Fast and Infuriating: Performance and Pitfalls of 60 GHz WLANs Based on Consumer-Grade Hardware

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SEMC SECURE MOBILE NETWORKING

60 GHz Wireless

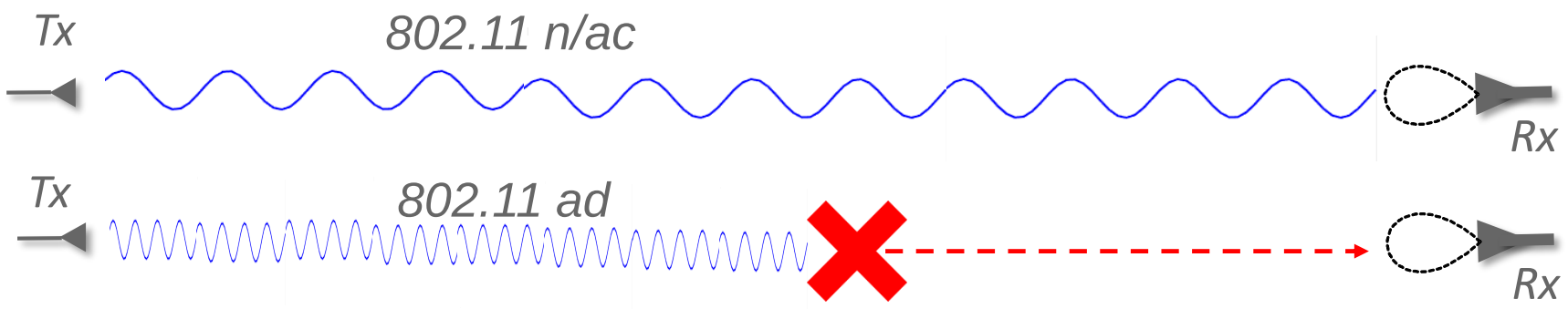
- **7 GHz** of unlicensed spectrum available around **60 GHz**

- Standardized under 802.11ad, which uses **2.16 GHz** wide channels

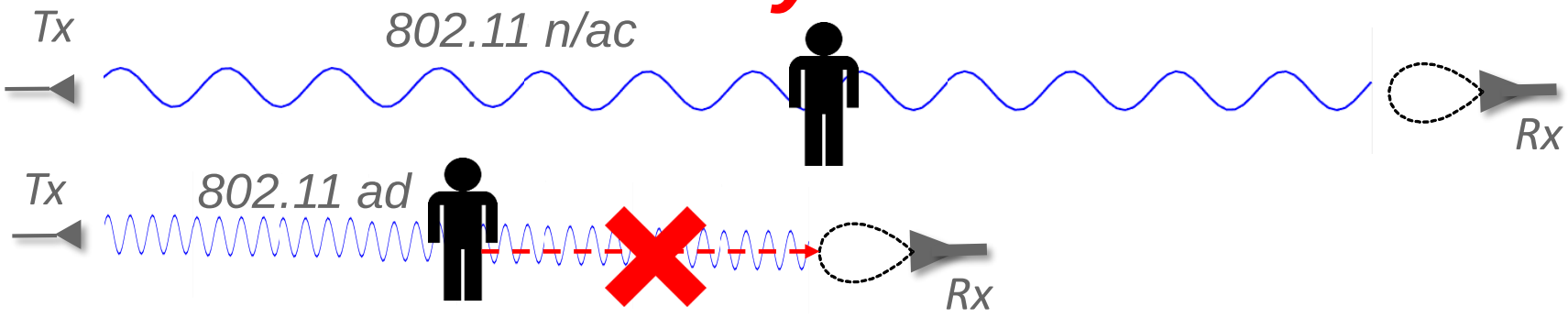
- 802.11ad is **350%** faster than 802.11ac

Utilizing the 60 GHz Band: Challenges

Short Range

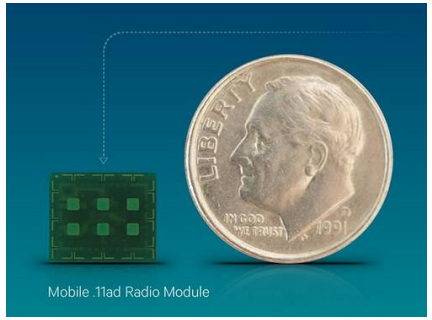


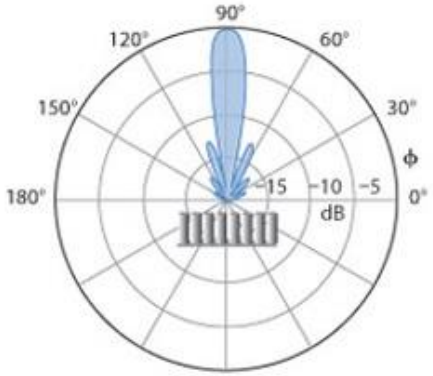
Easily Blocked



Increasing Range: Beamforming

- Using multiple antenna elements





- Codebook
  - Set of multiple pre-computed antenna weights (phase values)
  - Typically designed to cover wide sweep space
  - Device selects a beam from codebook in runtime

Directional Transmission

High frequency
Short/Limited Range

Directional Transmission
BEAMFORMING

Vulnerability to LOS Blockage

Non-resilience to Mobility

A lot of research efforts directed towards addressing these challenges

Most recent ***systems*** work is **experimentally** driven!

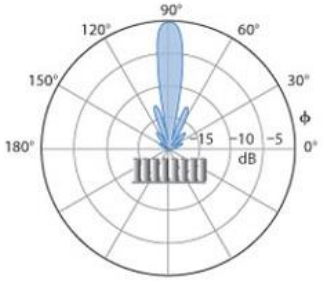
Current Choice of Measurement Platforms

- Software-Defined Radio (SDR)-based
- Used in conjunction with a 60 GHz up-converter
- Access to lower-layer PHY information
- Control over beam direction
- Deeper insights into link behavior

SDRs Vs. Commercial Off-the-Shelf (COTS) Hardware

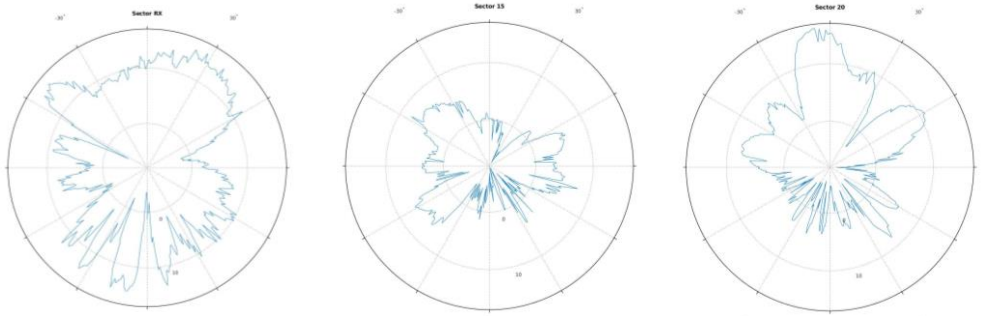
A. Limited to few 100 MHz of bandwidth

B. Use mechanically steerable horn antennas

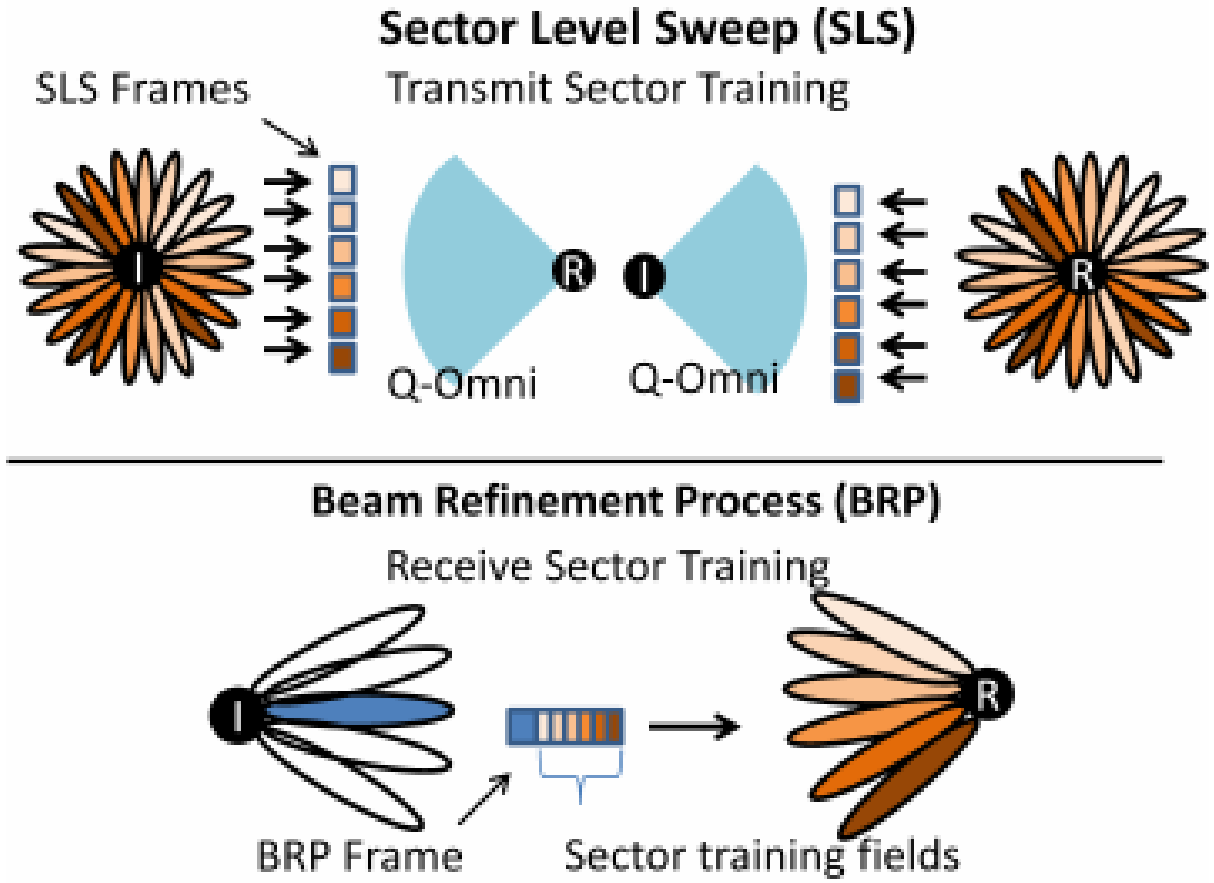


A. 802.11ad uses 2.16 GHz wide channels

B. 802.11ad COTS devices use phased-antenna arrays



802.11ad: Beamforming



Our COTS hardware does this procedure once every 10 frames
OR
On Loss of ACK

Experimental Setup: Devices (Access Point)

- *TP-Link* **TALON** AD7200
- First commercial 802.11ad router (rel. June 2016)
- QCA9008-SBD1 (QCA9500 chipset)
- Single carrier data rates up to 4.6 Gbps
- 32-element phased antenna array
- Includes only 1 G LAN interface

Experimental Setup: Devices (Access Point)

- *Netgear* **NIGHTHAWK** X10 Smart WiFi Router
- Released around October 2016
- Same chipset as the Talon
- 32-element phased antenna array
- Sports 10 G LAN SFP+ interface
- Actual throughput limited to around 2.3 Gbps

Experimental Setup: Devices (Client Laptop)

- *Acer* **Travelmate** P446-M
- Released in April 2016
- QCA9008-TBD1 (client version of the AP chipset)
- Fedora Linux (kernel 4.x)
- Open source wil6210 driver
- 32-element phased antenna array

Experimental Setup: Methodology

- Downlink TCP traffic generated using *iperf3*
- Additional Talon Router to sniff packets off air
- The devices use proprietary beam and rate adaptation mechanism
- In case of disconnection, radios automatically try to re-establish link through NLOS paths
- Collect link parameters:
  - **A. Tx and Rx MCS**
  - **B. MAC Layer Throughput**
  - **C. Signal Quality Indicator (SQI)**
  - **D. Beamforming Status: OK/Failed/Retrying**
  - **E. Sector (beam direction) used by AP and Client**

Link Performance: Distance

Open Space
Minimal reflectors

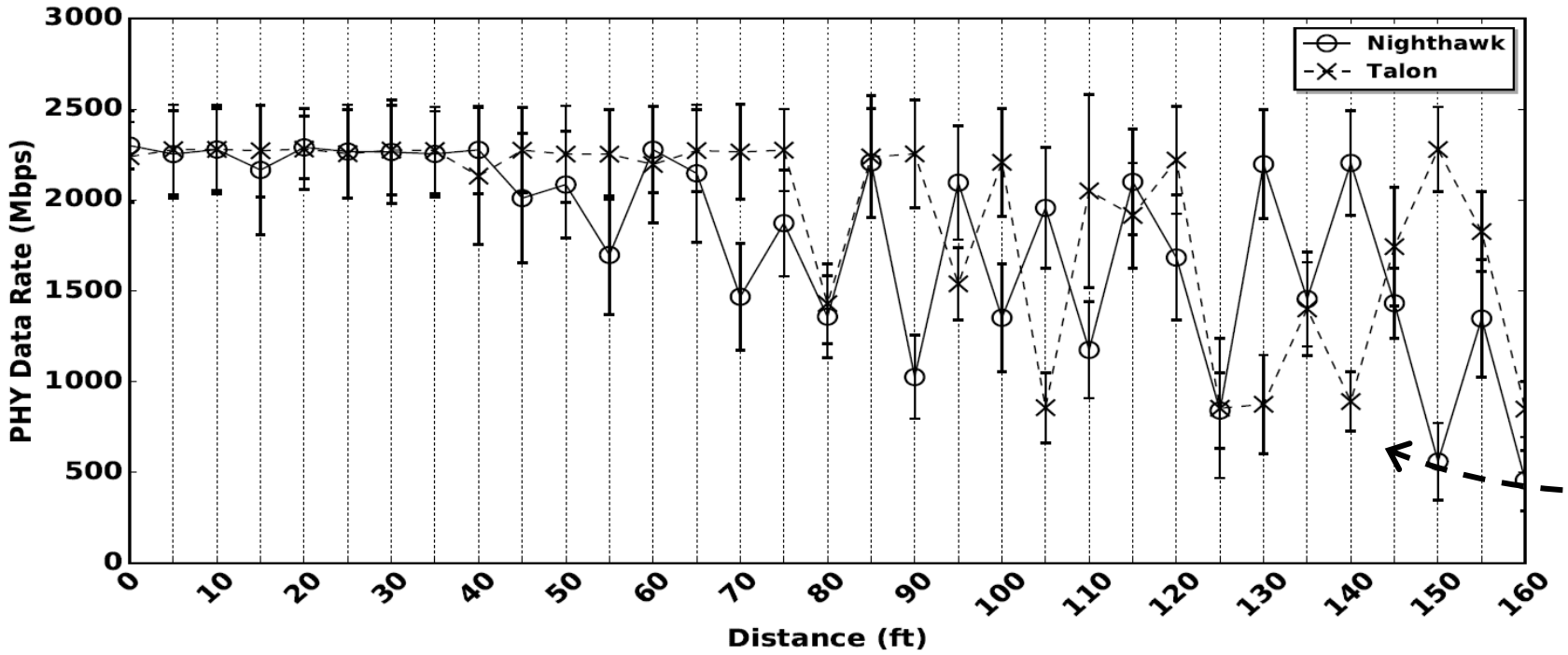
Narrow
Walls on both sides

	Outdoor		Lobby		Corridor	
	>2 Gbps	>1 Gbps	>2 Gbps	>1 Gbps	>2 Gbps	>1 Gbps
Nighthawk	23 ft	65 ft	55 ft	80 ft	140 ft	155 ft
Talon	-	-	80 ft	80 ft	155 ft	155 ft

Gbps range limited to around 65 ft.

MUCH larger range 80/155 ft. (> 1Gbps) Corridor > Lobby

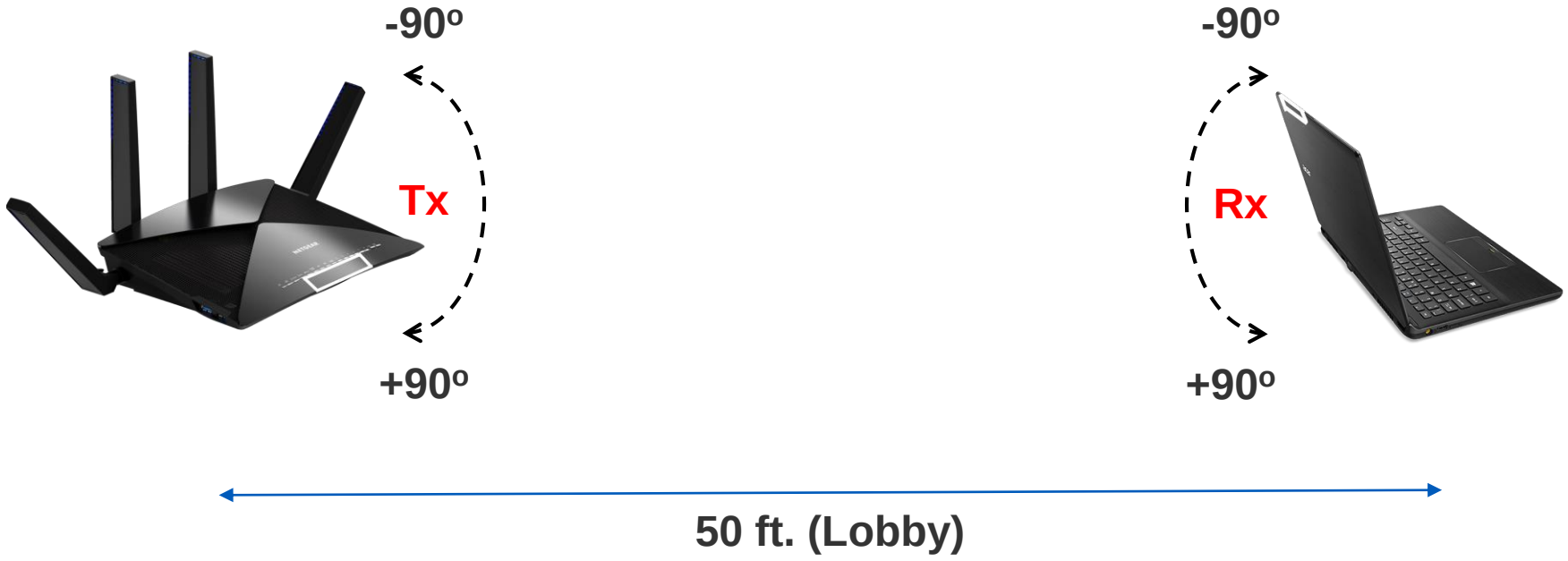
Link Performance: Distance



(b) PHY data rate over distance in the Corridor.

Large variations in throughput for distances > 50-75 ft.

Link Performance: Orientation (Setup)

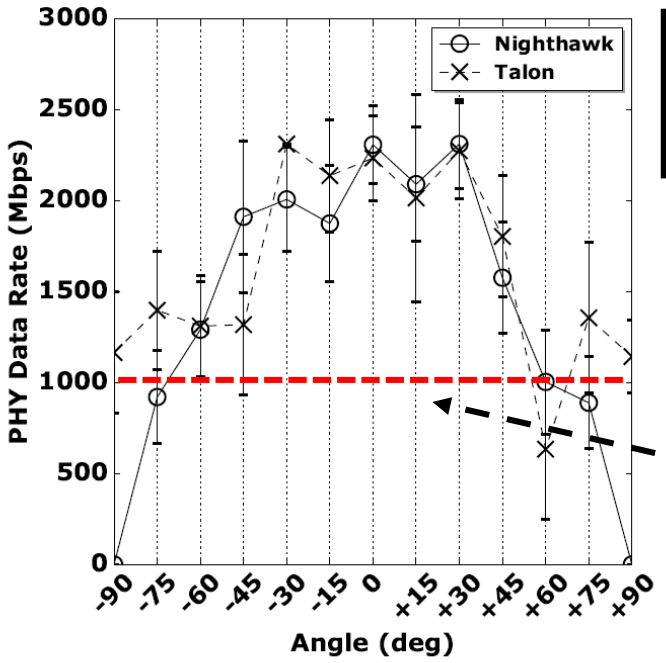


Link Performance: Orientation (Rx)

- *Rx sector* (beam direction) **never** changes
- We tried extreme angles
- Gbps communication possible between [-75º, 75º] angles
- **Quasi-omni beam patterns**

Gbps rates are possible even without beamforming gains on Rx side

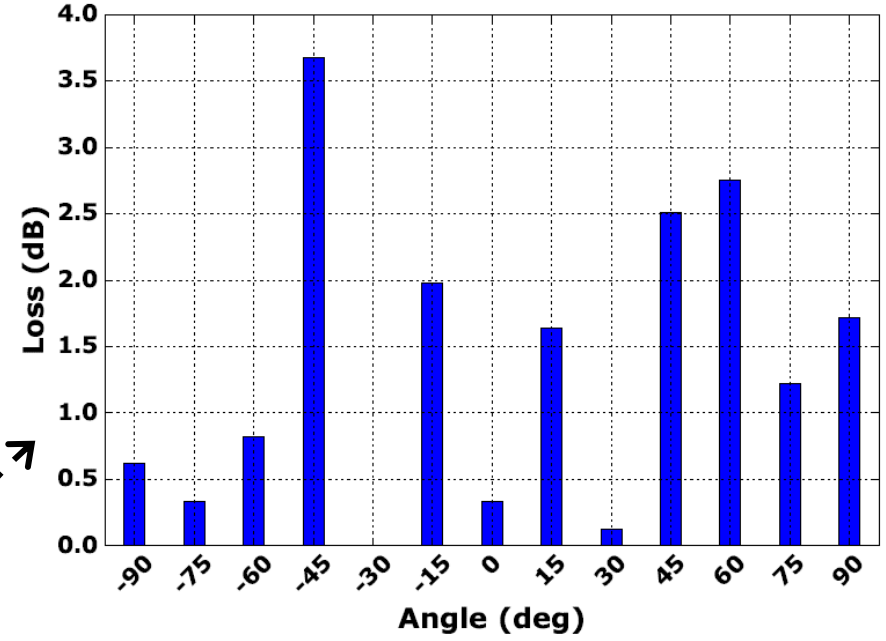
Link Performance: Orientation (Tx)



(a) Performance for different Tx angles with both routers.

NIGHTHAWK maintains higher data rates between [-45, 30] deg.

TALON maintains >1 Gbps rates almost at all angles

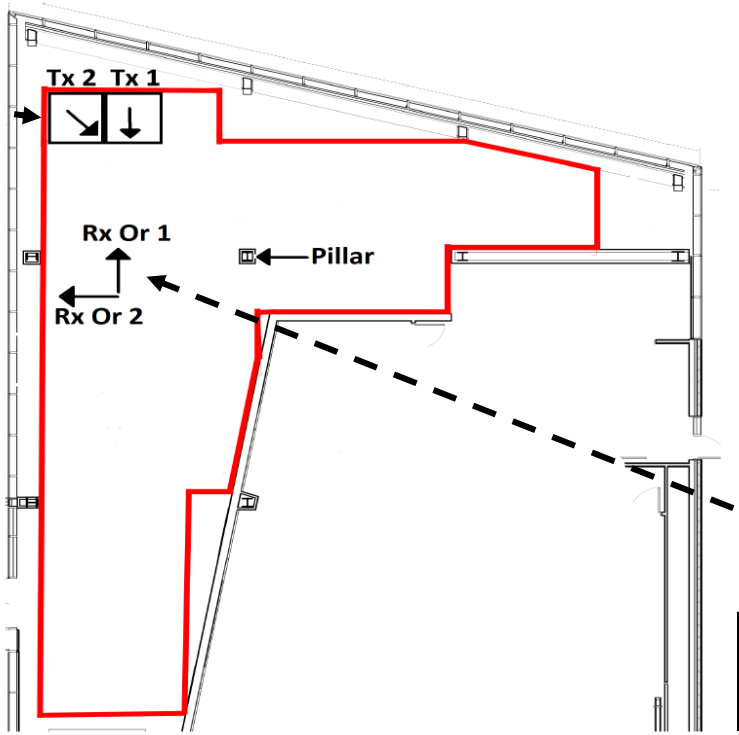


(b) Loss due to suboptimal Tx sector with Talon for different Tx angles.

TALON still selects mostly sub-optimal Tx sectors

Coverage: Experiment Setup

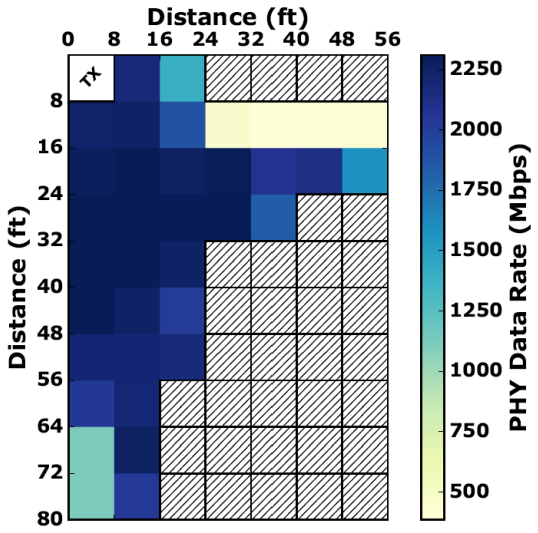
Two Tx (AP) positions:
Tx1 and Tx2



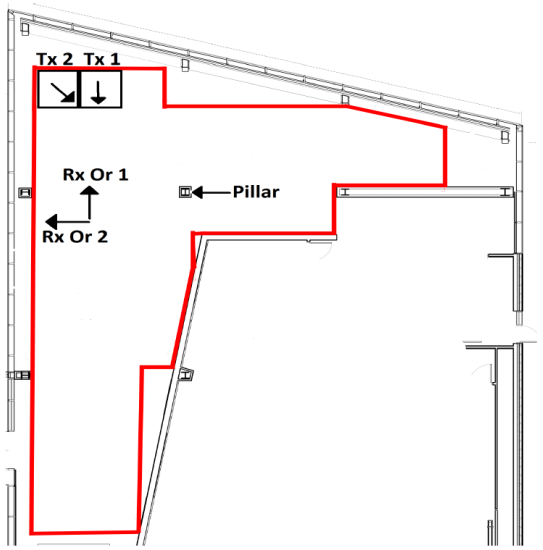
Two Rx (Laptop) orientations:
Rx Or1 and Rx Or 2

(a) Lobby floorplan.

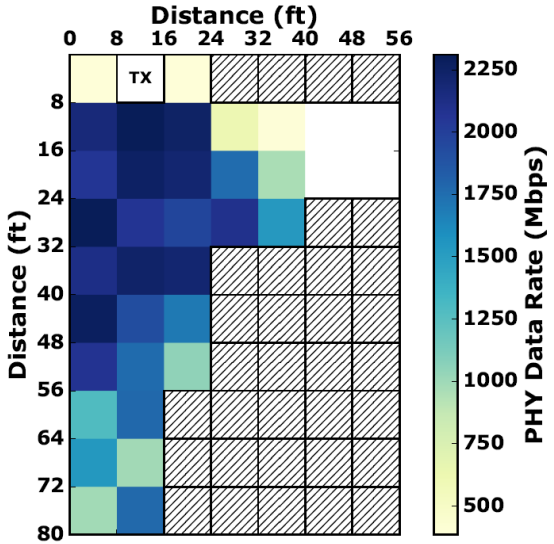
Coverage: Tx Orientation



(c) AP at Tx2, client orient. 1.

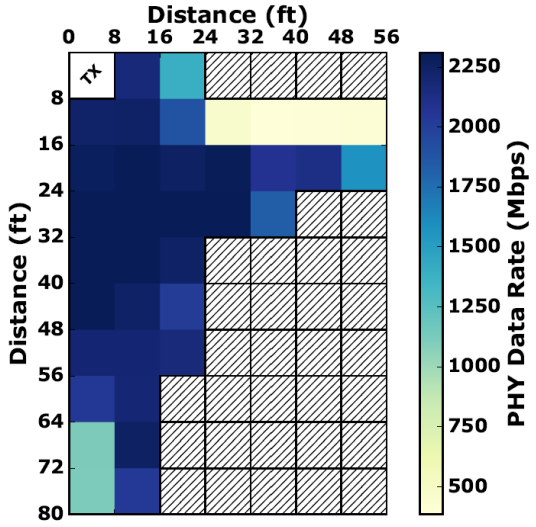


(a) Lobby floorplan.

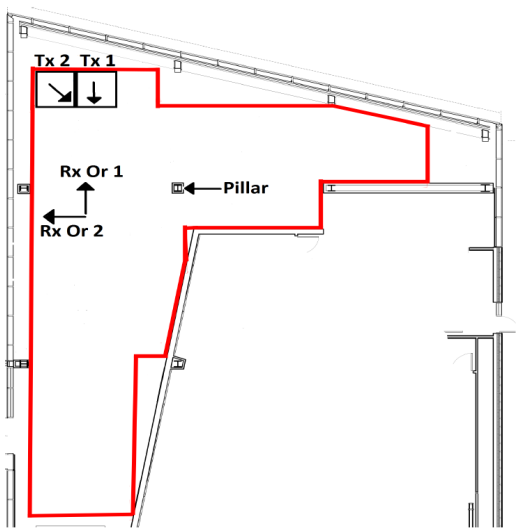


(a) AP at Tx1, client orient. 1.

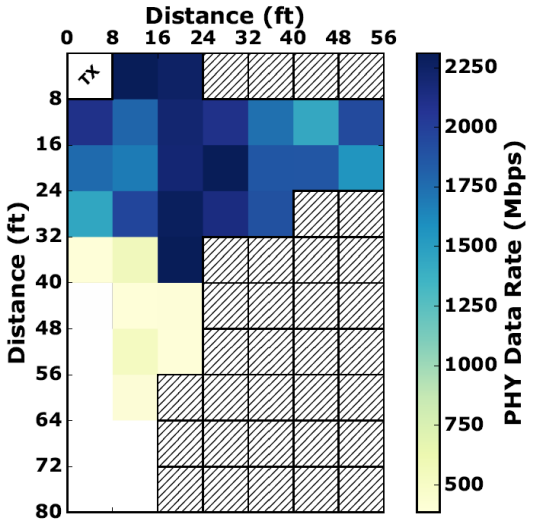
Coverage: Rx Orientation



(c) AP at Tx2, client orient. 1.



(a) Lobby floorplan.

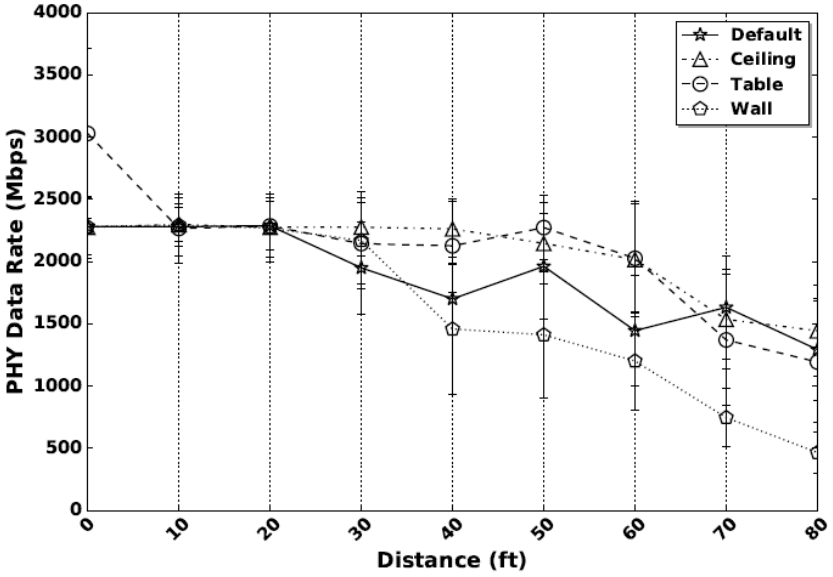


(d) AP at Tx2, client orient. 2.

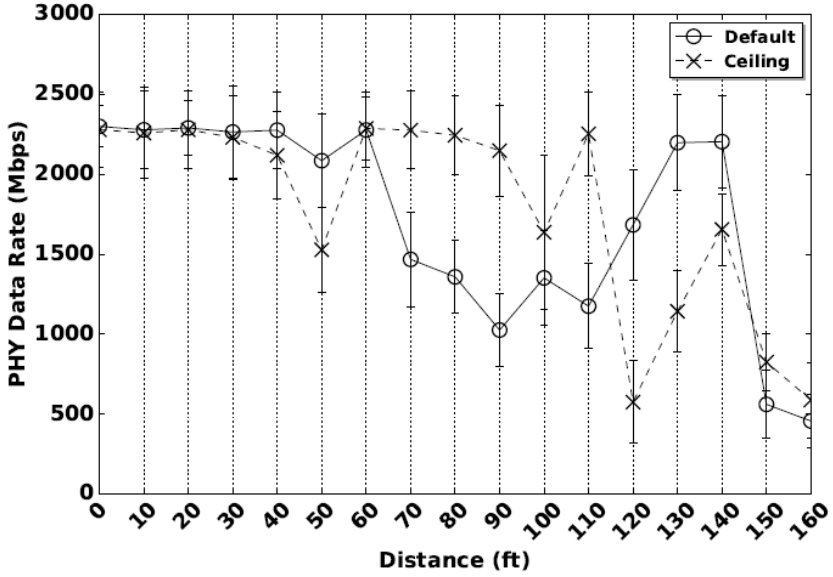
Access Point (AP) Placement

- Compare four placement options
  - A. **Default (used in most measurements in the paper)**
  - B. **Table (Home WiFi Networks)**
  - C. **Wall-mounted (Enterprise WiFi Networks)**
  - D. **Ceiling-mounted (Dense Enterprise WiFi Networks)**

Access Point (AP) Placement



(a) Lobby

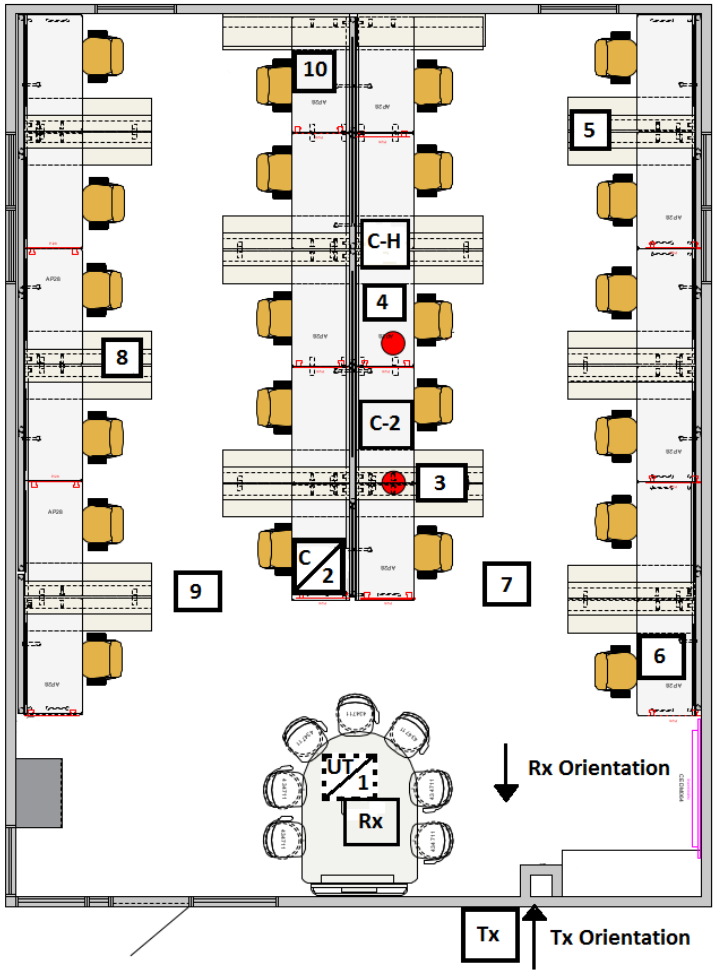


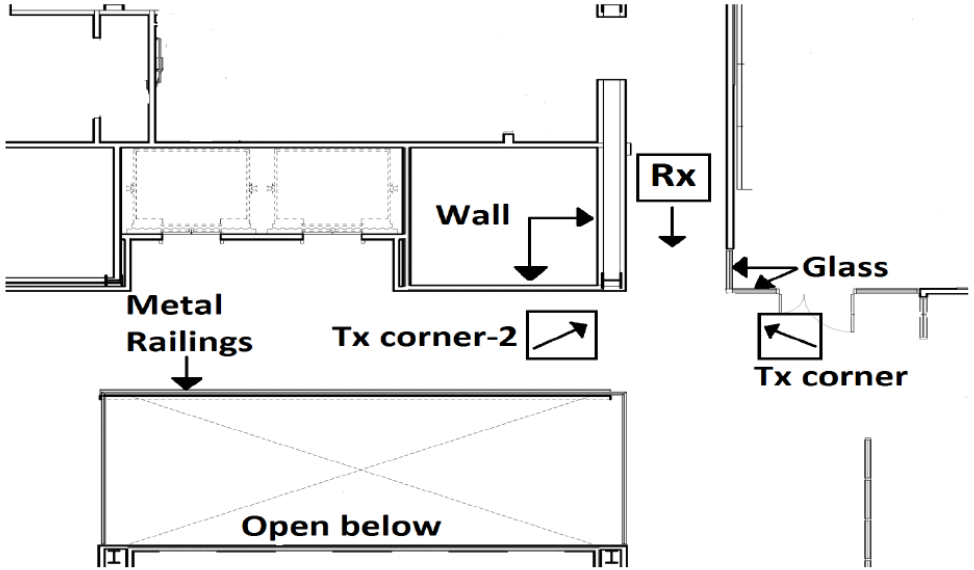
(b) Corridor

Table and Ceiling performs best >2.3 Gbps (up to 60 ft.)

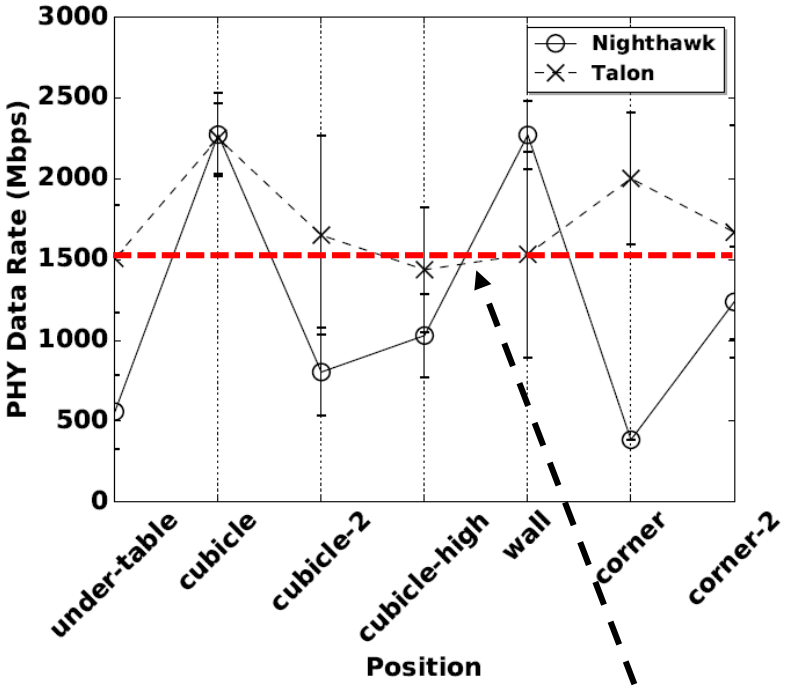
Ceiling performs better for < 60 ft. Default better over larger distances

AP Placement: NLOS Performance

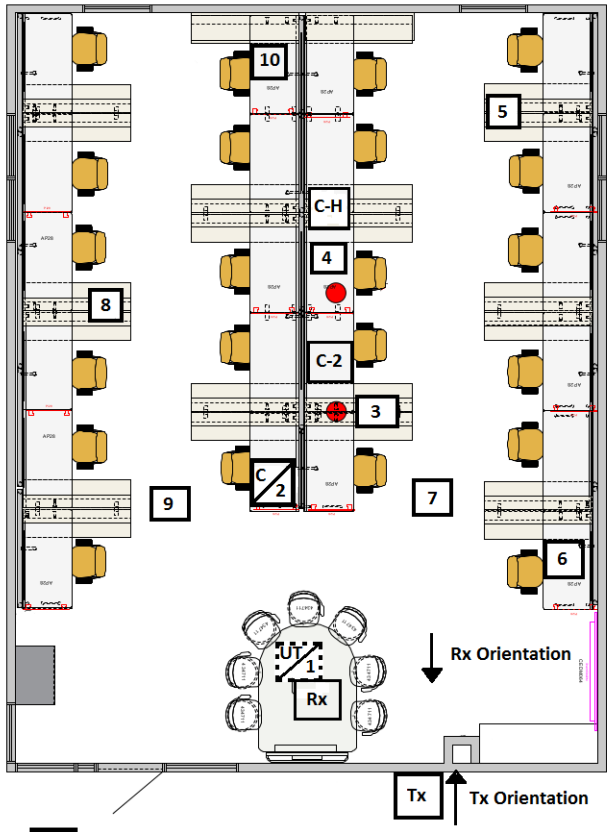


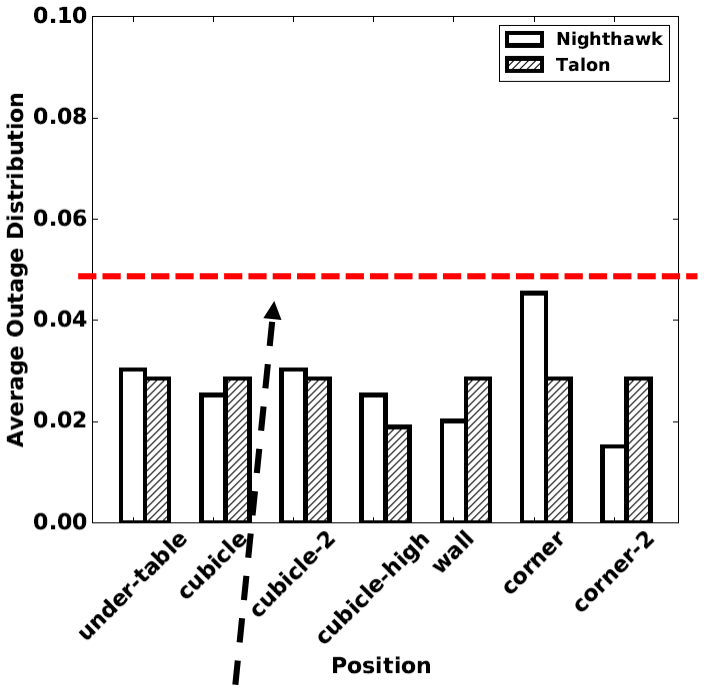


AP Placement: Communication through Reflections



(a) Average PHY Data Rate.



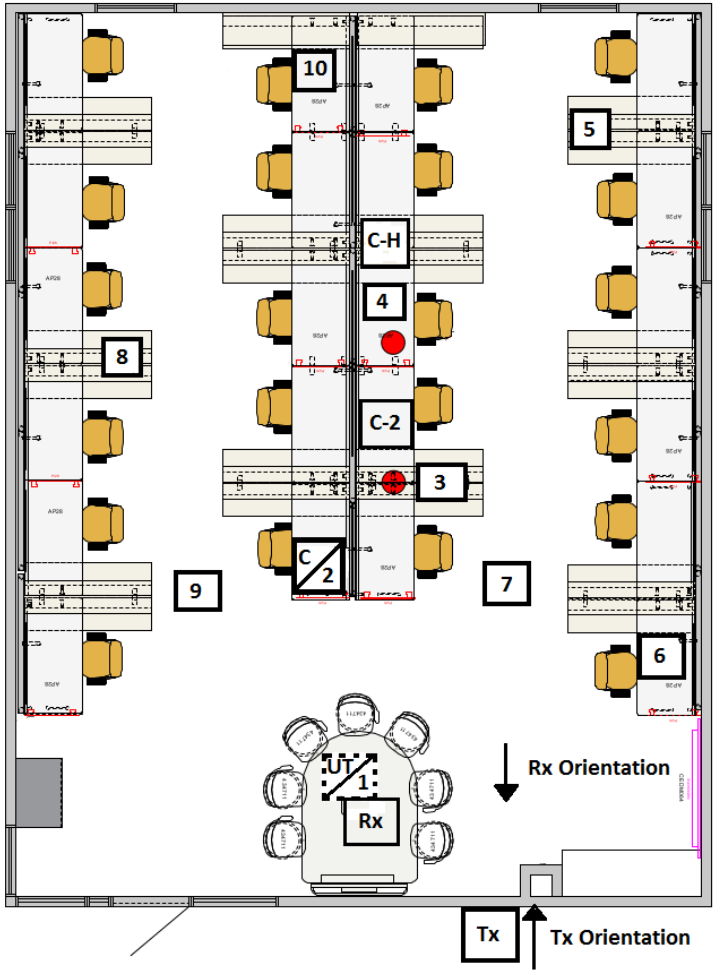


(b) Percentage of outage time.

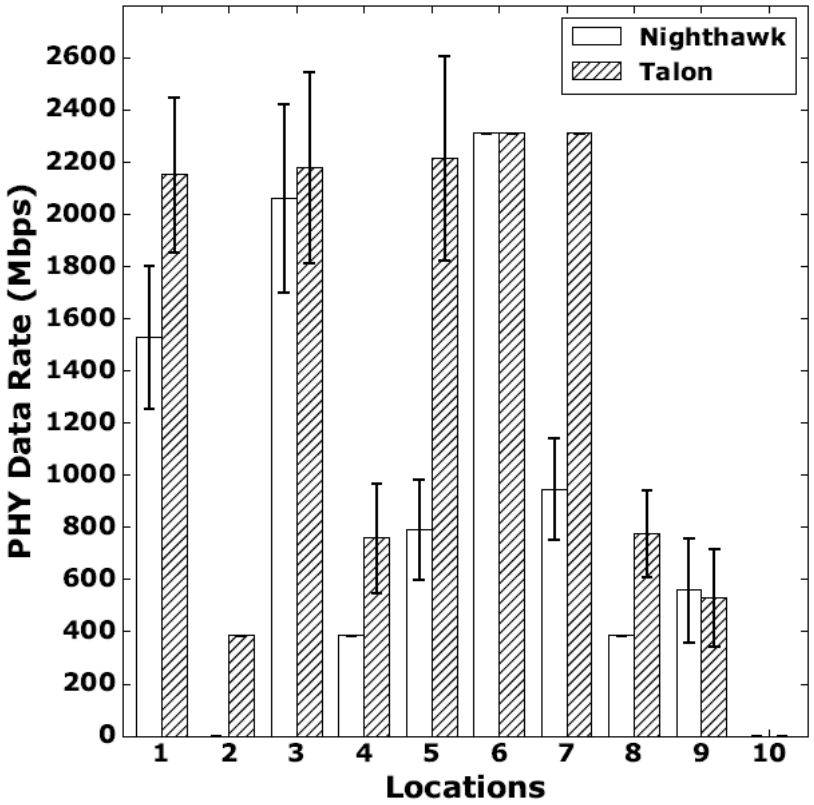
TALON maintains >1.5 Gbps rates in ALL topologies

Outage time is upper bounded by 5% in ALL topologies

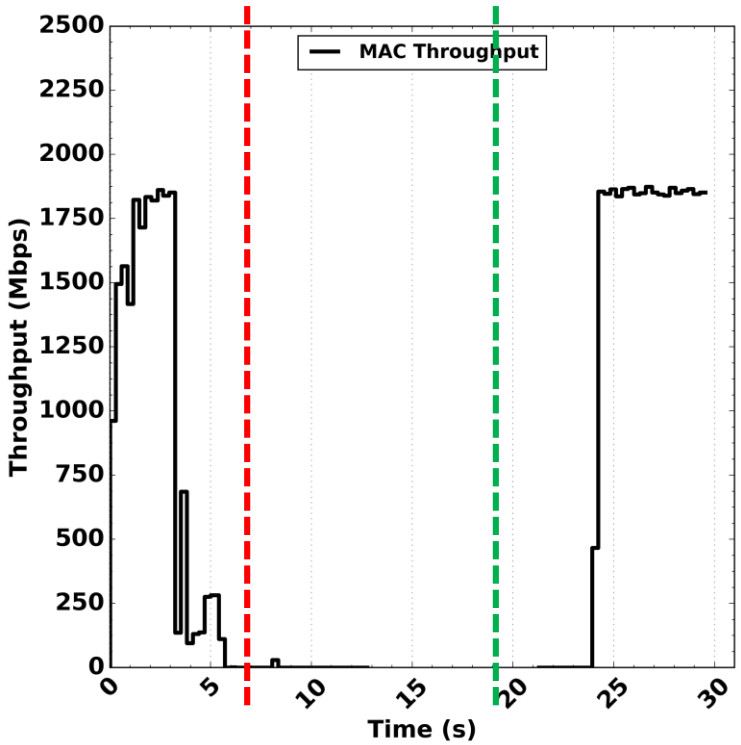
AP Placement: Communication through Walls



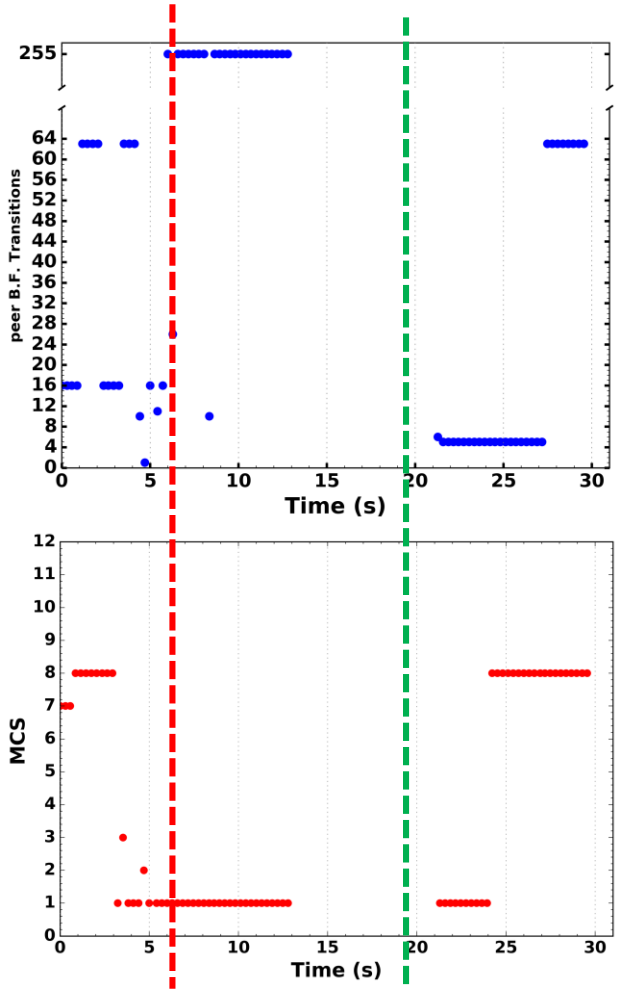
Variation in performance from 0 Mbps to 2.3 Gbps



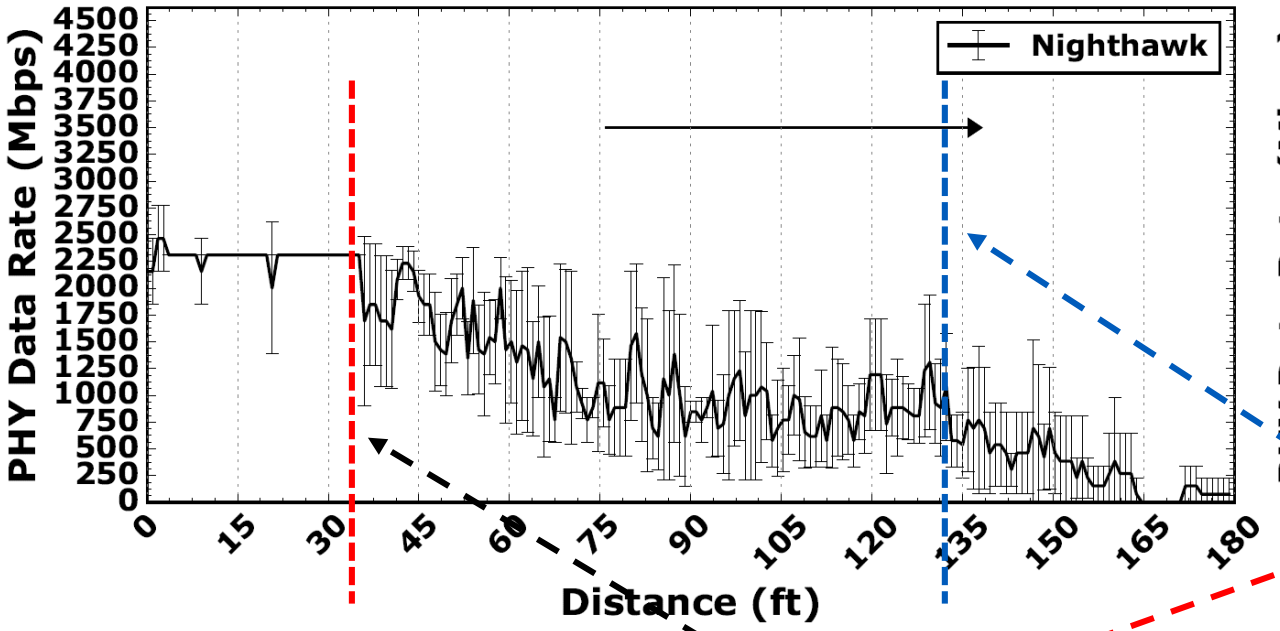
Blockage: Mobile Client, Wall Blockage

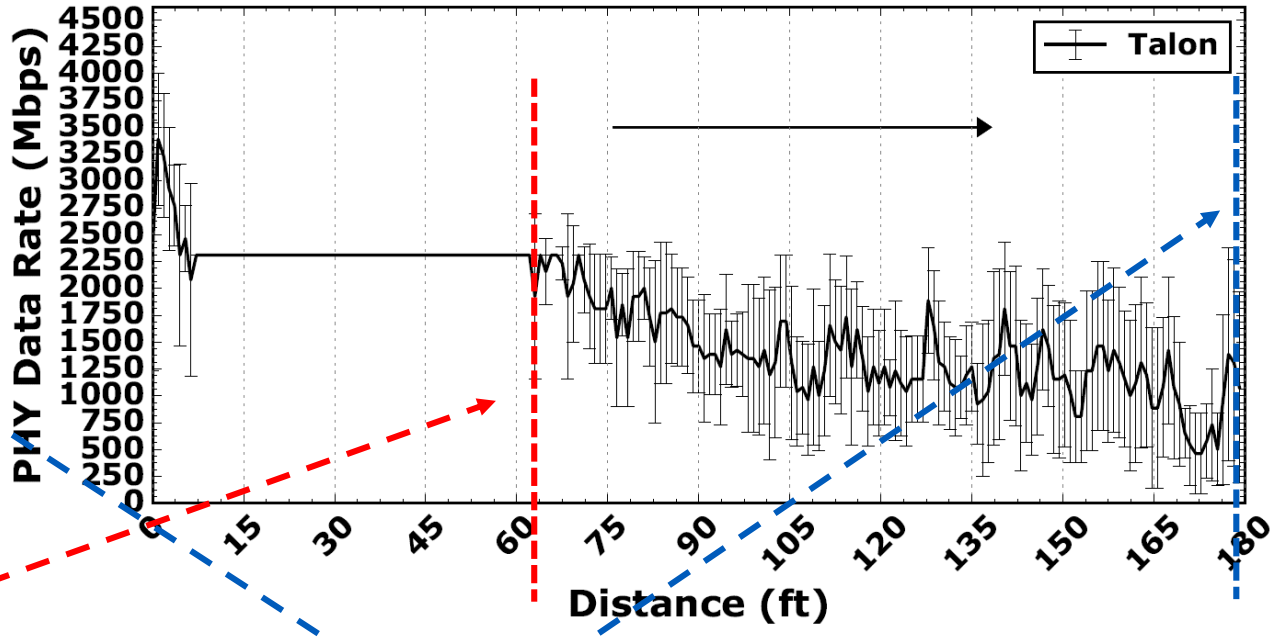


Too many SLS failures makes the driver abandon re-connection



Mobility: Away from the AP

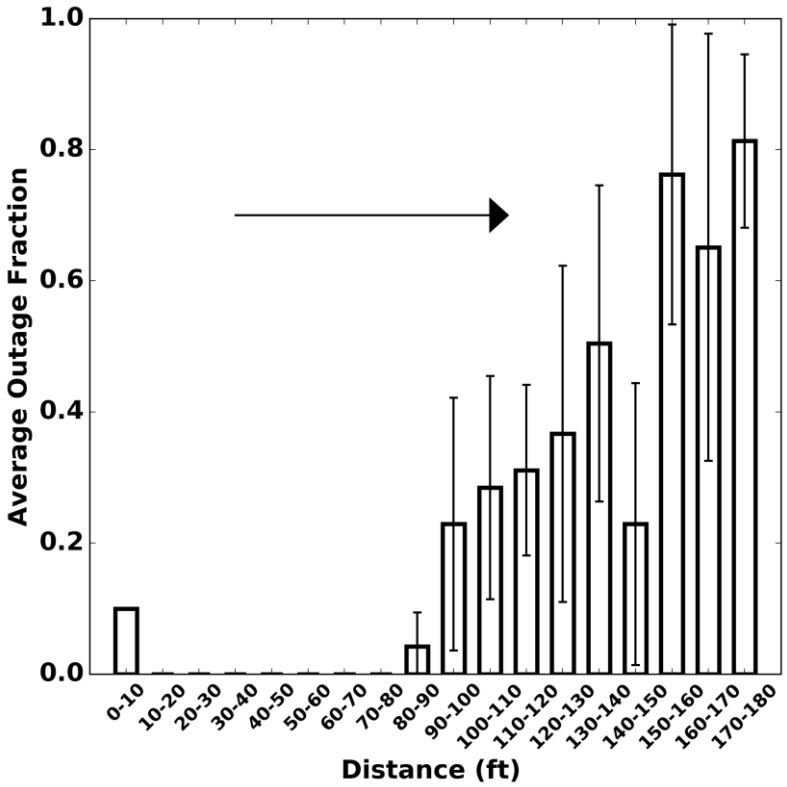


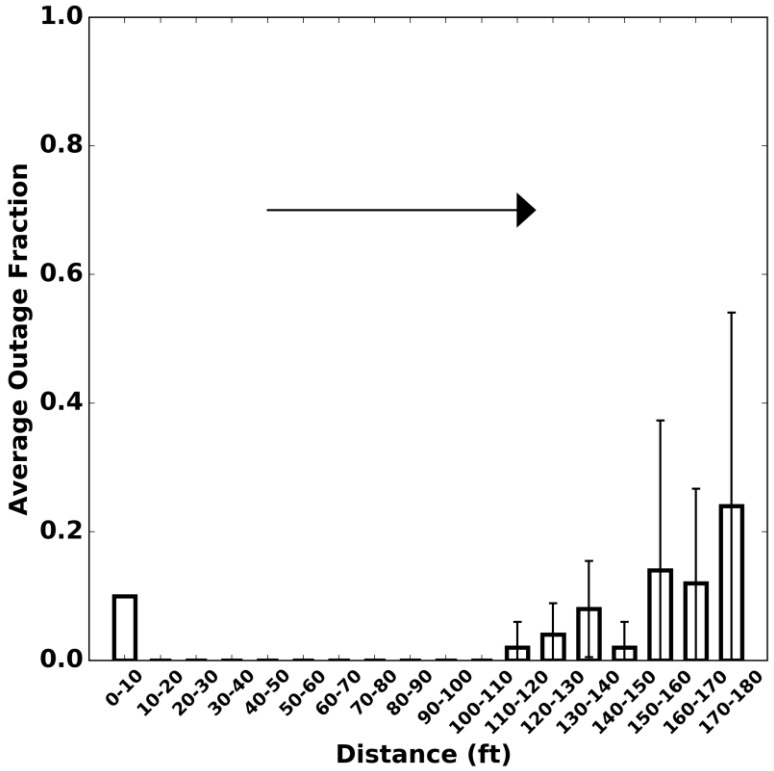


TALON: >2.3 Gbps up to 67 ft.
NIGHTHAWK: >2.3 Gbps up to 37 ft.

TALON: >1 Gbps up to 180 ft.
NIGHTHAWK: >1 Gbps up to 135 ft.

Mobility: Away from the AP [Beamforming Failures]

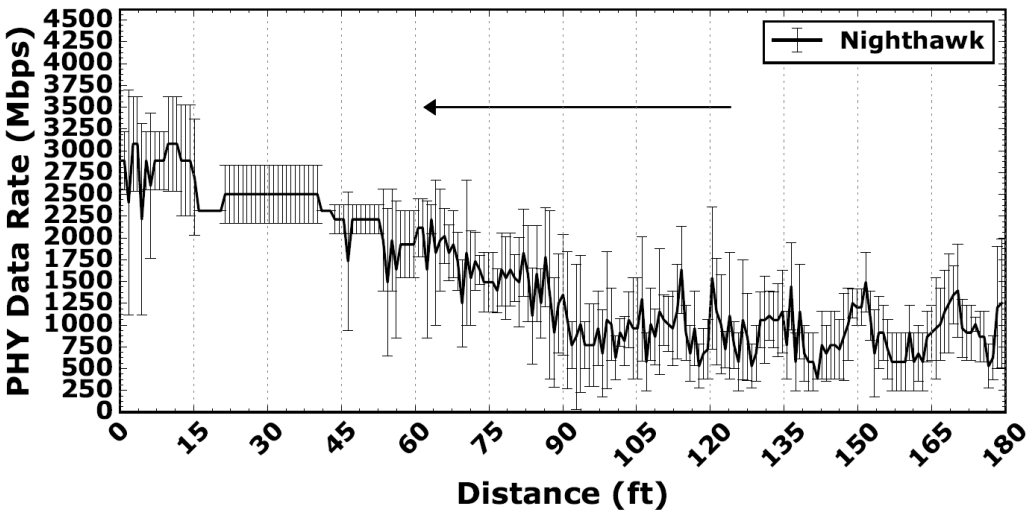


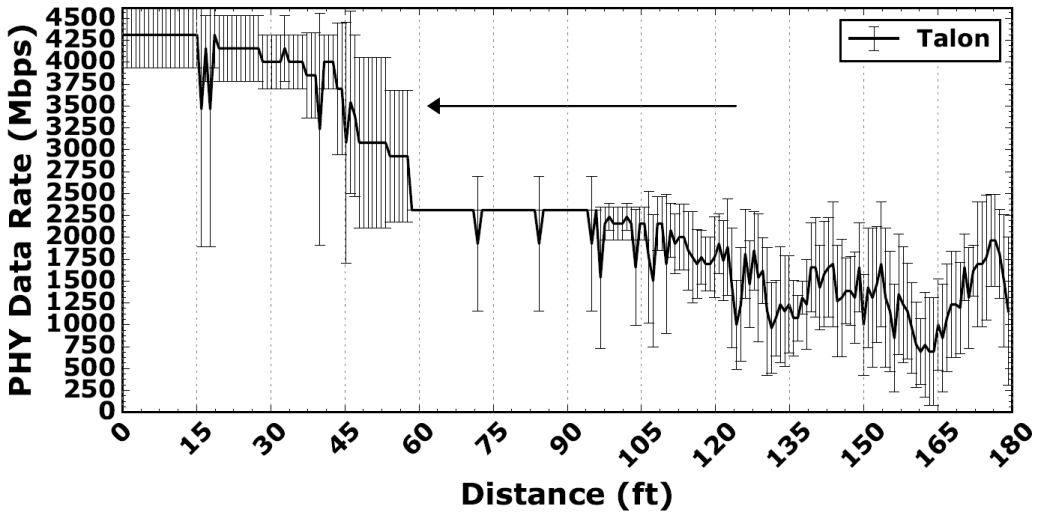


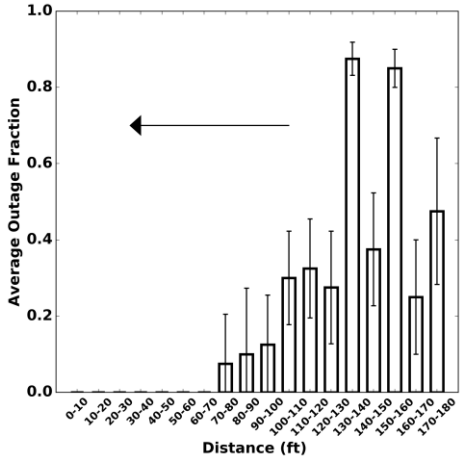
SQI changes **falsely** trigger beam-adaptation

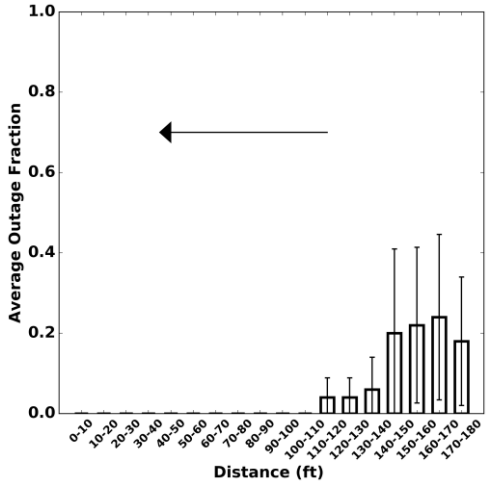
Beamforming failures hurt performance !

Mobility: Towards the AP









Challenges: Summary

Non-critical Challenges

- ✓ Transient human blockage has minimal impact

  802.11ad COTS devices perform frequent sector sweeps

- ✓ Sector sweeps take less than 1ms (blockage occurs at 100 ms timescale)

  Devices train only their Tx sectors and use quasi-omni Rx

- ✓ Through-wall communication is feasible and can allow a single AP to serve multiple rooms.

Challenges: Summary

Unexpected Challenges

- ✓ Interaction between beam training and rate control critical
  Incorrect beam and rate severely hurt performance

- ✓ Beam steering accuracy strongly degrades beyond 60 degress

- ✓ Placement of antenna inside AP dictates performance
  AP deployment should take AP form factor into consideration

Challenges: Summary

Expected Challenges

- ✓ Movement and rotation: Strong impact on performance
- ✓ Mobility scenarios cause link adaptation failures

  Loss differentiation critical to solve this
- ✓ Rate control just based on link quality indicators which can be uncorrelated to the 60 GHz channel state

THANK YOU!

Questions?