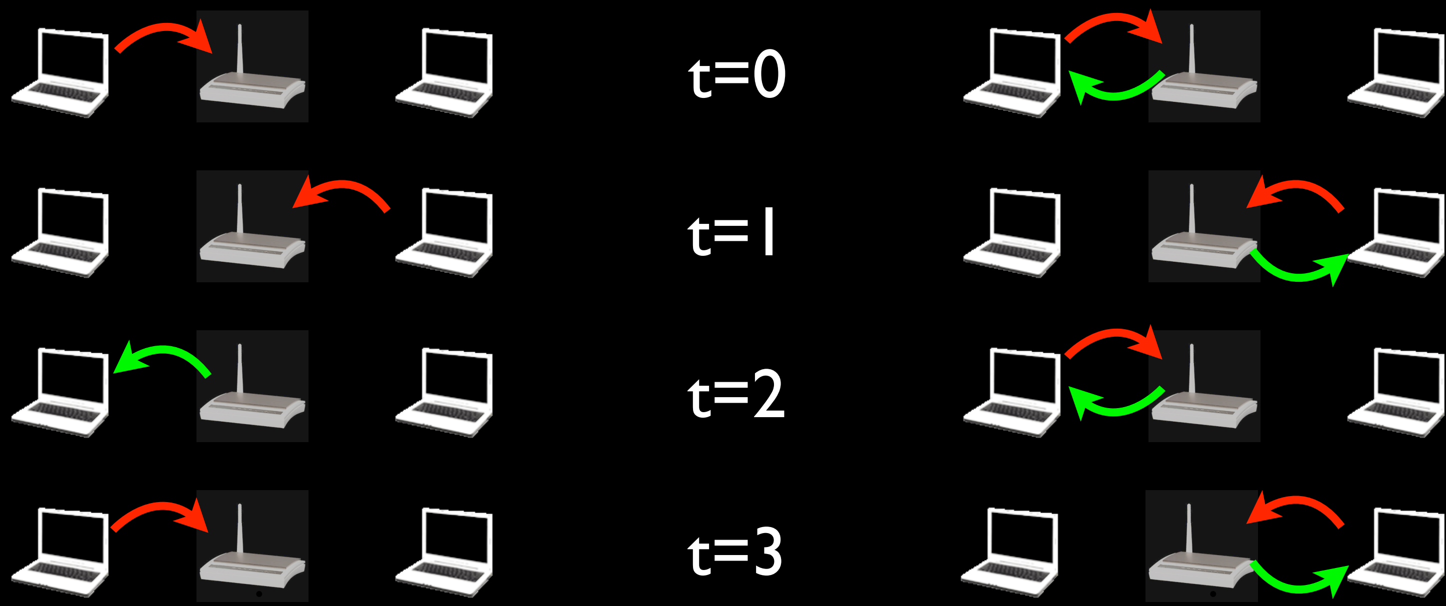

Without full-duplex

- APs contend with clients for wireless access
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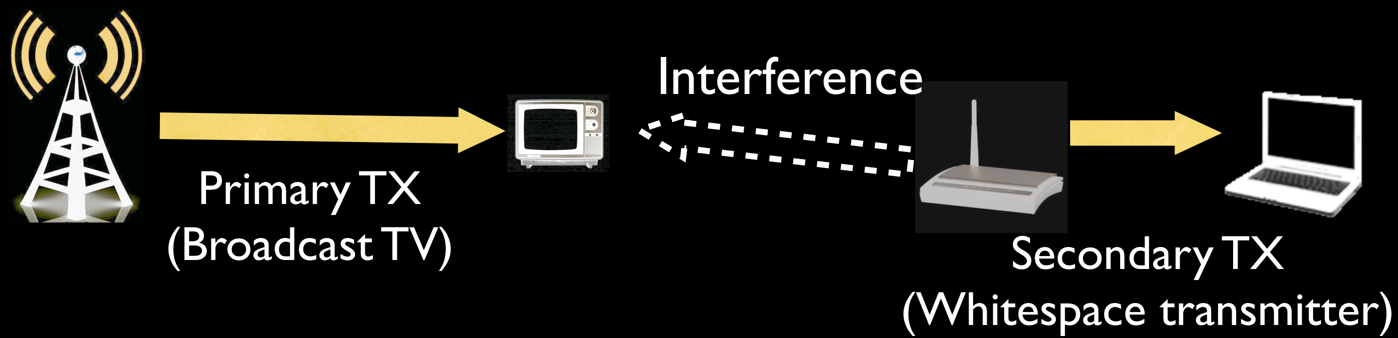
Full-duplexing reduces congestion

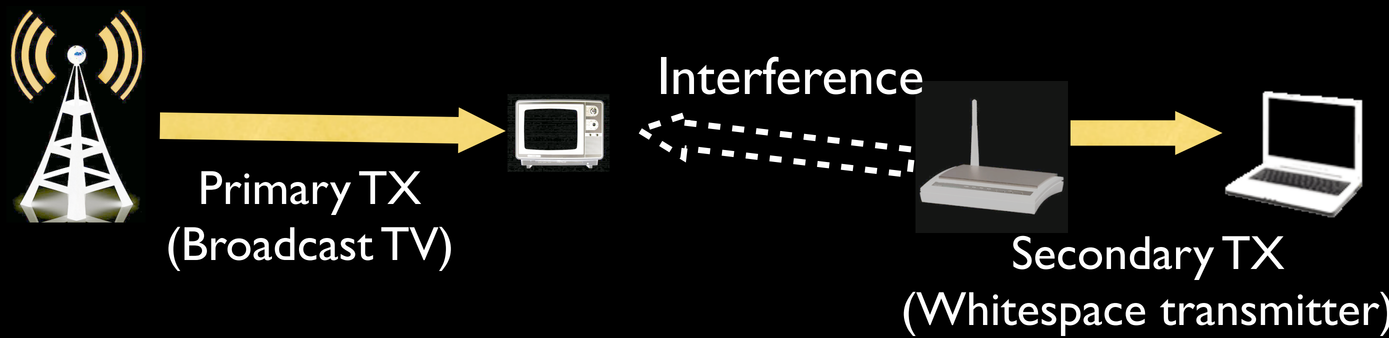
- AP transmits and receives at the same time
- Downlink = Uplink = 1

Primary Detection in Whitespaces



Secondary transmitters should not interfere with primary transmissions

Primary Detection in Whitespaces



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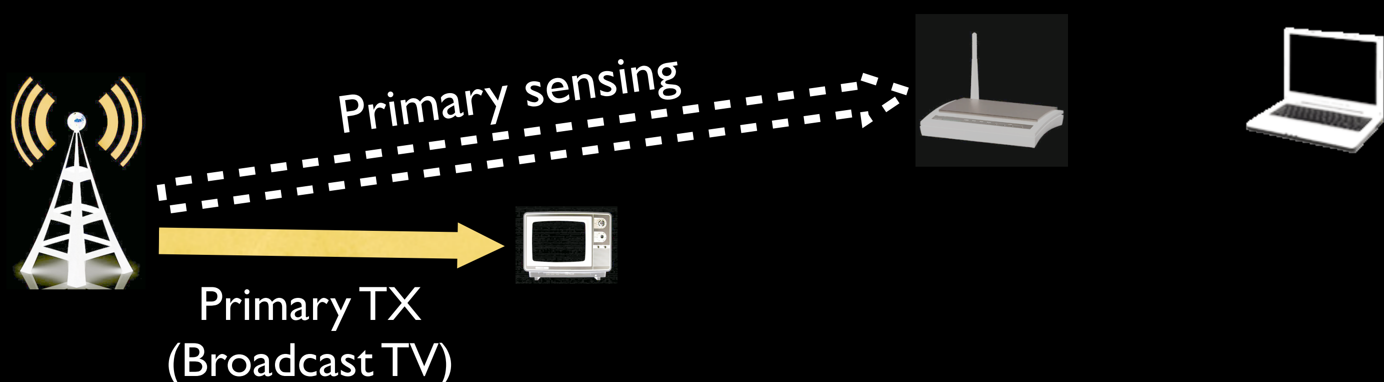

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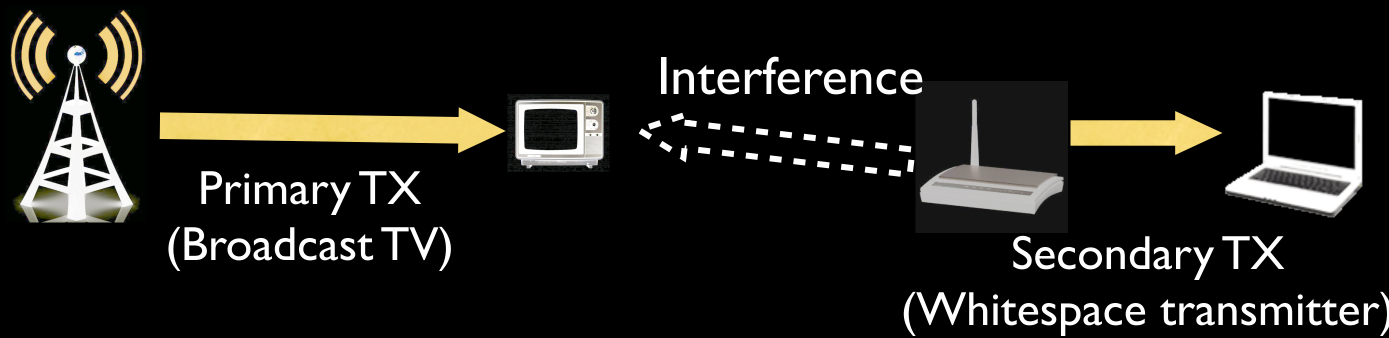

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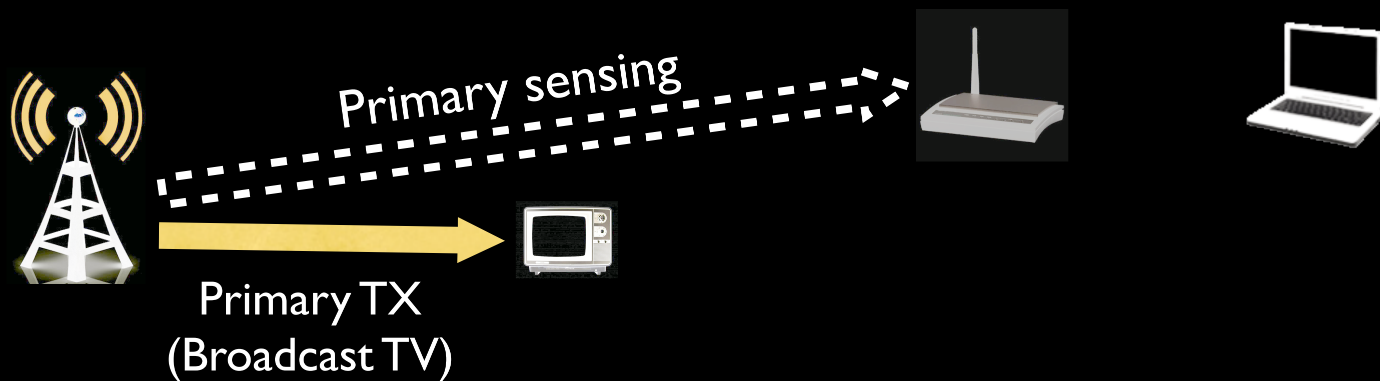
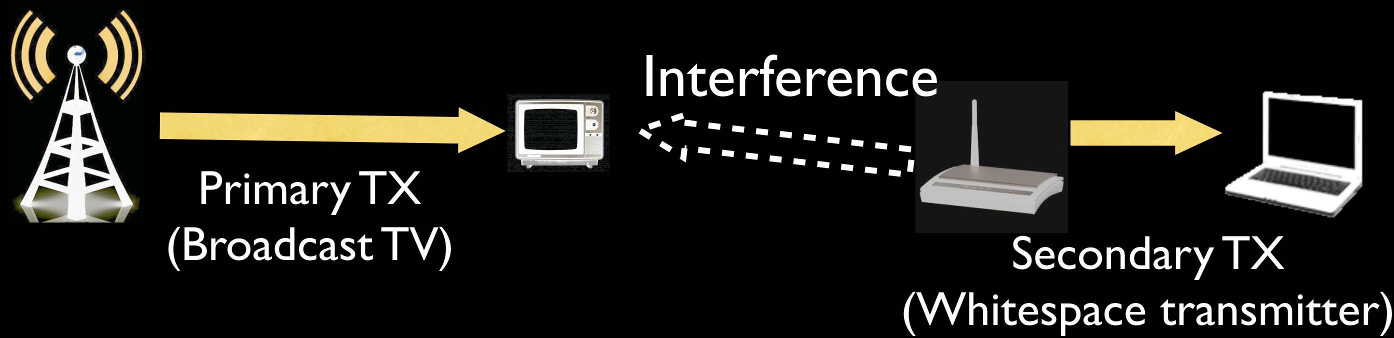


Traditional nodes can’t send and sense at the same time

Primary Detection in Whitespaces



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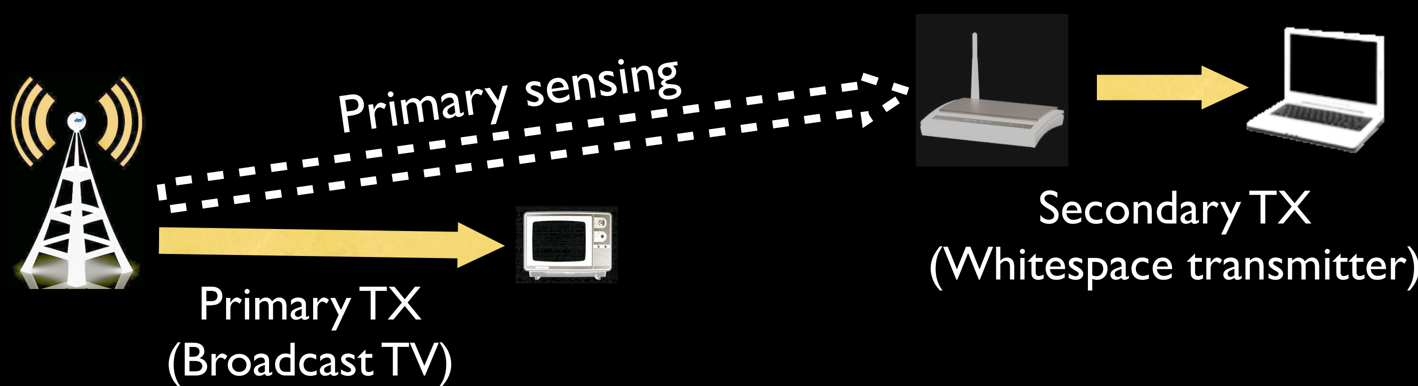
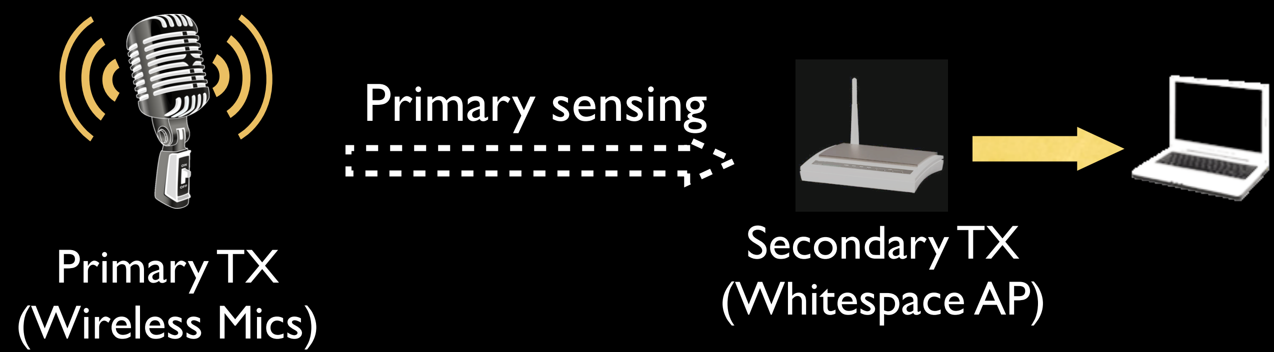


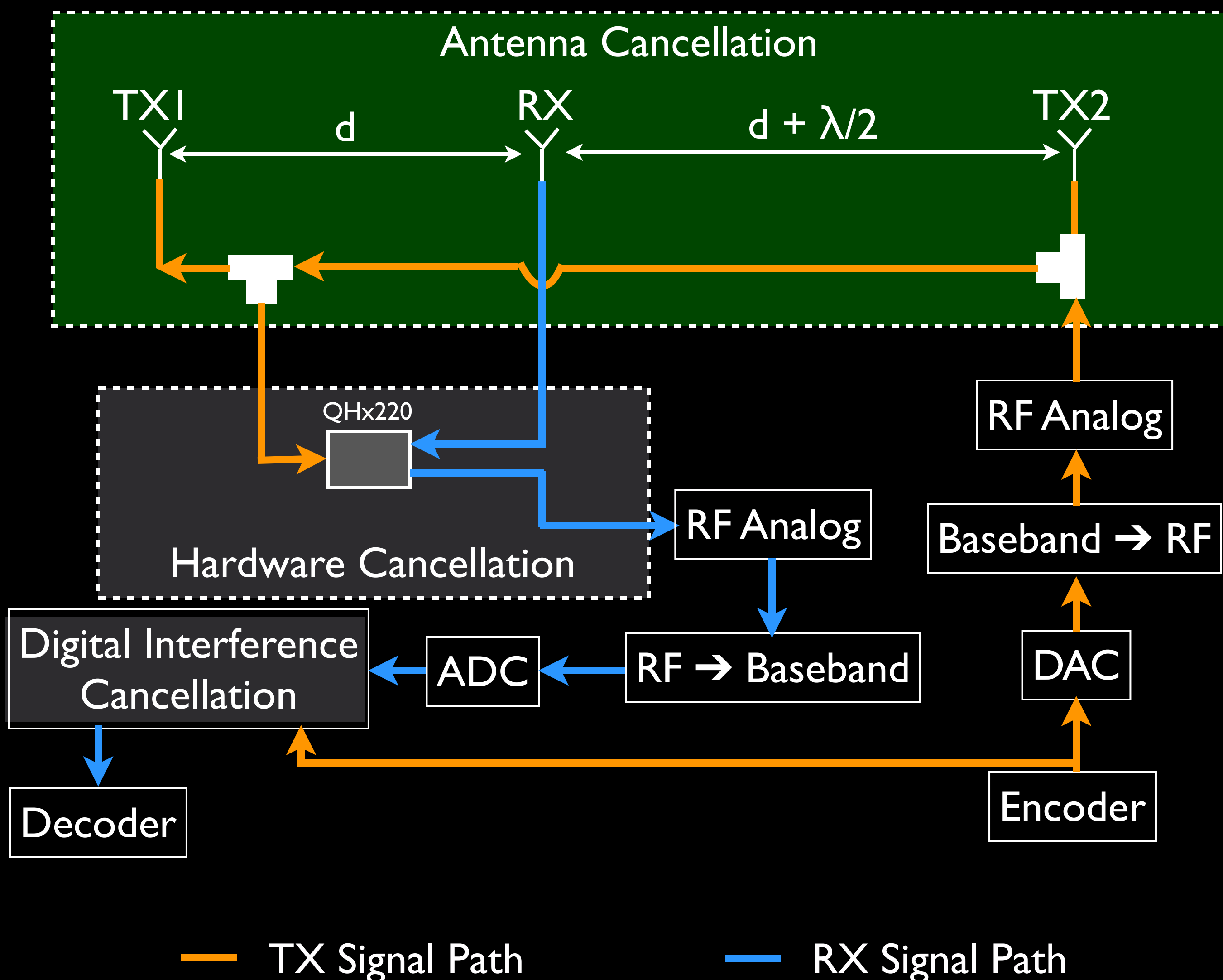
Full-duplex nodes can

Primary Detection in Whitespaces



Secondary transmitters should sense for primary transmissions before channel use

Bringing It Together



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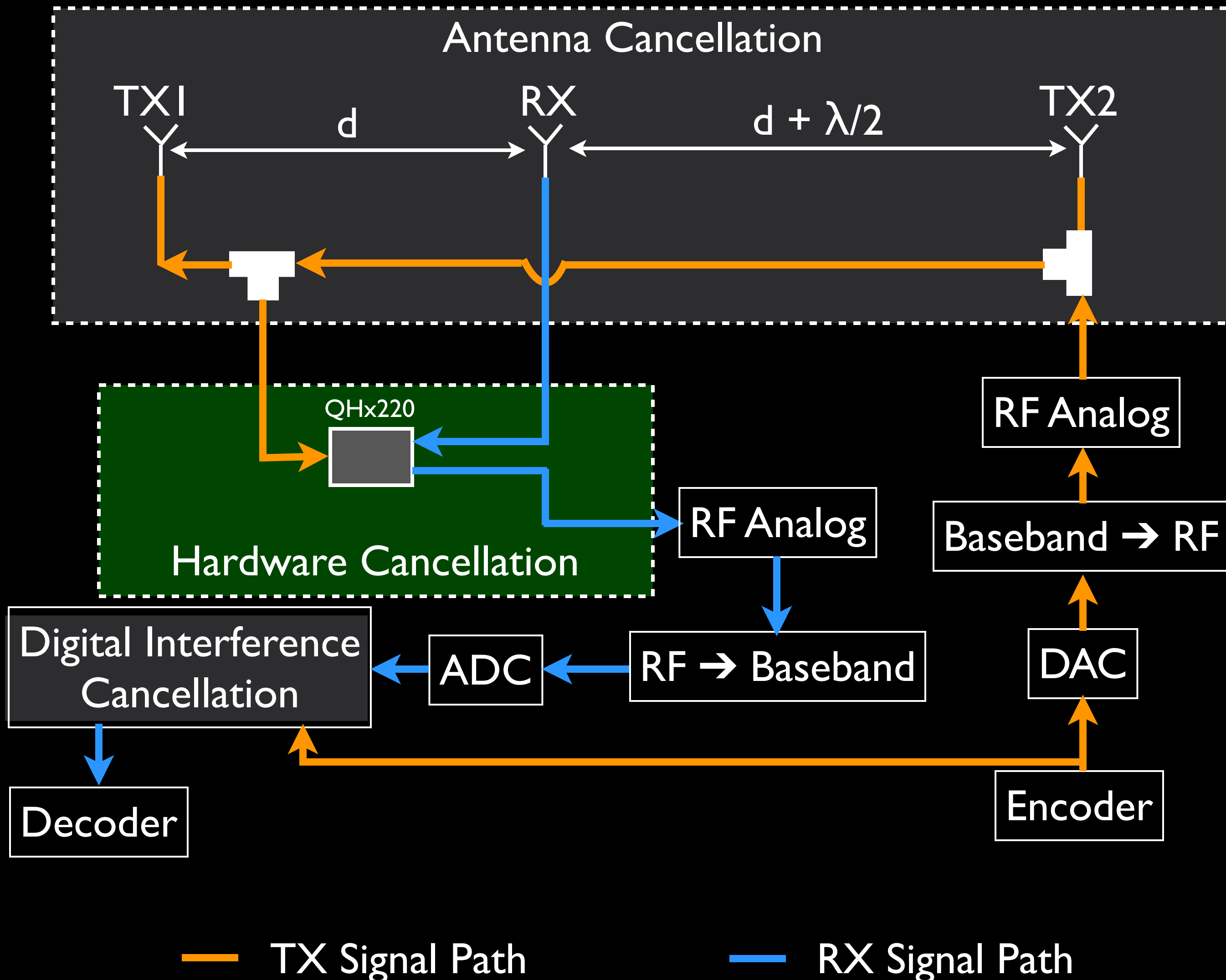
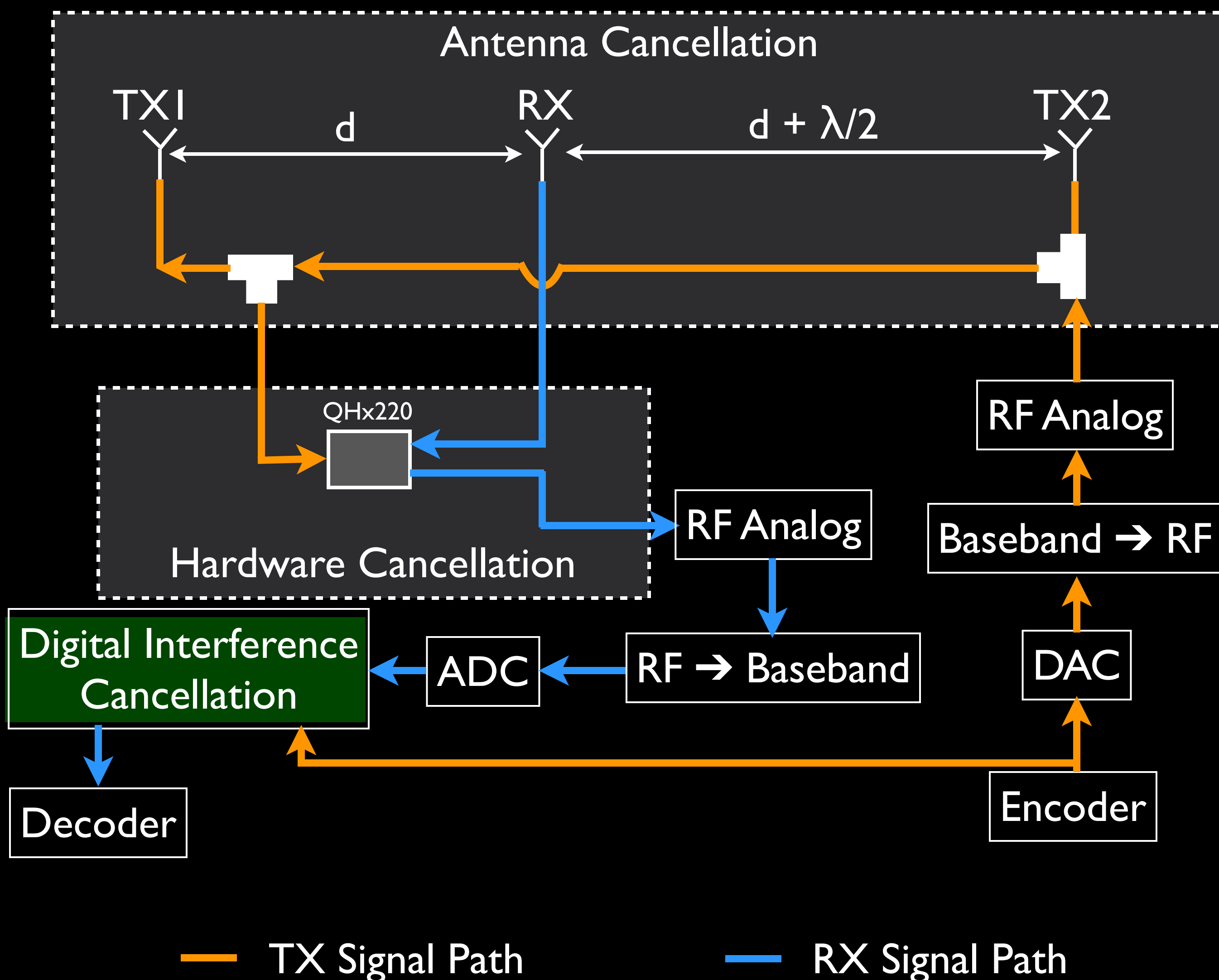
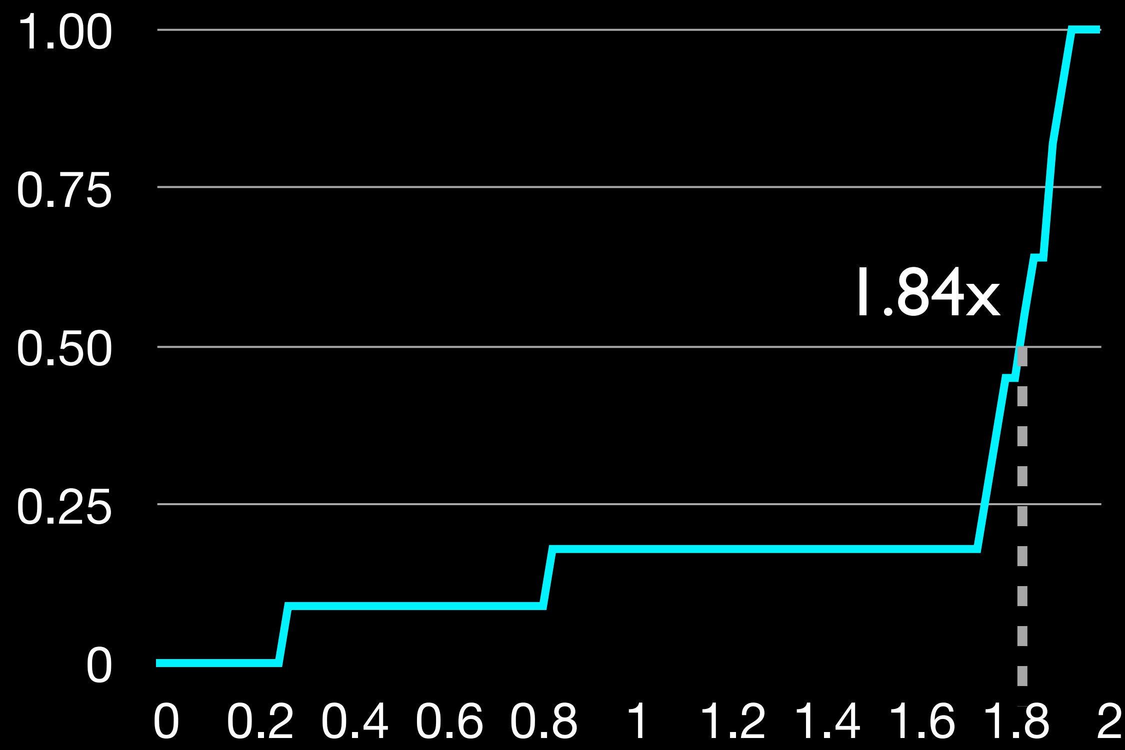


Bringing It Together

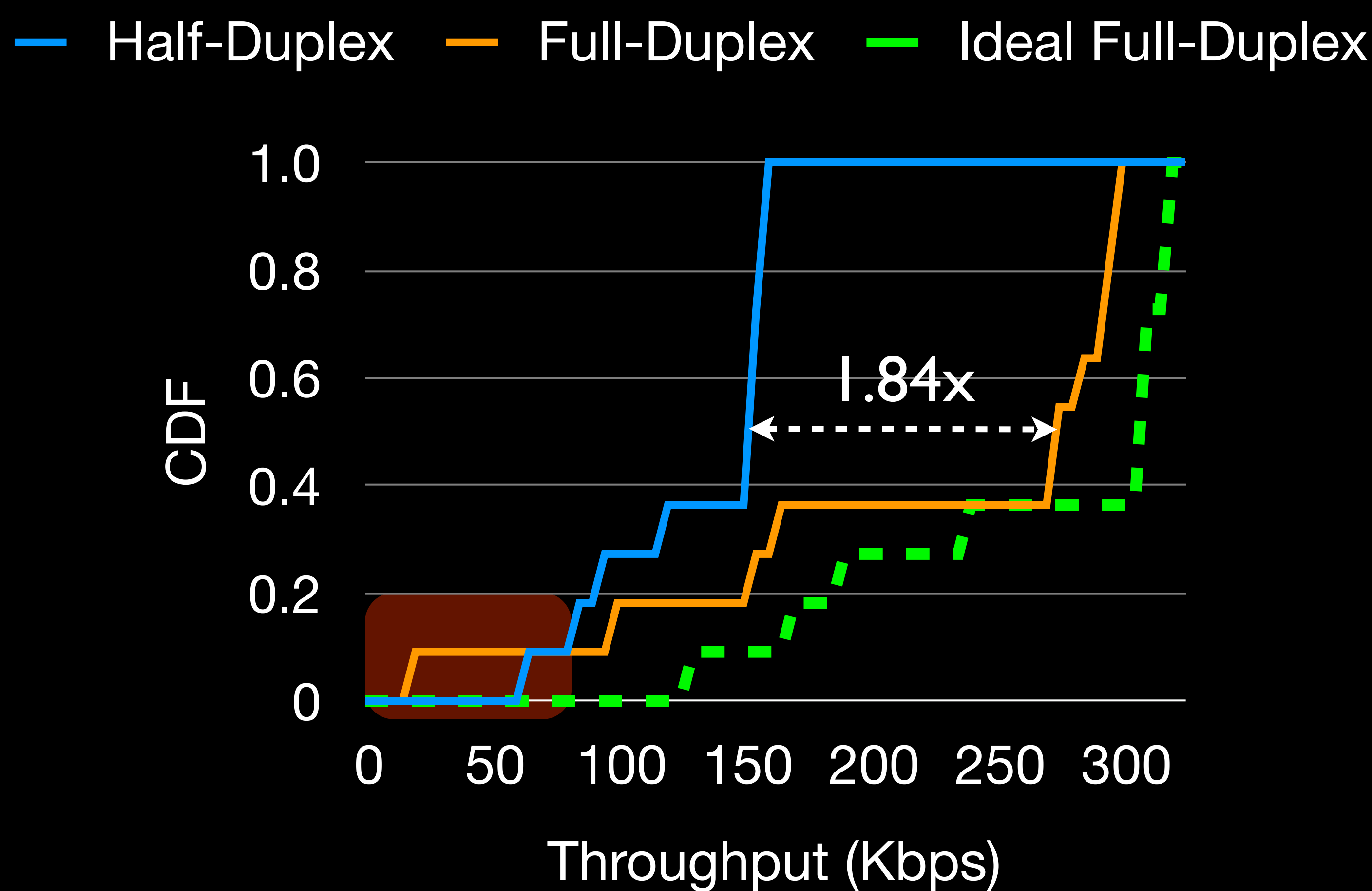


Throughput



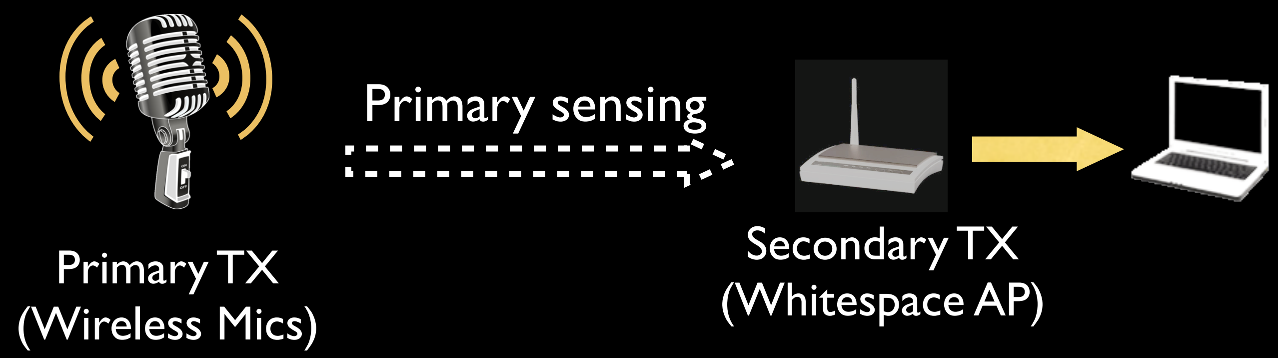
Median throughput 92% of ideal full-duplex

Throughput



Performance loss at low SNR

Primary Detection in Whitespaces

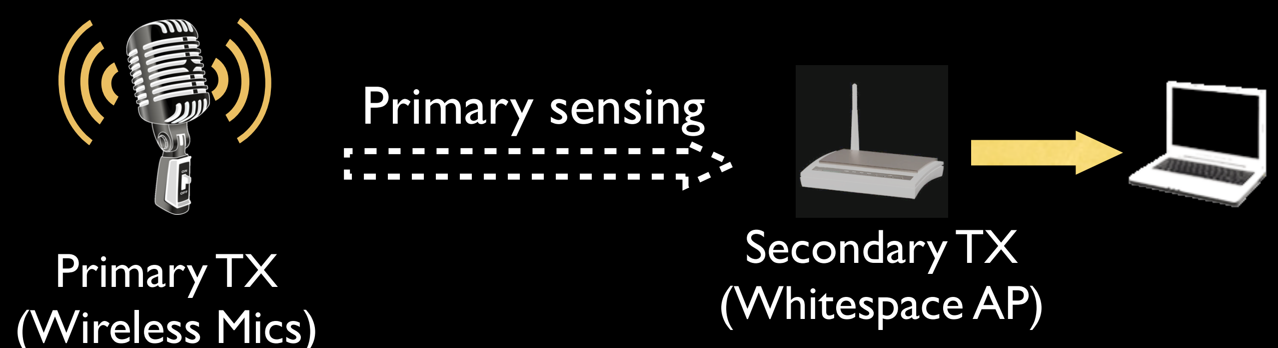


Secondary transmitters should sense for primary transmissions before channel use

Traditional nodes may still interfere during transmissions

Primary Detection in Whitespaces

Secondary transmitters should sense for primary transmissions before channel use



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