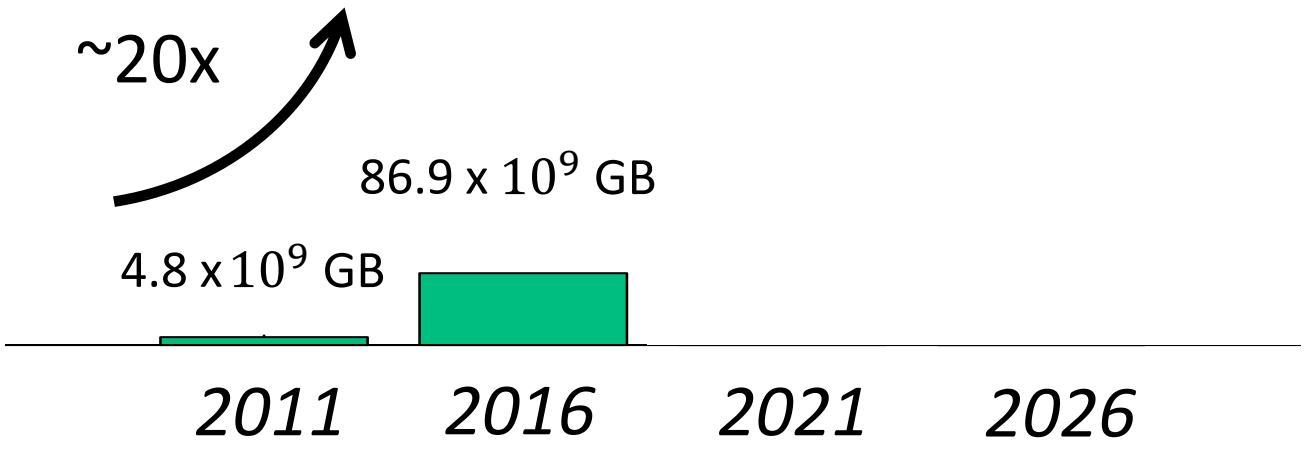
MUST: WiFi-Assisted 60 GHz Wireless Networks

Sanjib Sur, Ioannis Pefkianakis, Xinyu Zhang, Kyu-Han Kim

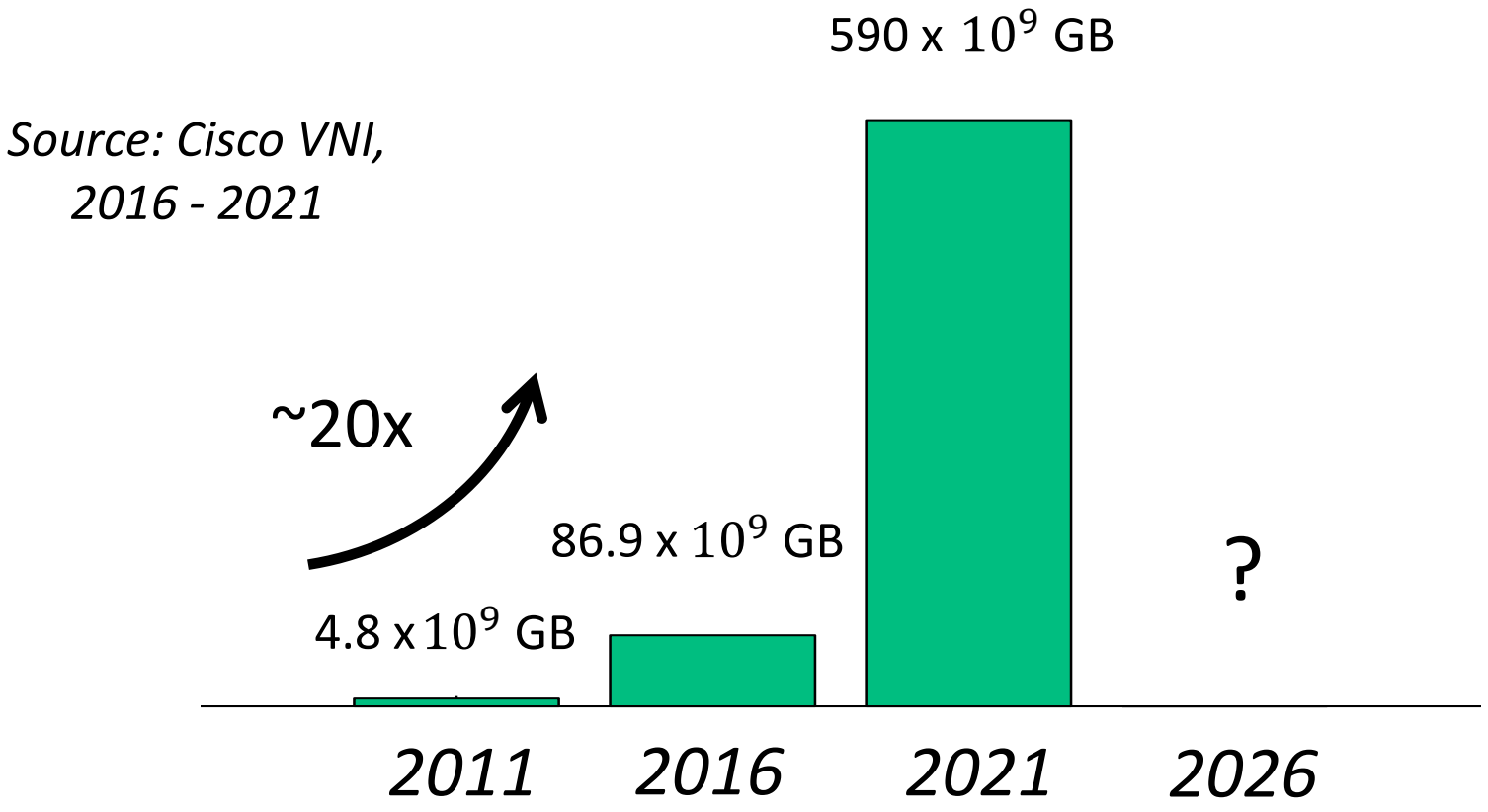
ACM MobiCom 2017

Global demand for mobile data is skyrocketing

Source: Cisco VNI, 2016 - 2021



Global demand for mobile data is skyrocketing



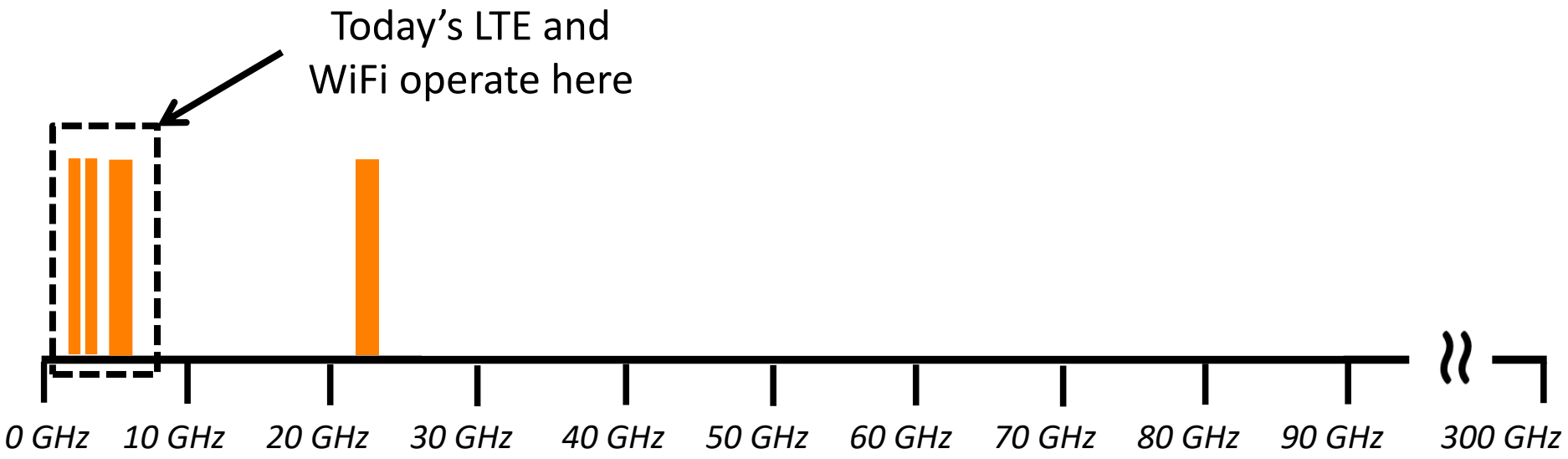
Nearly 10x increase in next 5 years and possibly 100x in the next 10 years

Millimeter-wave spectrum

Large *unlicensed spectrum* at millimeter-wave

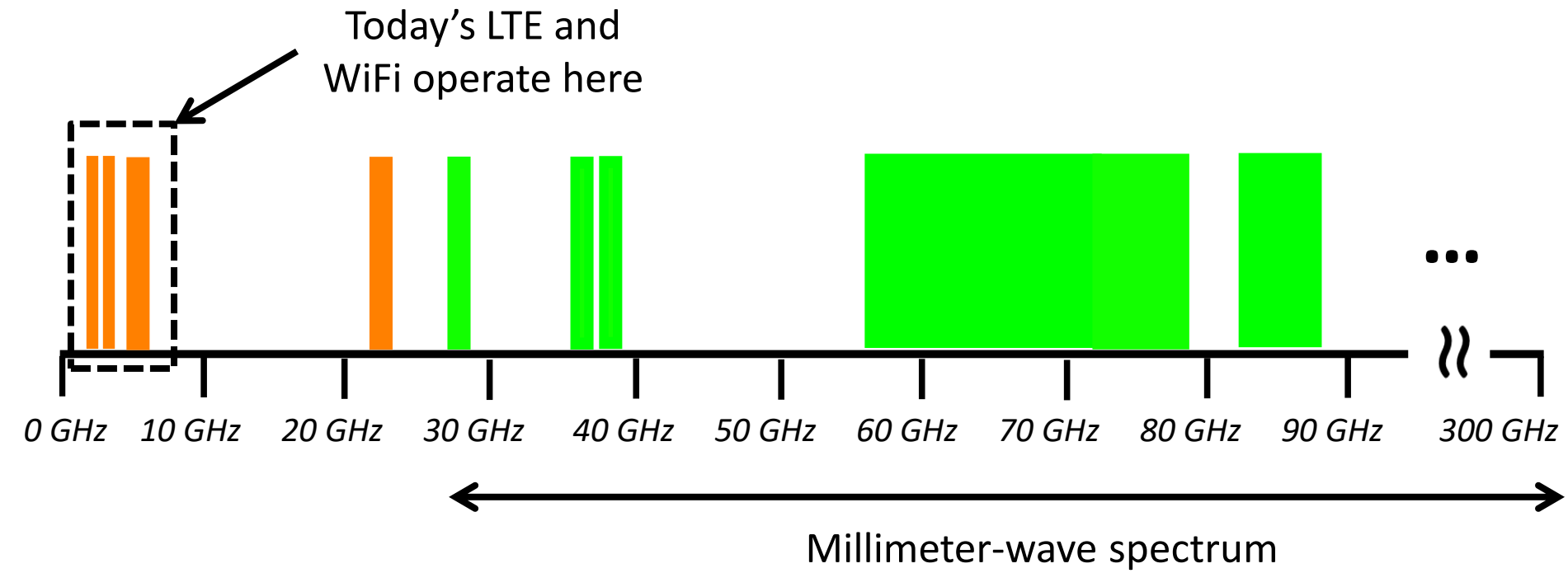
Millimeter-wave spectrum

Large *unlicensed spectrum* at millimeter-wave



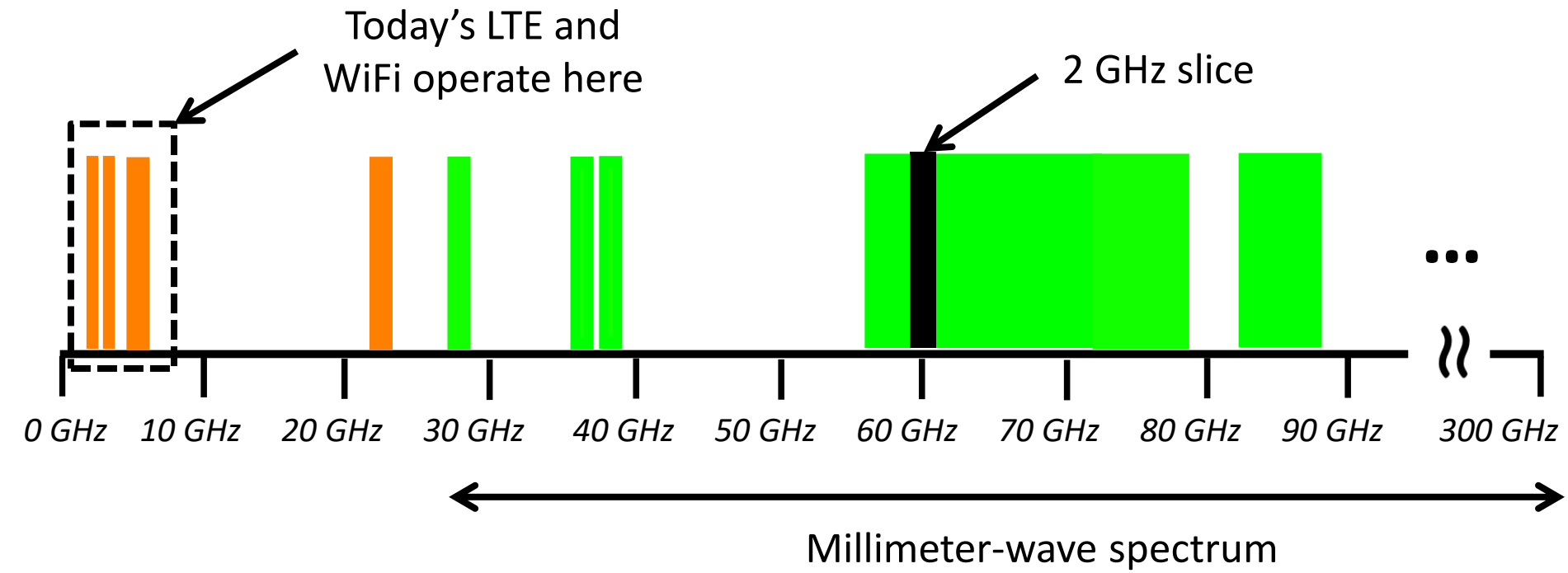
Millimeter-wave spectrum

Large *unlicensed spectrum* at millimeter-wave



60 GHz millimeter-wave spectrum

Large *unlicensed spectrum* at millimeter-wave



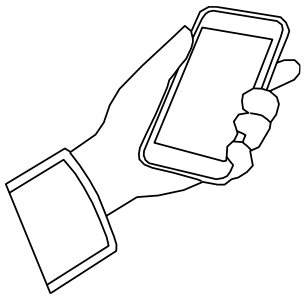
Off-the-shelf devices offer up to 7 Gbps of wireless bit-rate!

60 GHz link challenges

60 GHz link challenges
Link adaptation

60 GHz radios use phased-array antenna to focus the signal energy towards one direction

Large latency for link recovery

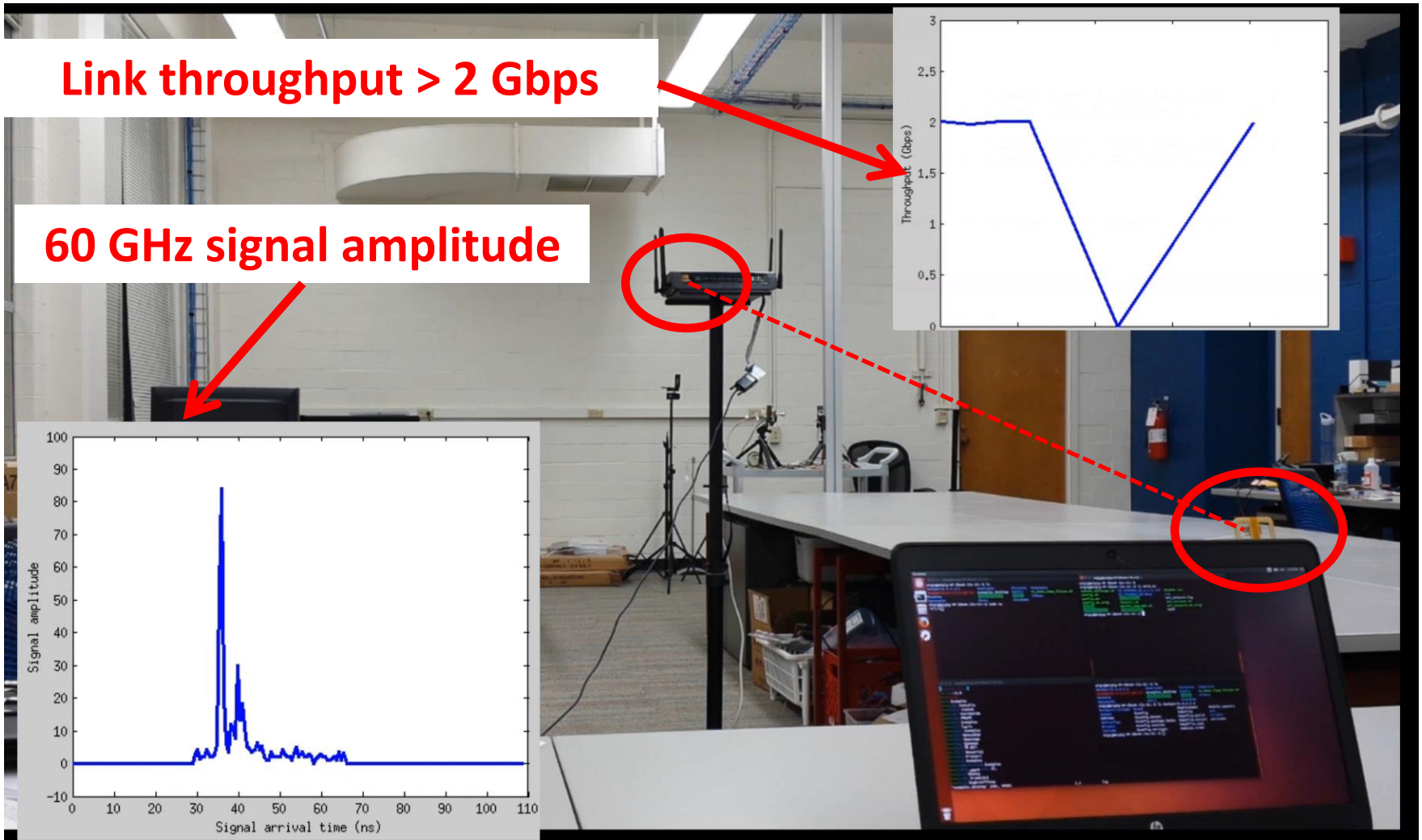


8 mm

17 mm

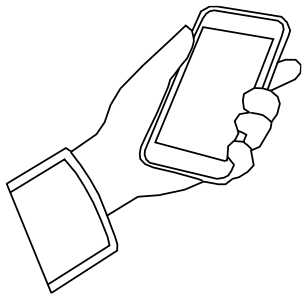
60 GHz link challenges
Blockage

Even aligning the beams does not guarantee link connectivity



Multi-band cooperation for stable 60 GHz link

MUST design principle: WiFi as an anchor for stable 60 GHz link



Challenges for multi-band cooperation

60 GHz link adaptation

Switching decision

Shared system resources

Challenges for multi-band cooperation

60 GHz link adaptation

Switching decision

Shared system resources

Challenges for multi-band cooperation

60 GHz link adaptation

Switching decision

Shared system resources

Challenges for multi-band cooperation

60 GHz link adaptation

Switching decision

Shared system resources

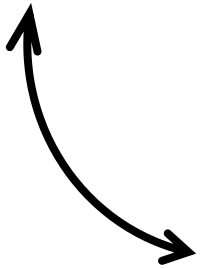
Challenges for multi-band cooperation

60 GHz link adaptation

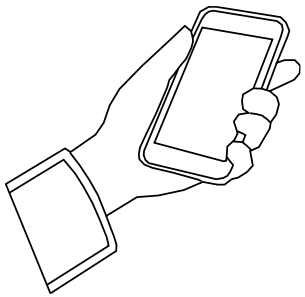
Switching decision

Shared system resources

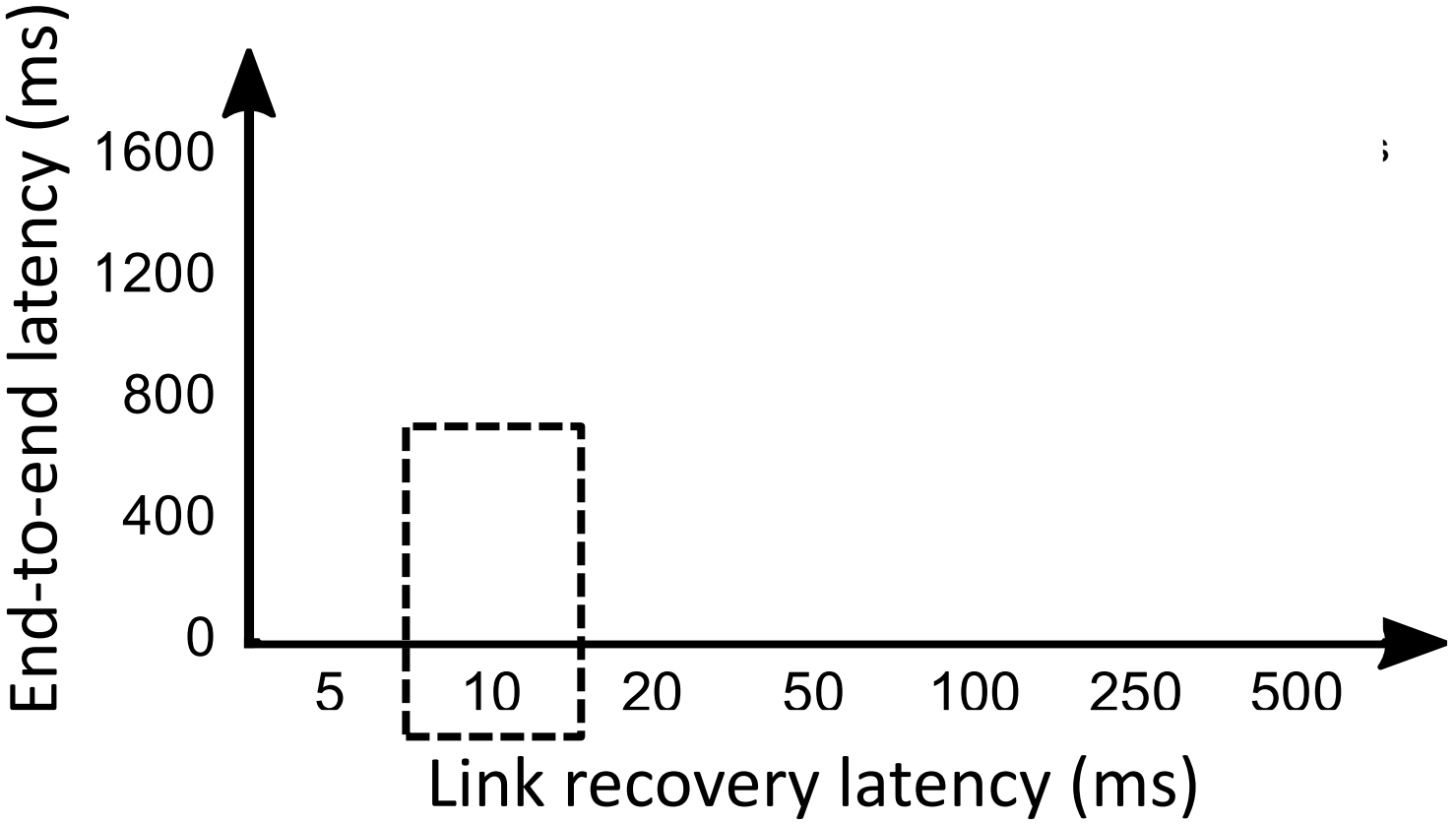
Challenge: 60 GHz link adaptation



10 ms – 1000 ms
link recovery latency

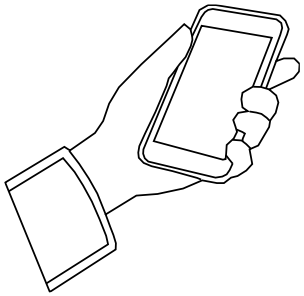


Link recovery latency amplifies Gbps TCP end-to-end latency



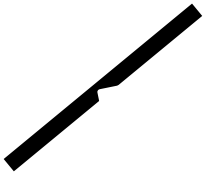
Even 10 ms recovery latency amplifies TCP end-to-end by 10x!

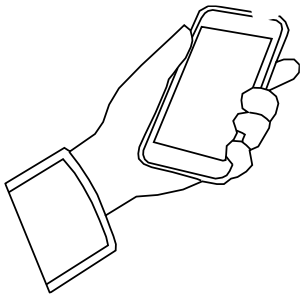
MUST proactive link adaptation



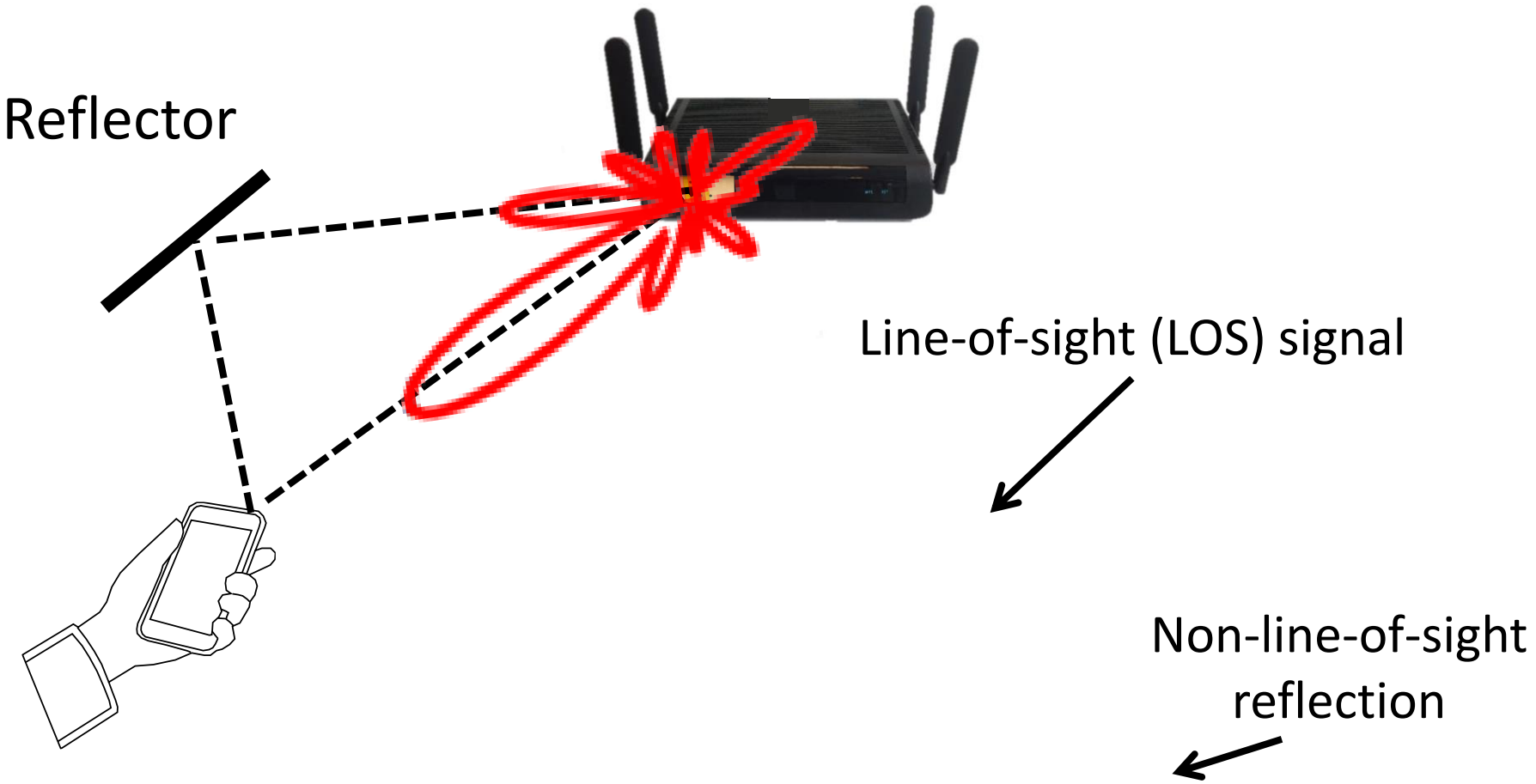
MUST proactive link adaptation

Reflector

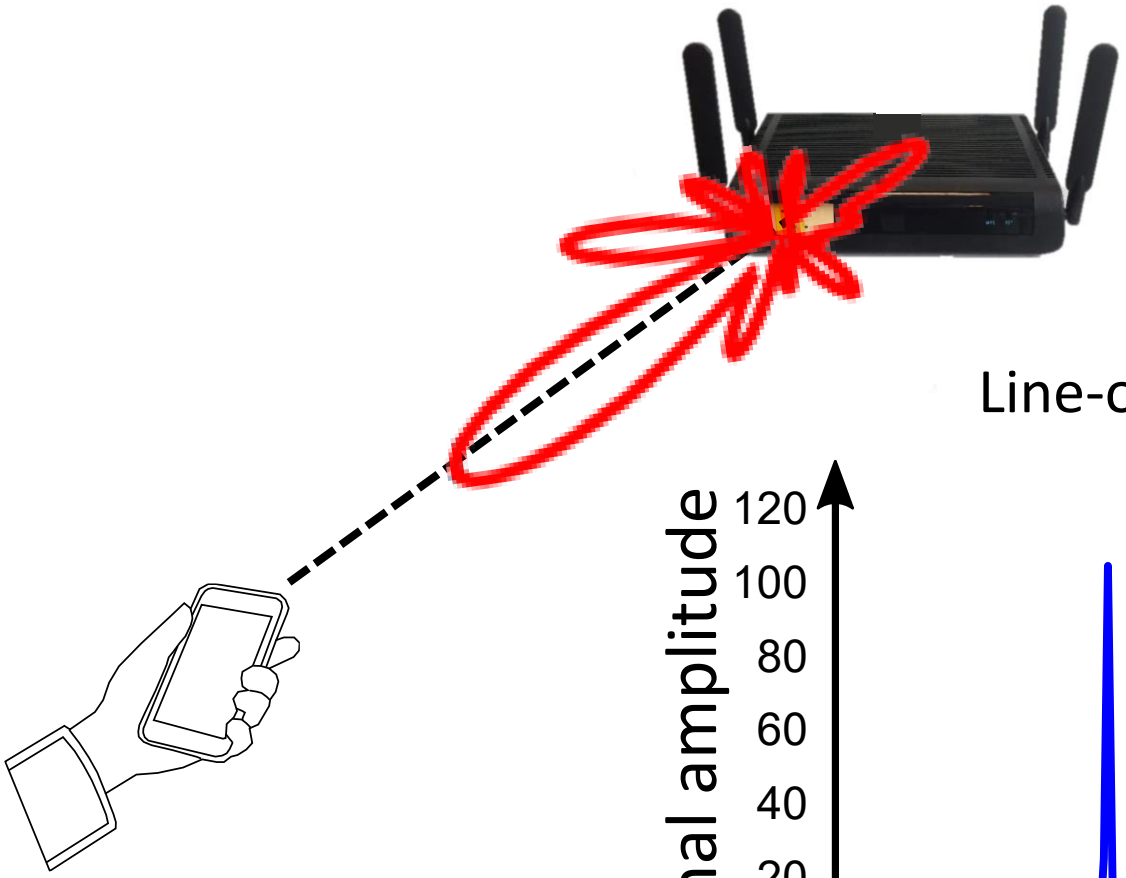




MUST proactive link adaptation

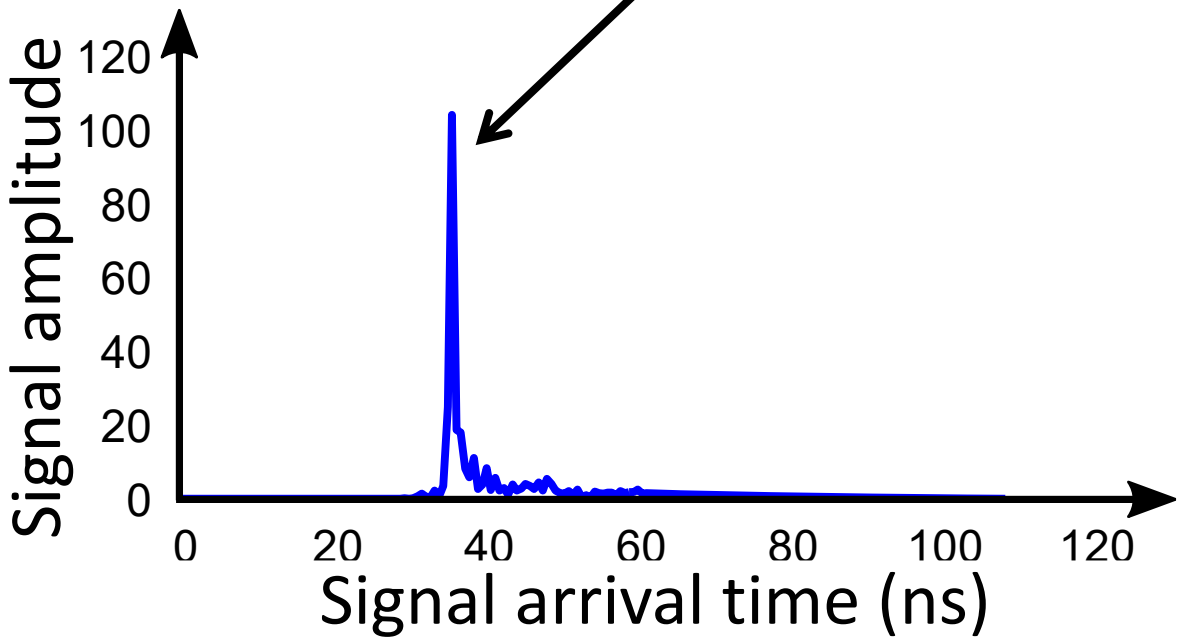


MUST proactive link adaptation

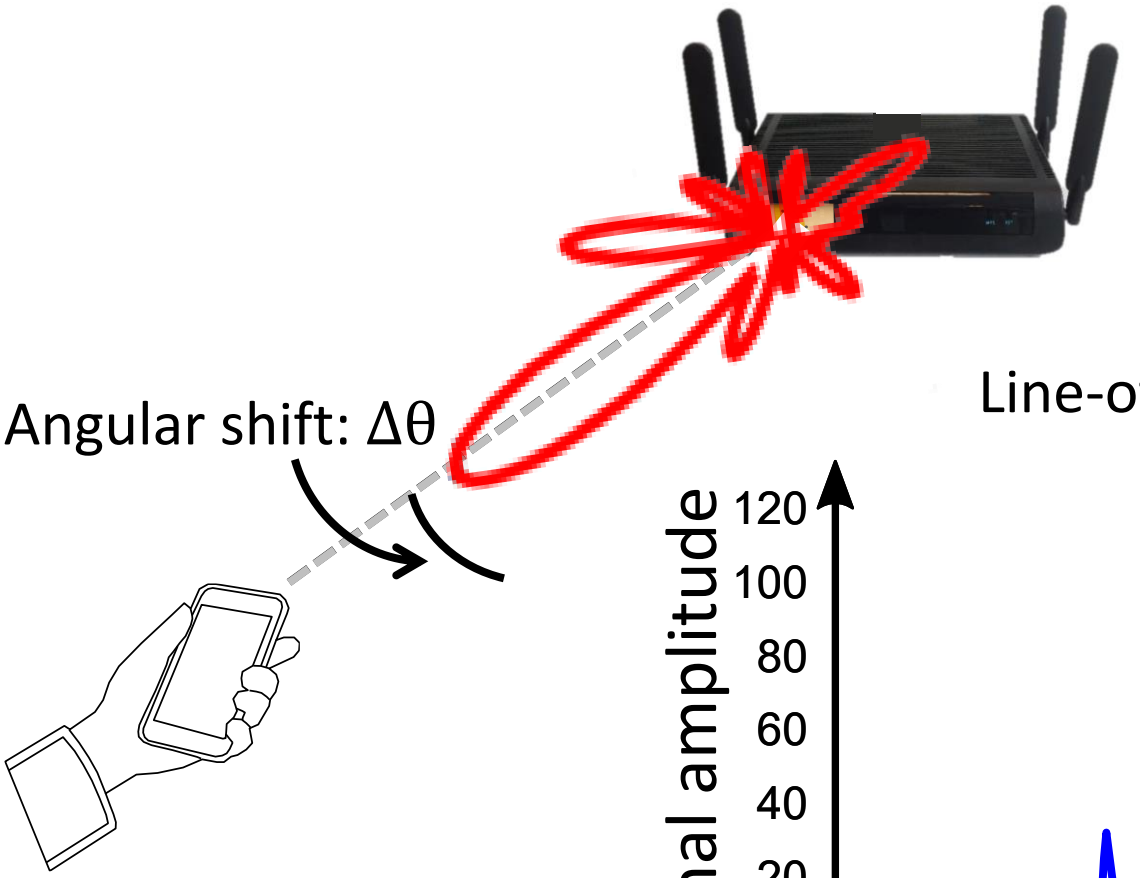


Throughput: 2 Gbps

Line-of-sight (LOS) signal



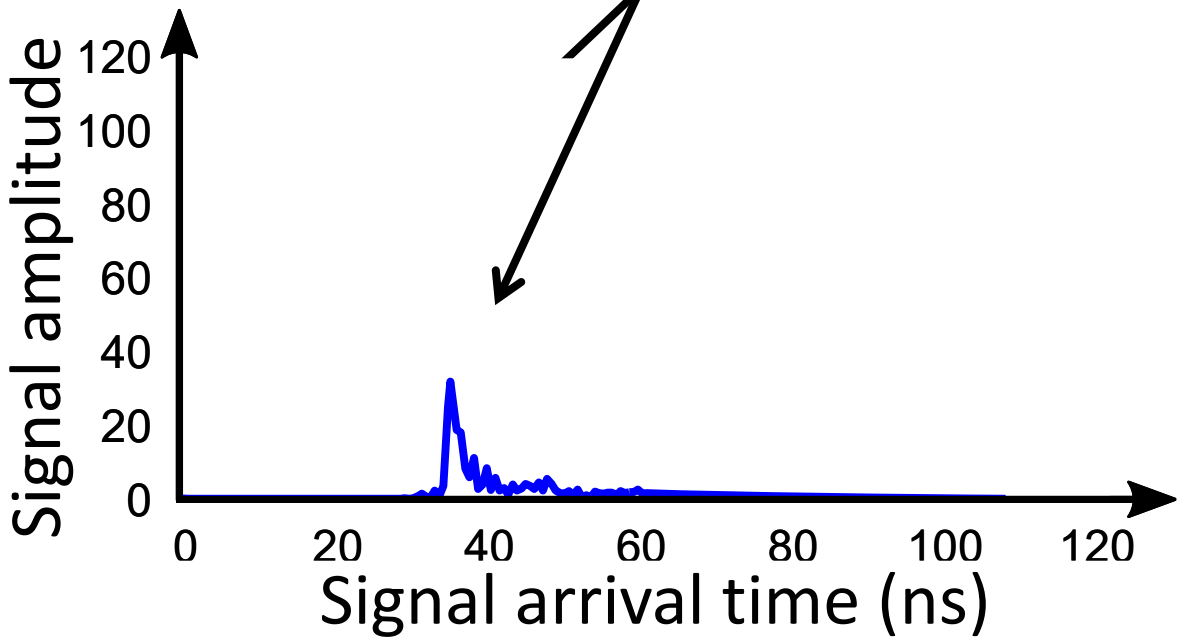
MUST proactive link adaptation



Throughput: 385 Mbps

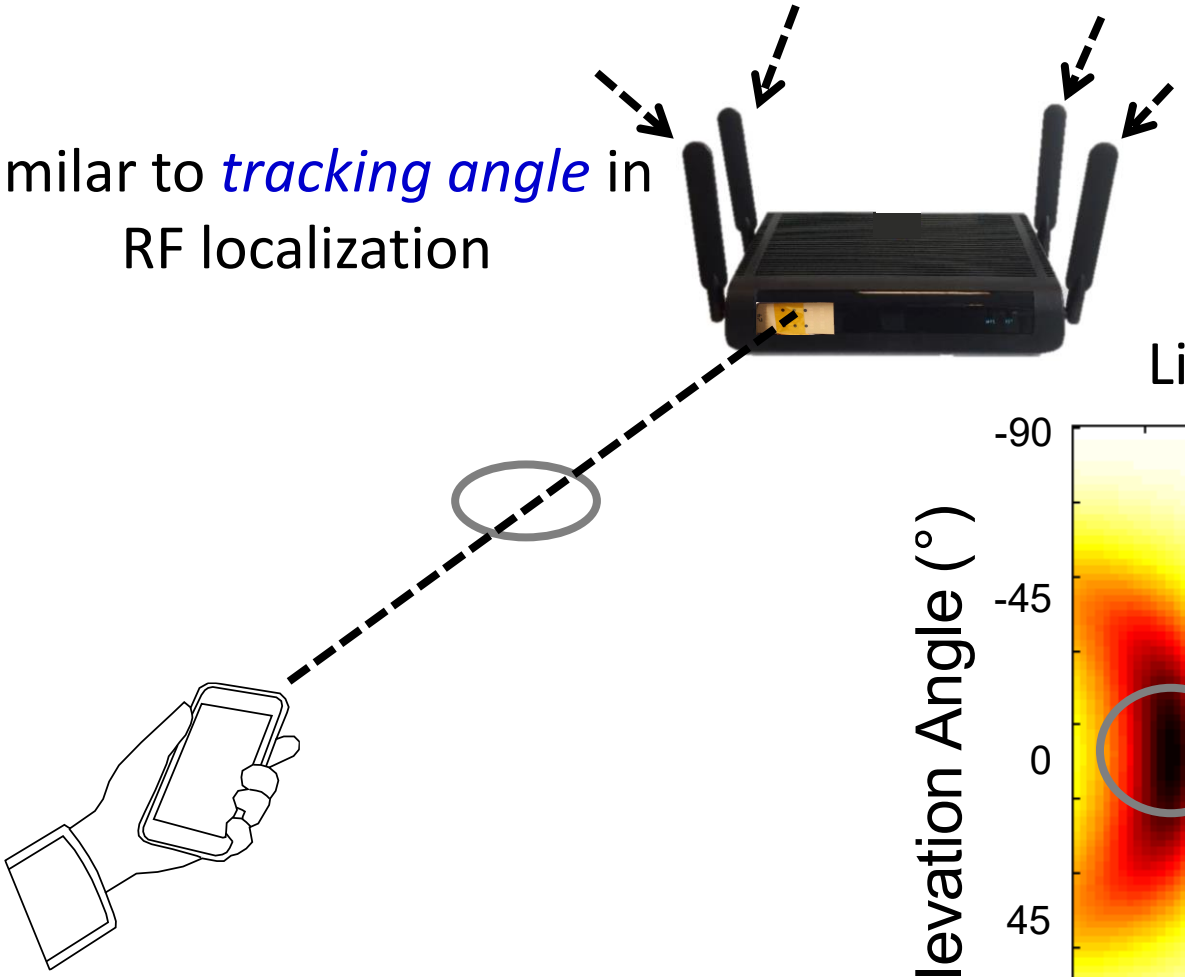
Angular shift: Δθ

Line-of-sight (LOS) signal

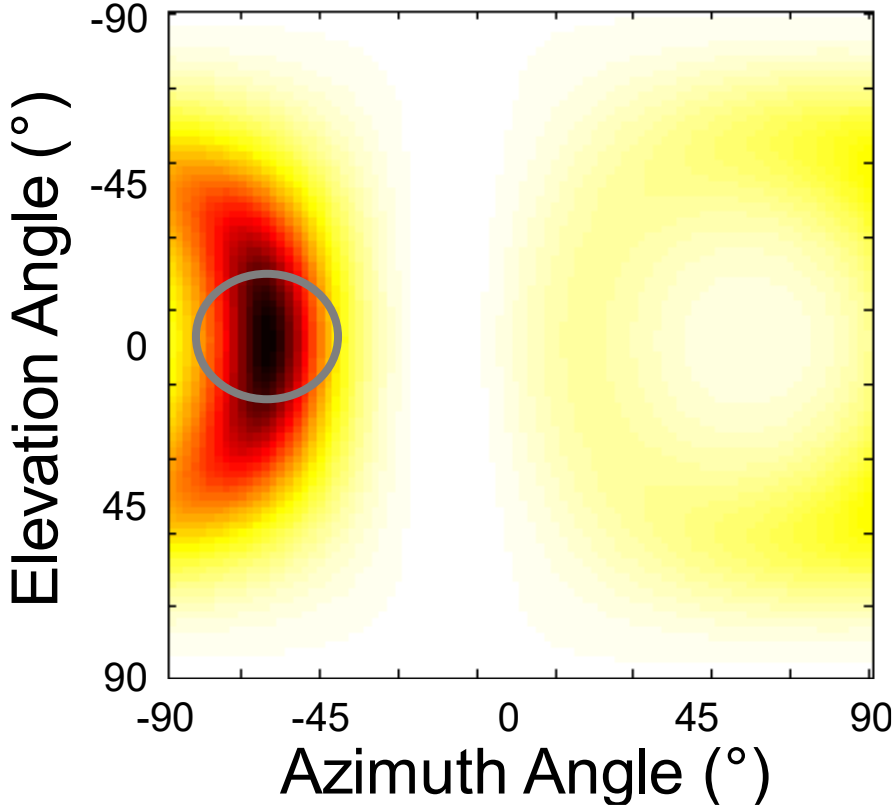


WiFi-assisted LOS path tracking

Similar to *tracking angle* in RF localization



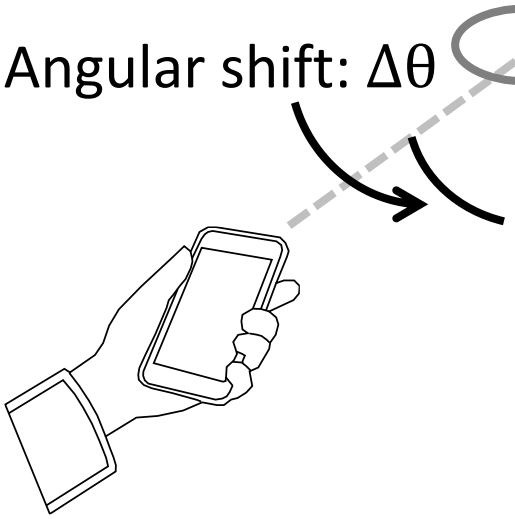
Likelihood of LOS path



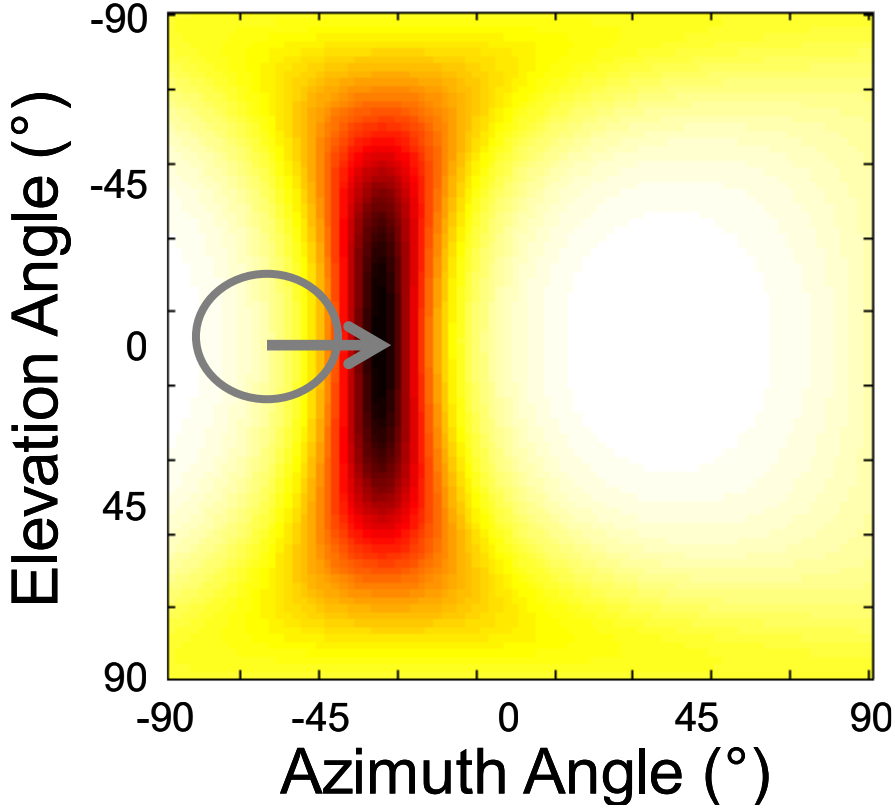
WiFi-assisted LOS path tracking

Similar to *tracking angle* in RF localization

Angular shift: $\Delta\theta$



Likelihood of LOS path



Challenges for multi-band cooperation

60 GHz link adaptation

Switching decision

Shared system resources

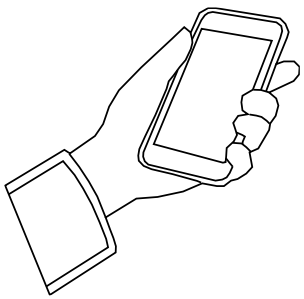
Challenges for multi-band cooperation

60 GHz link adaptation

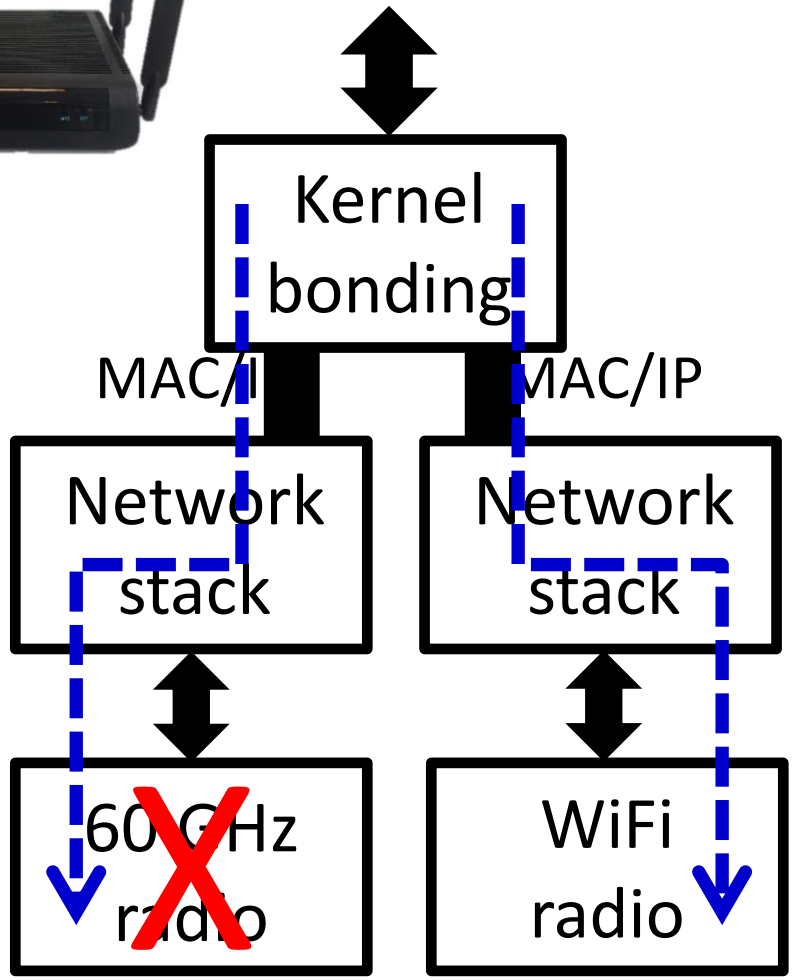
Switching decision

Shared system resources

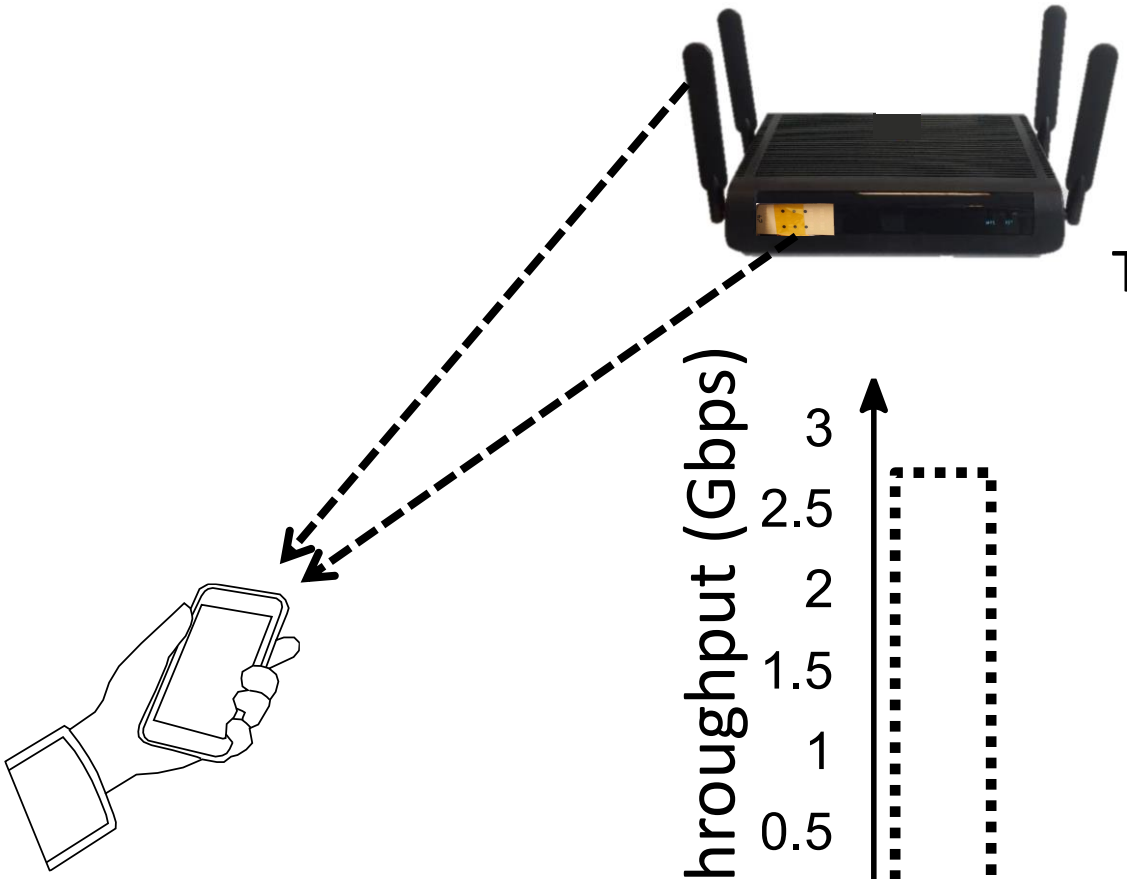
Dual transmission to avoid switching decision



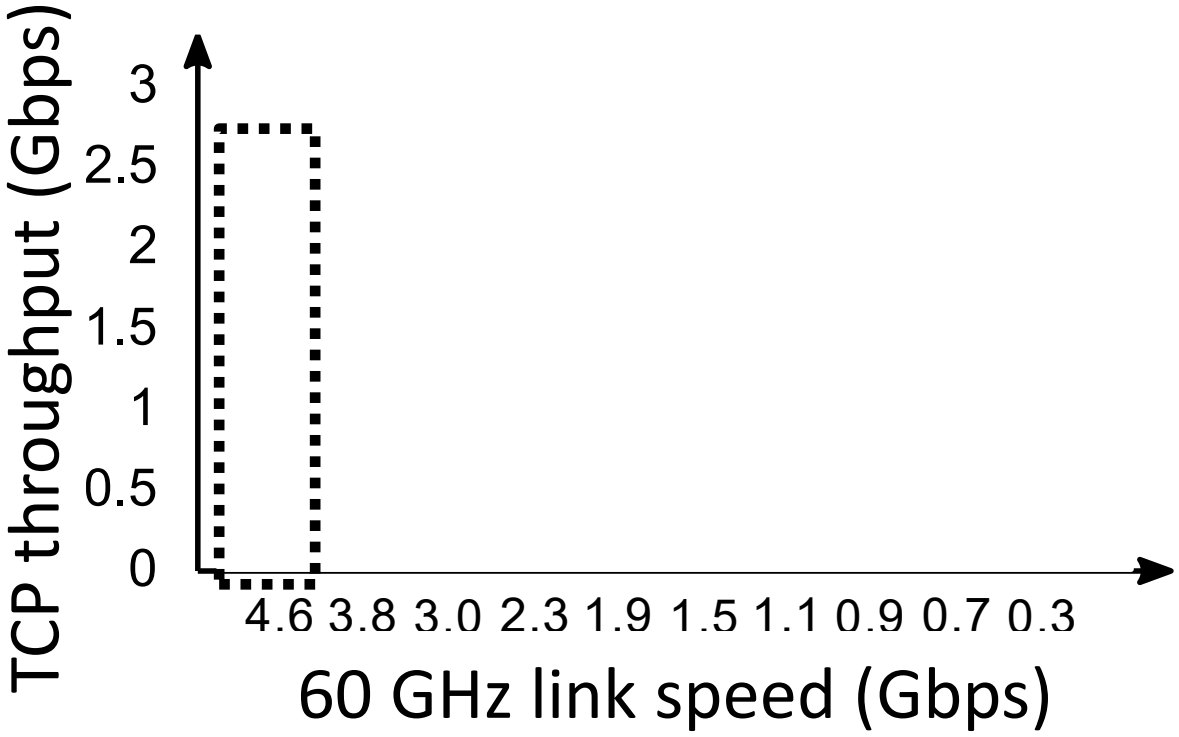
Single MAC/IP for
dual transmission



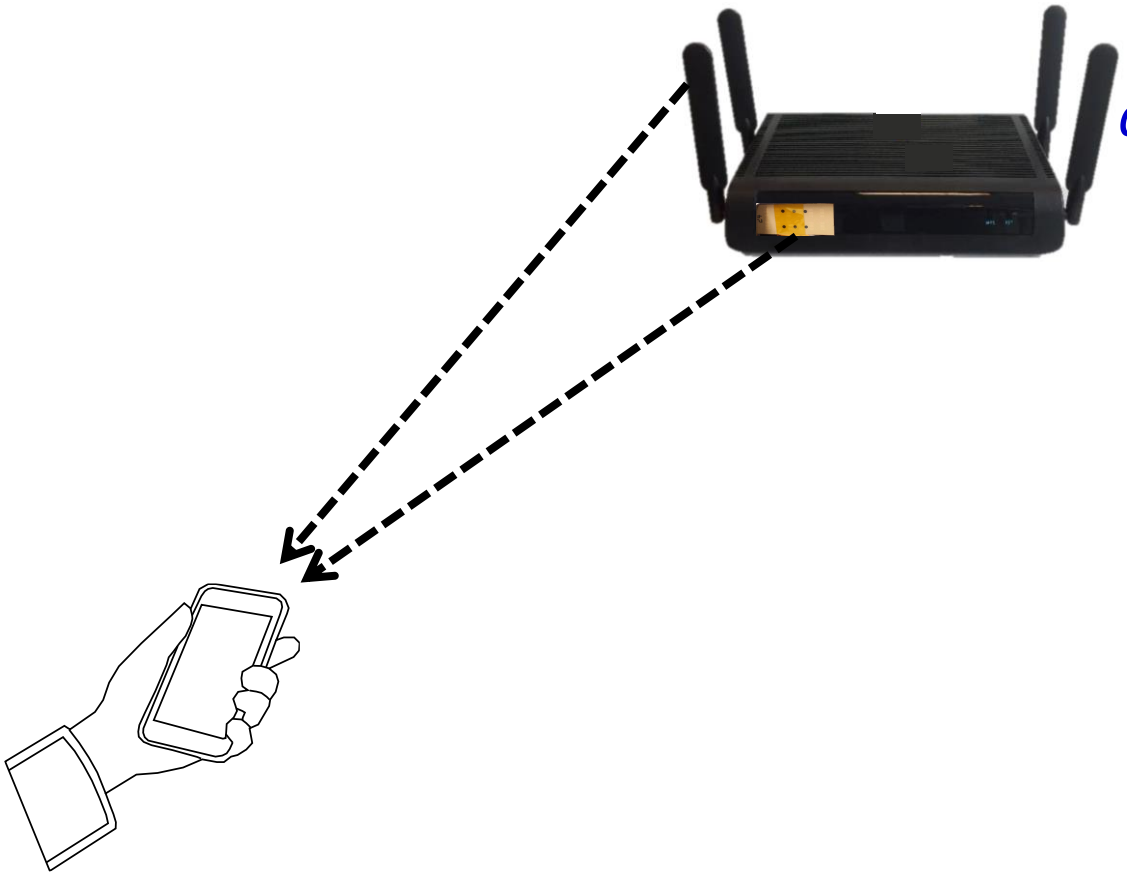
TCP throughput drops in dual transmission



TCP throughput drops 5x

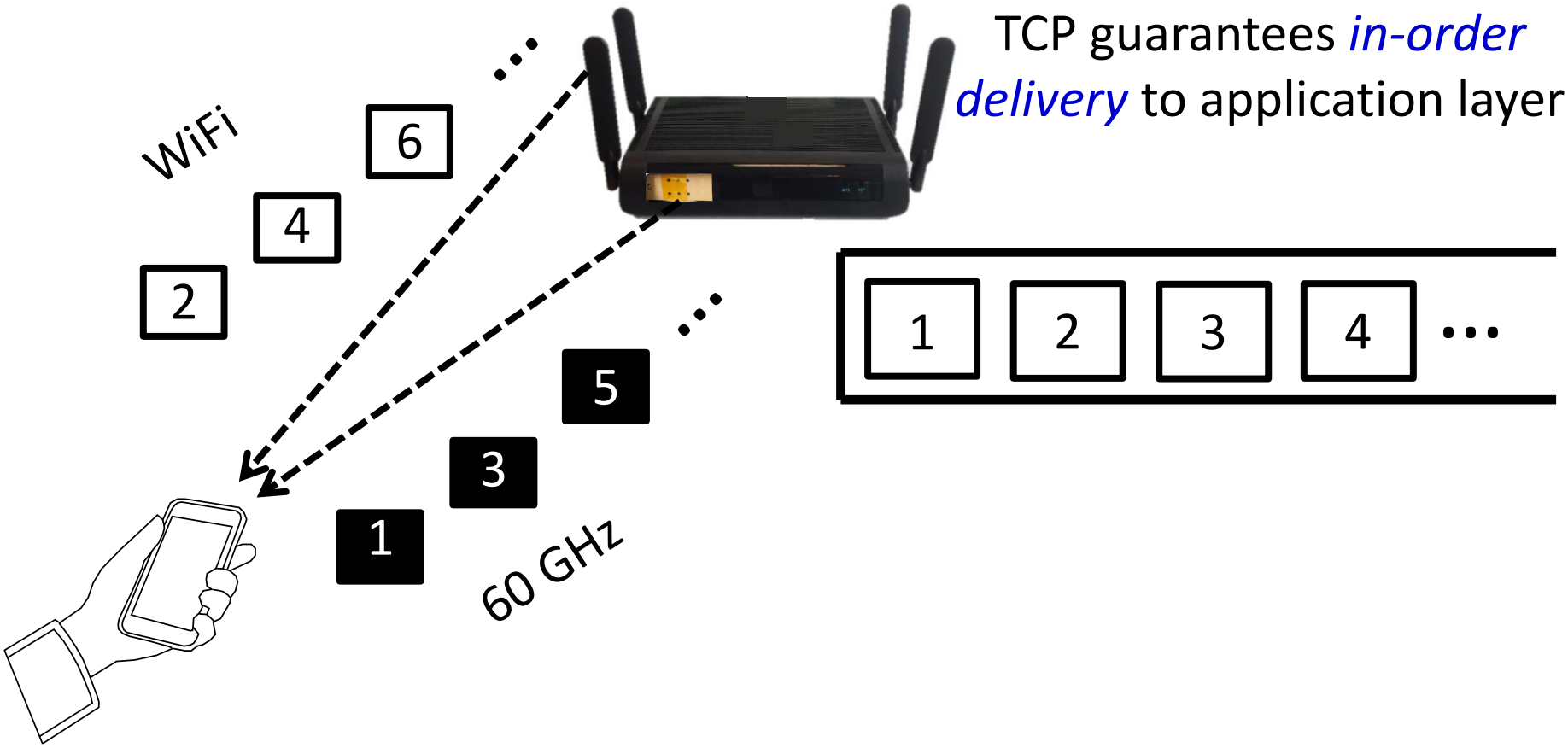


In-order TCP delivery causes throughput drop



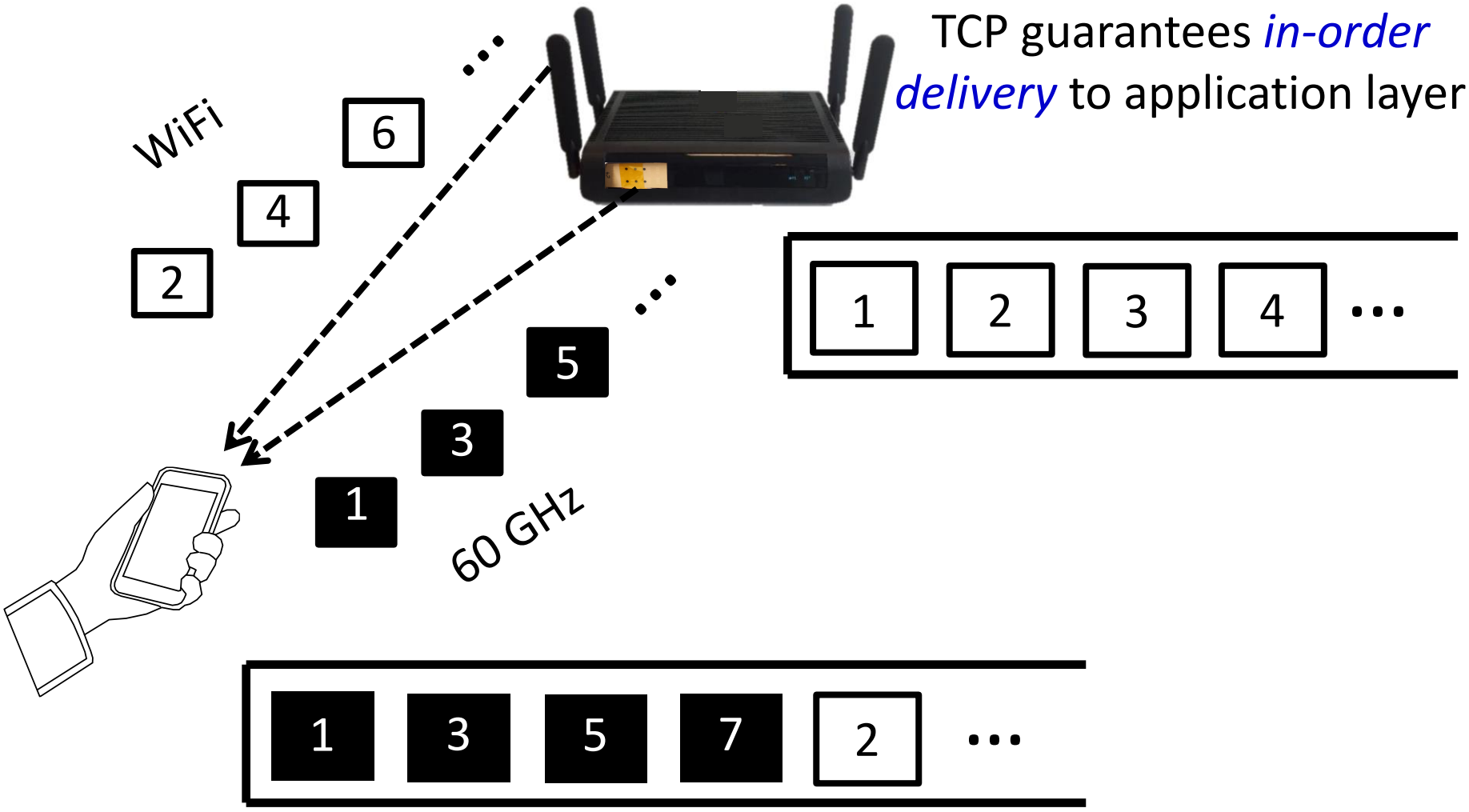
TCP guarantees *in-order delivery* to application layer

In-order TCP delivery causes throughput drop

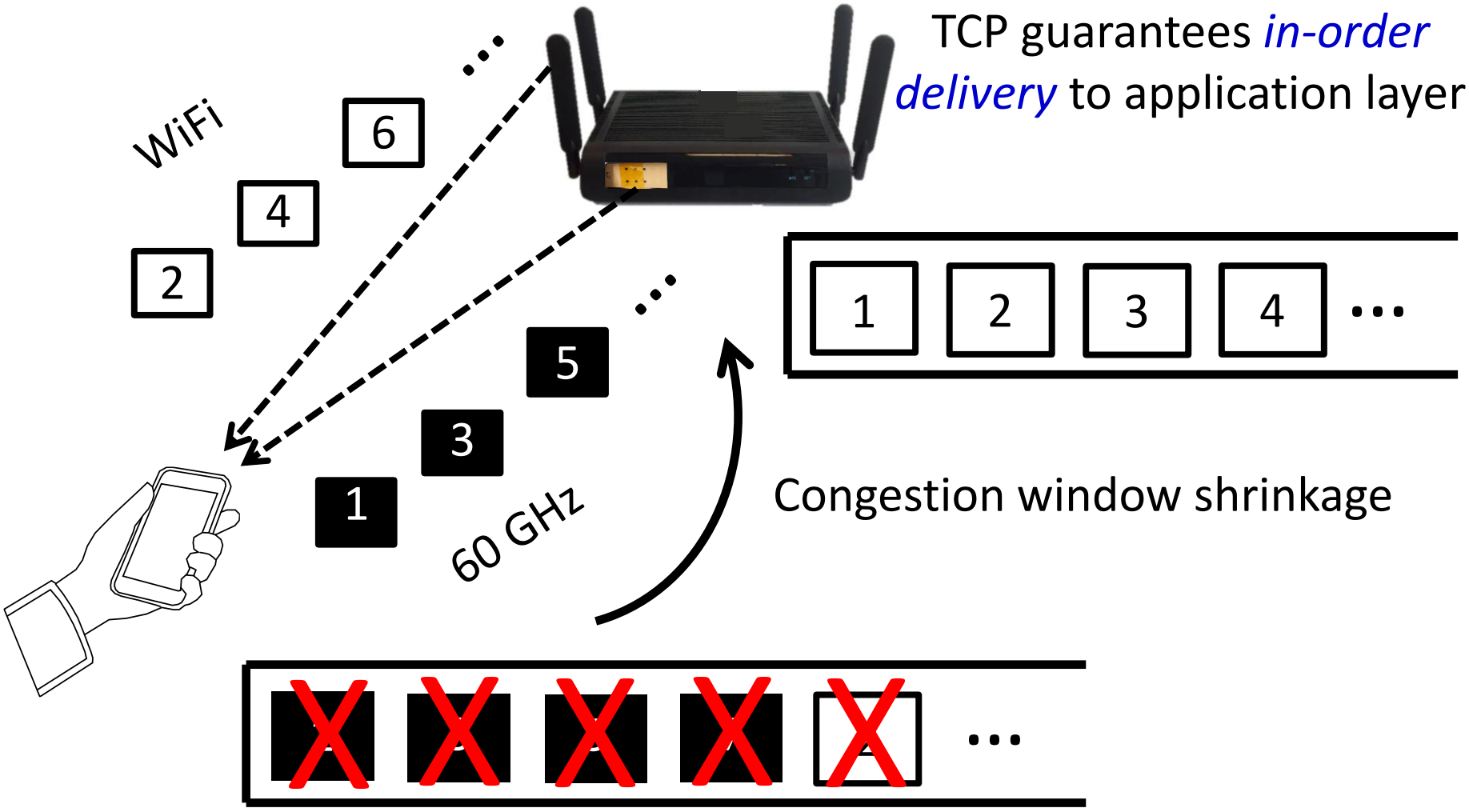


TCP guarantees *in-order delivery* to application layer

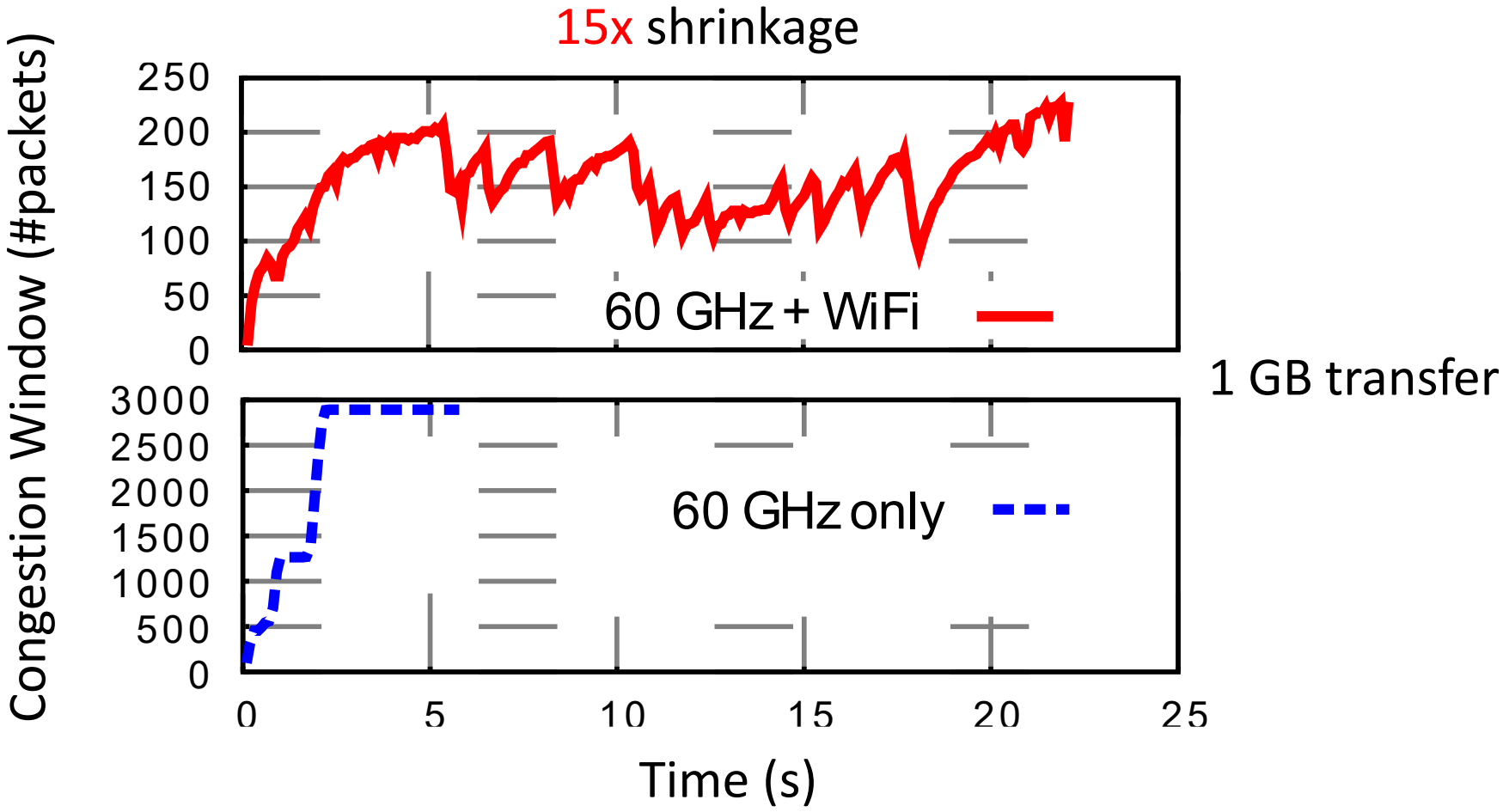
In-order TCP delivery causes throughput drop



In-order TCP delivery causes throughput drop

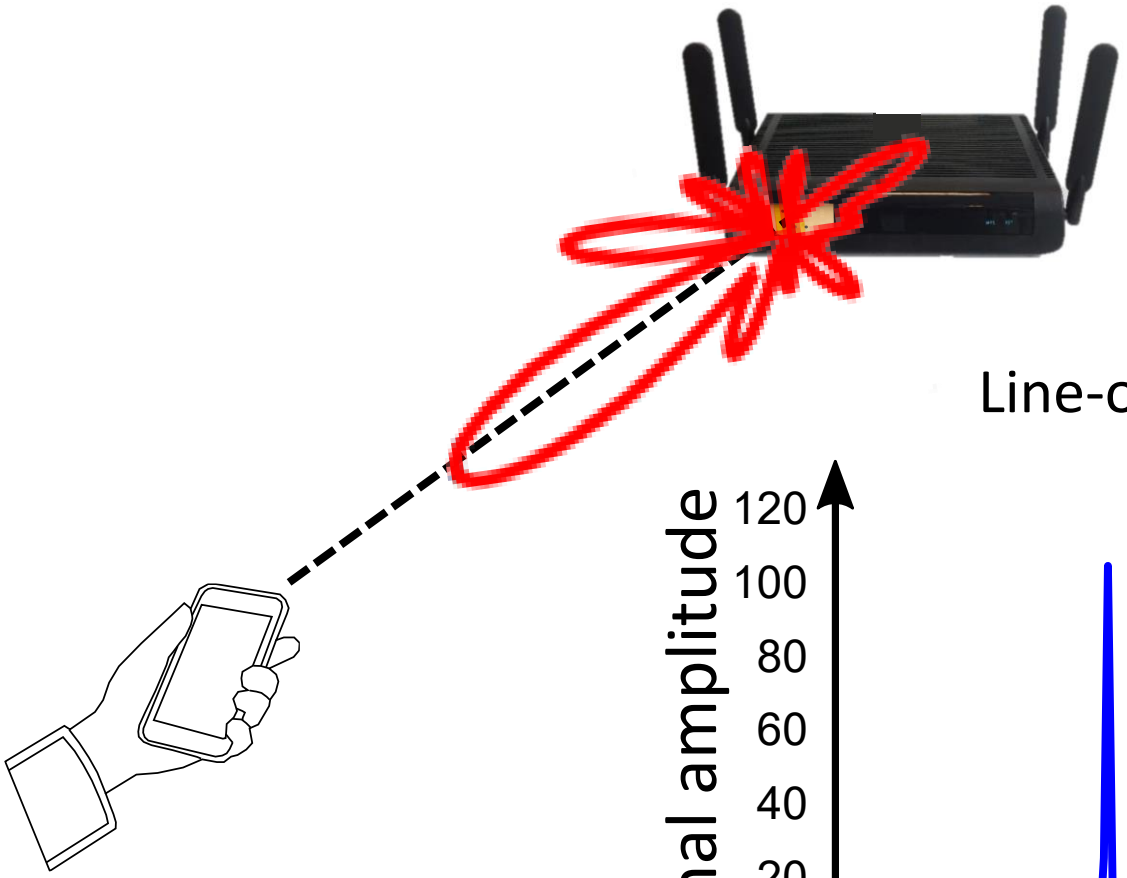


Congestion window shrinks in dual transmission



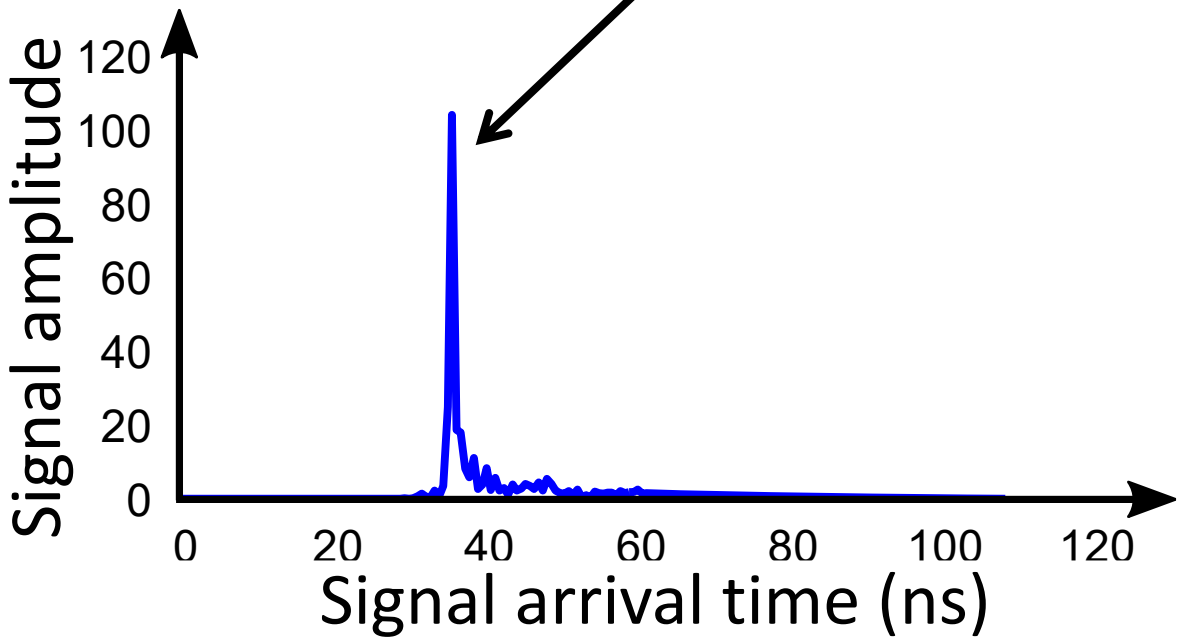
Even flow control with MPTCP causes 7~45% throughput loss

Challenge: Switching decision

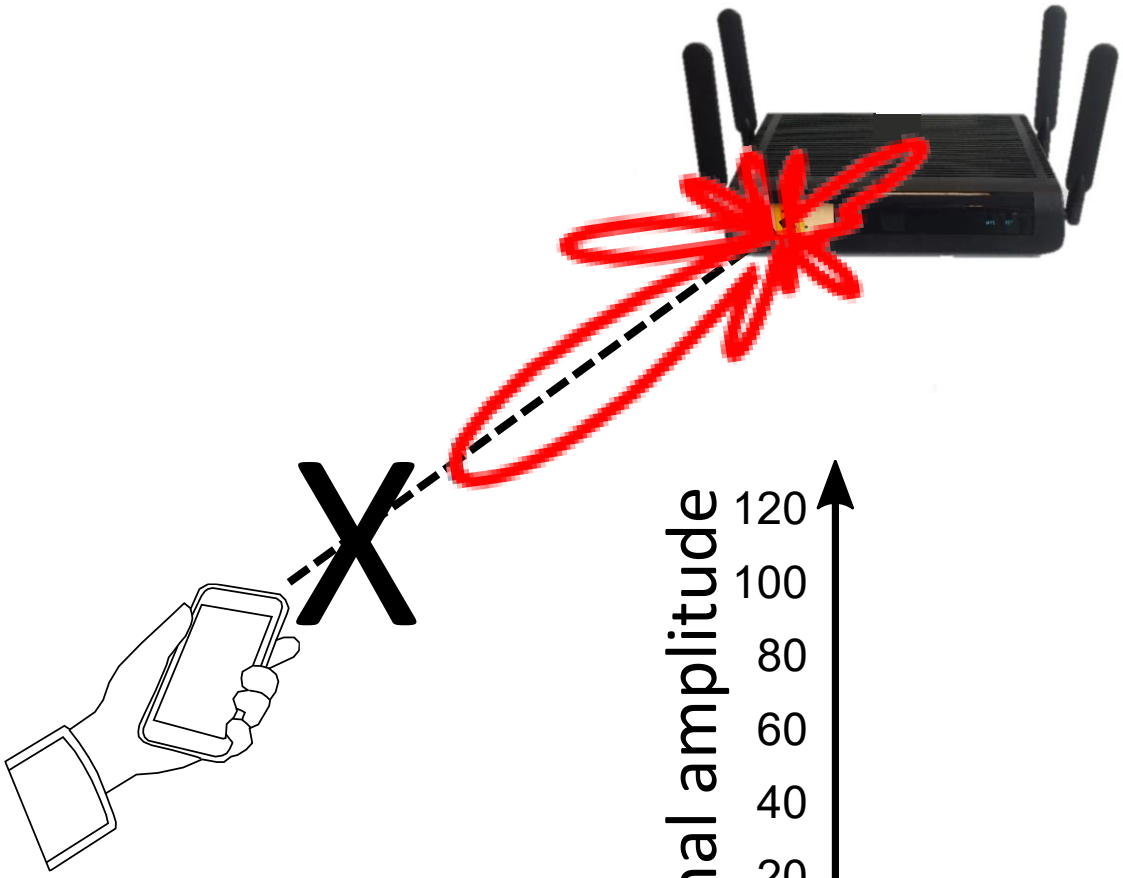


How to *identify* LOS blockage?

Line-of-sight (LOS) signal

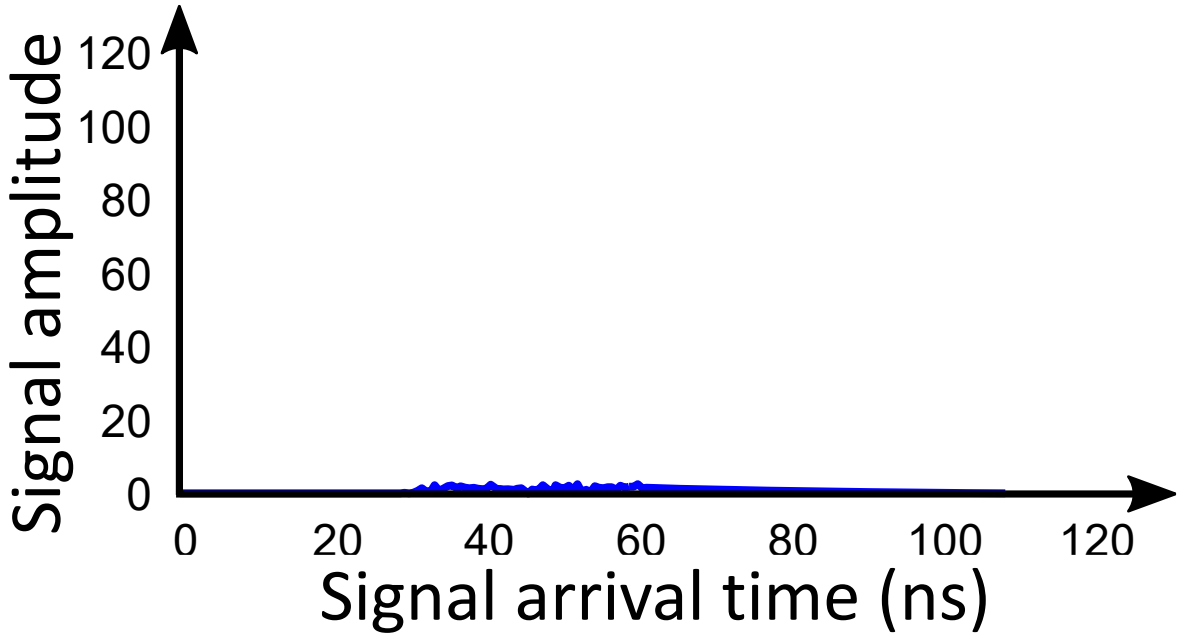


Challenge: Switching decision



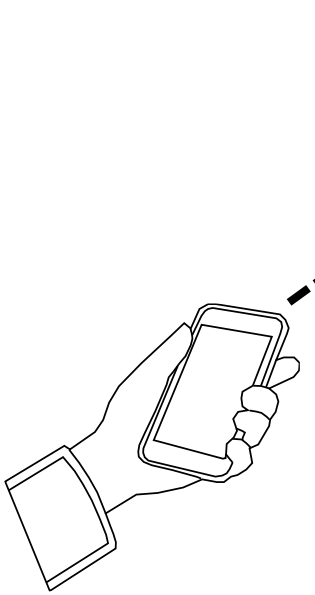
How to *identify* LOS blockage?

LOS blockage

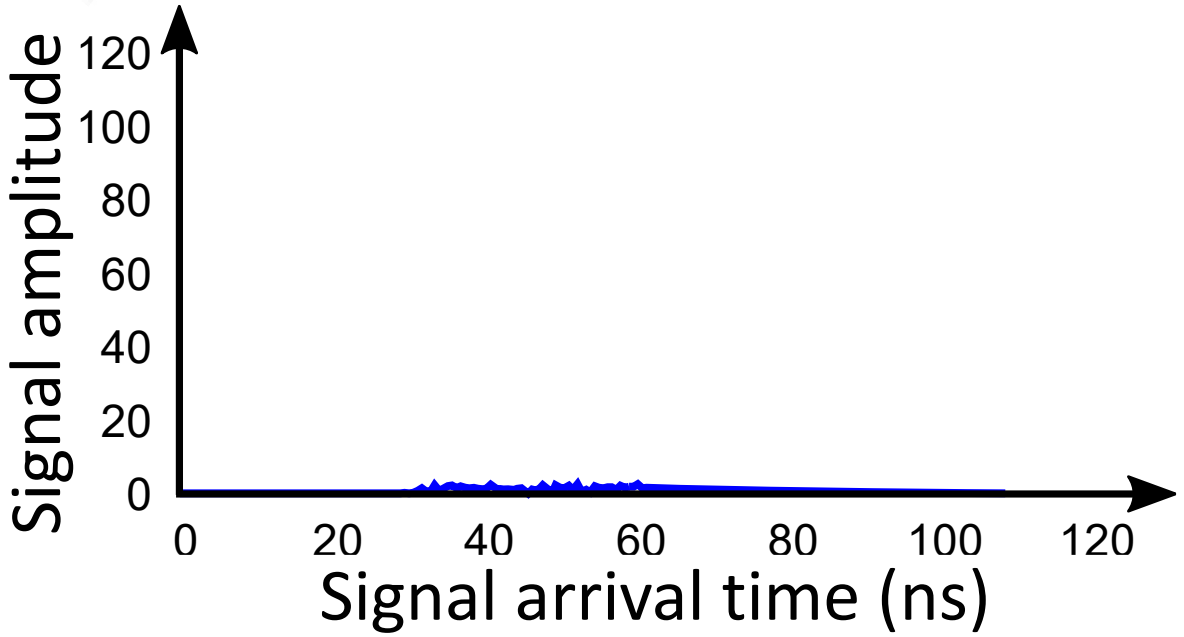


Challenge: Switching decision

How to *identify* LOS blockage?



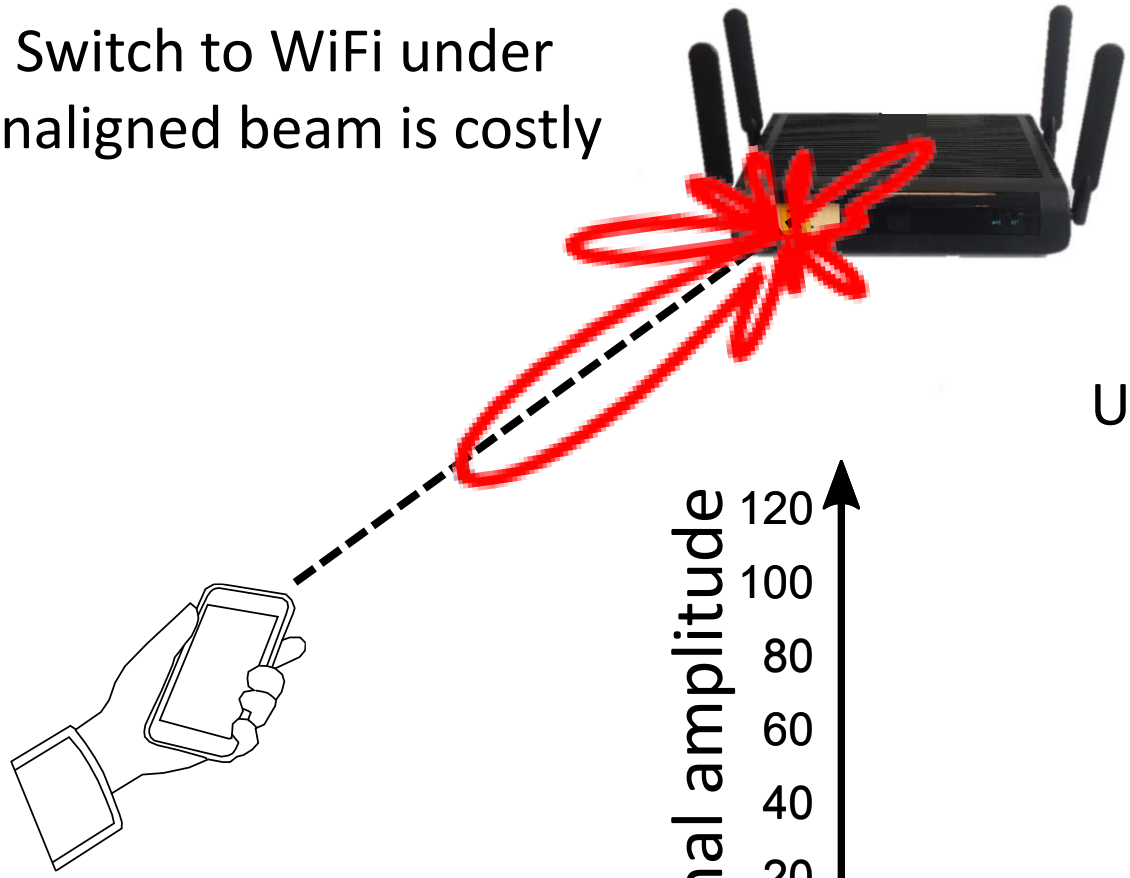
Unaligned beam



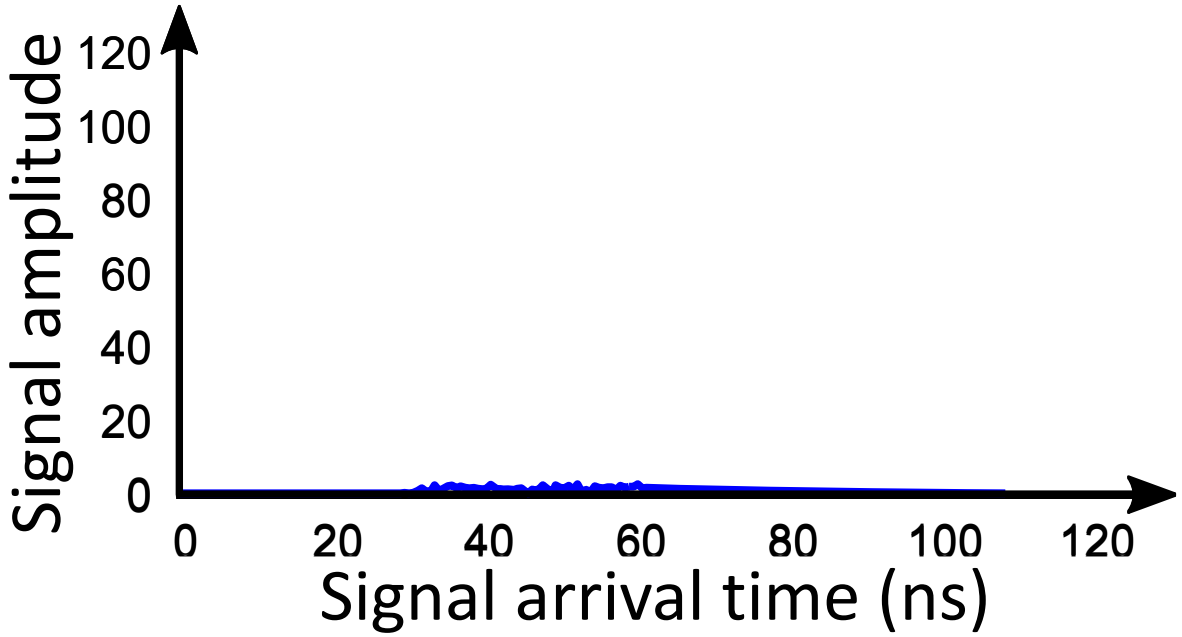
Challenge: Switching decision

Switch to WiFi under unaligned beam is costly

How to *identify* LOS blockage?



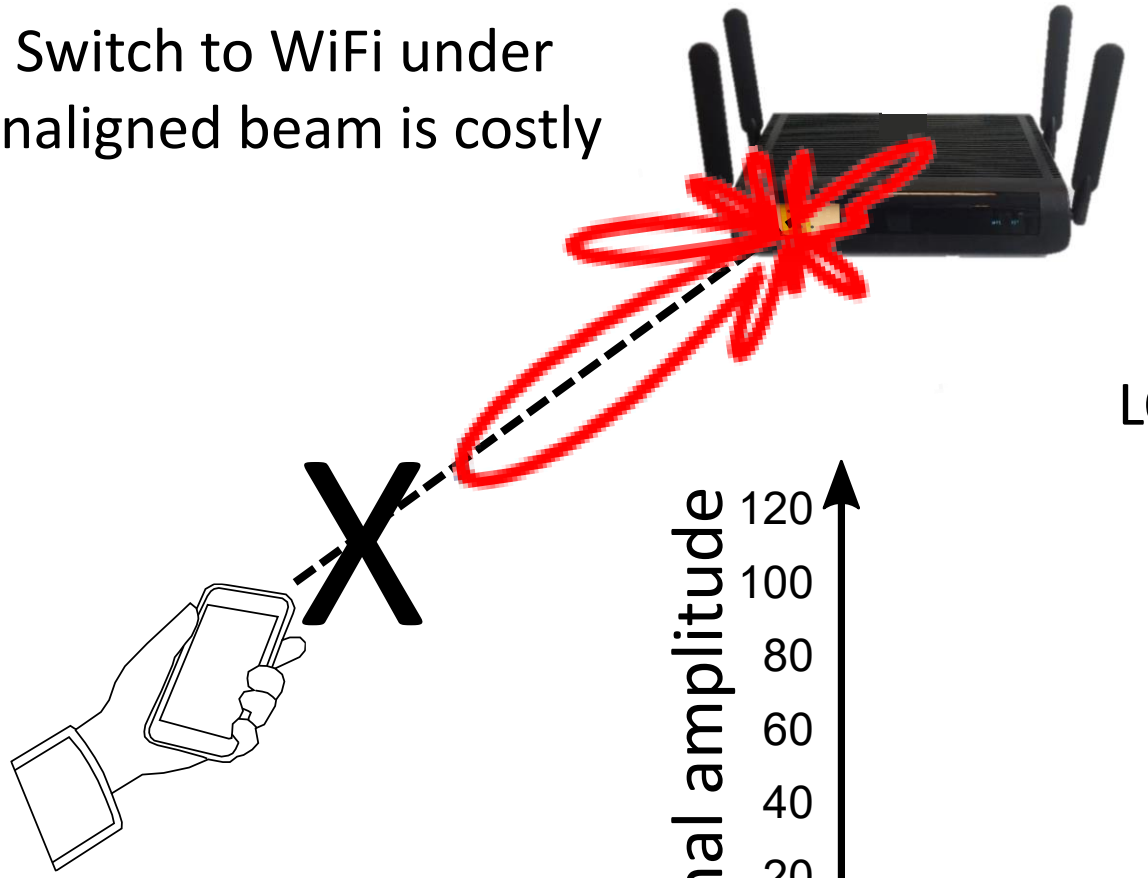
Unaligned beam



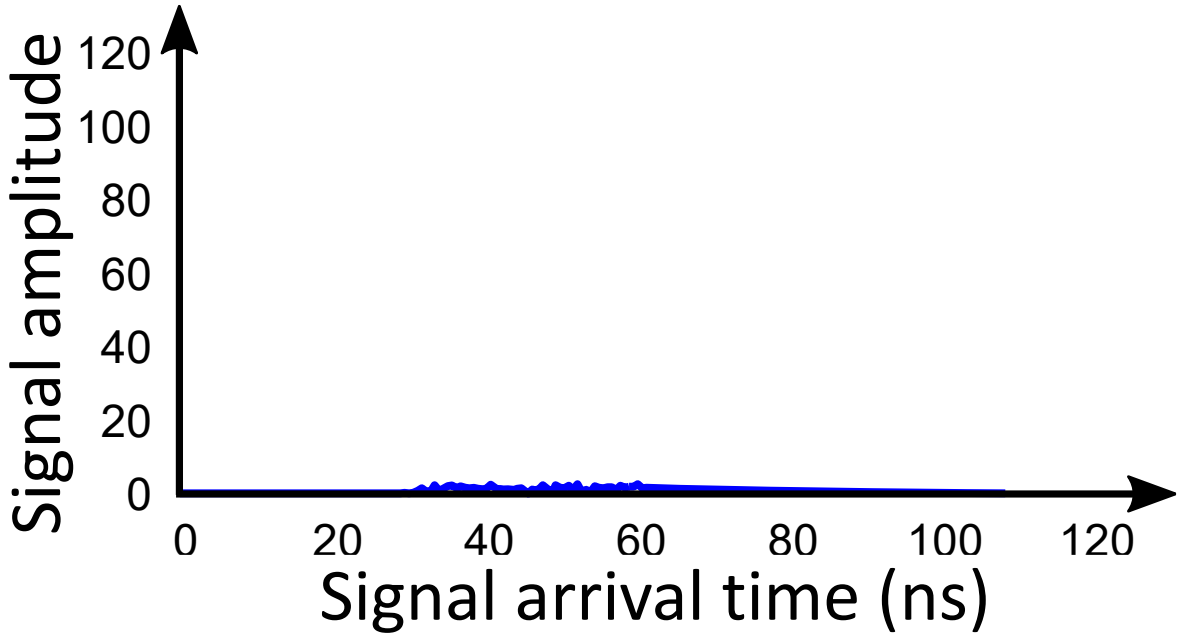
Challenge: Switching decision

Switch to WiFi under unaligned beam is costly

How to *identify* LOS blockage?



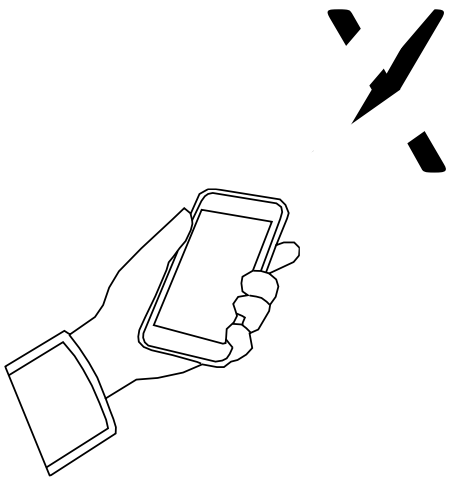
LOS blockage?

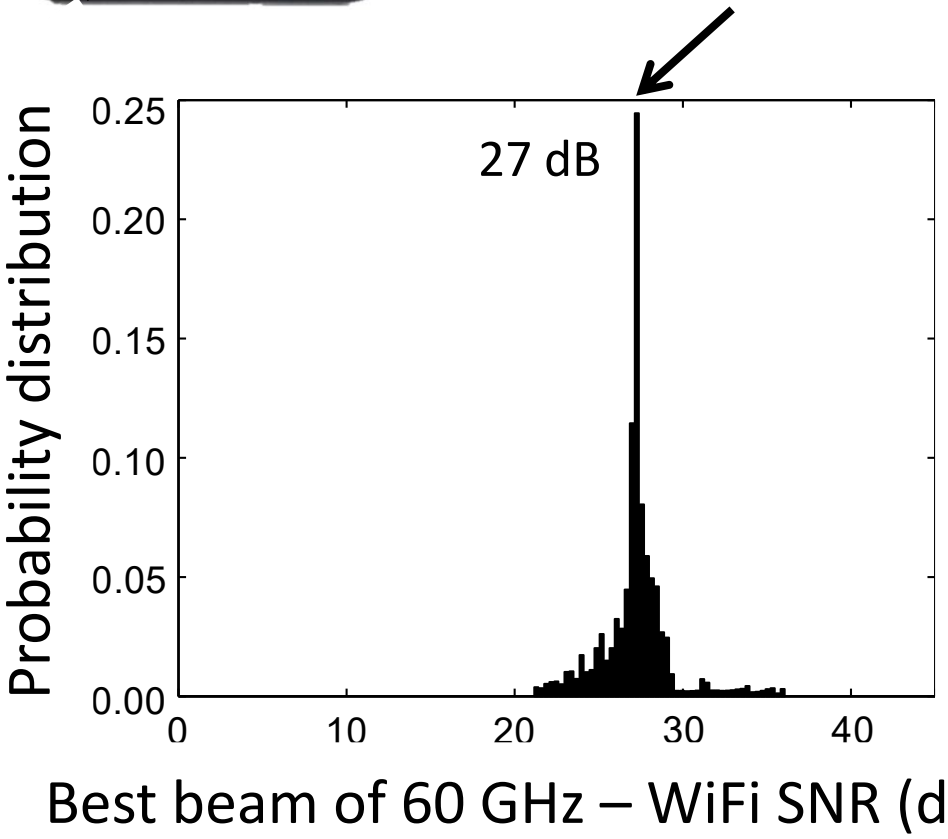


WiFi signal as hint for LOS blockage

Same blockage affect 60 GHz and WiFi *differently*

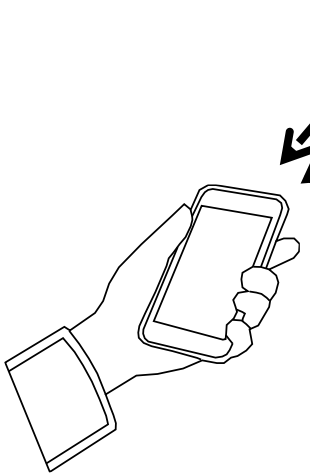
Signal strength difference in *open LOS*



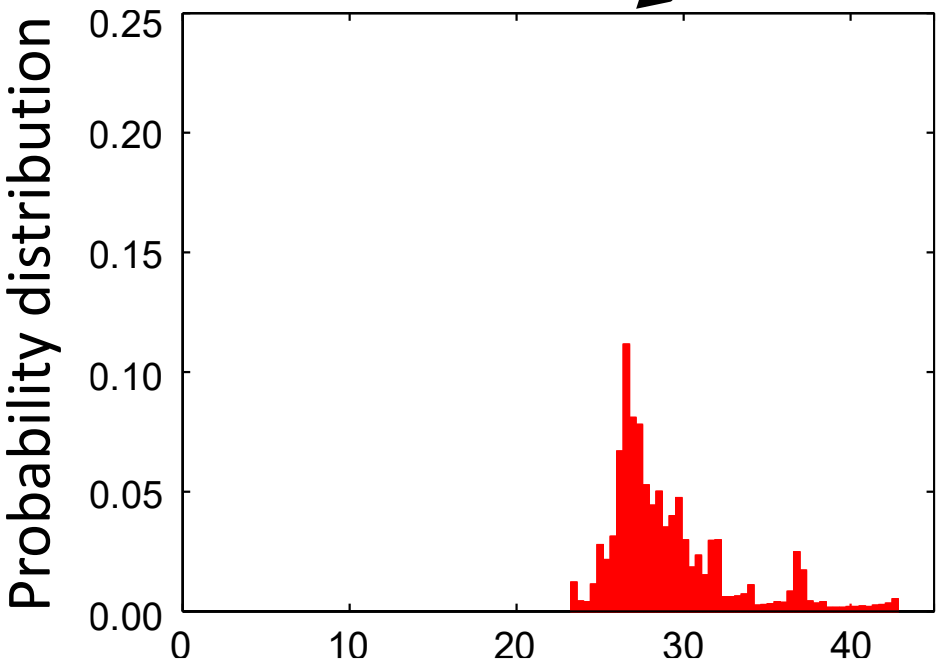


WiFi signal as hint for LOS blockage

Same blockage affect 60 GHz and WiFi *differently*



Signal strength difference in *blocked LOS*



Challenges for multi-band cooperation

60 GHz link adaptation

Switching decision

Shared system resources

Challenges for multi-band cooperation

60 GHz link adaptation

Switching decision

Shared system resources

Challenge: Shared system resources

Heterogeneous interfaces stress the system differently

Challenge: Shared system resources

To Ethernet backhaul

Upper network stack, Ethernet forwarding

32-bit PCIe bus

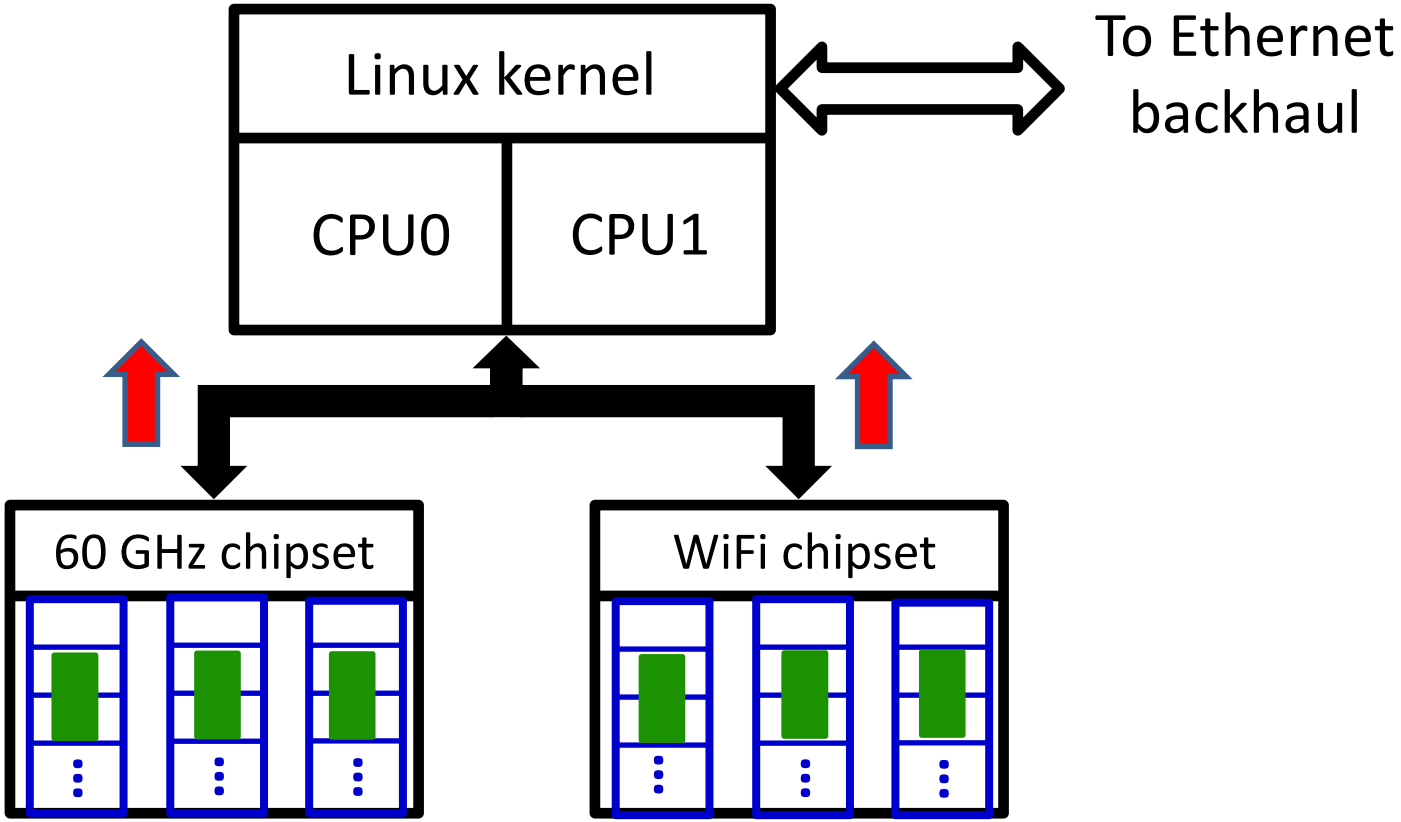
Core MAC/PHY, beam steering, rate adaptation

Core MAC/PHY, user grouping, rate selection

Challenge: Shared system resources

Interrupt

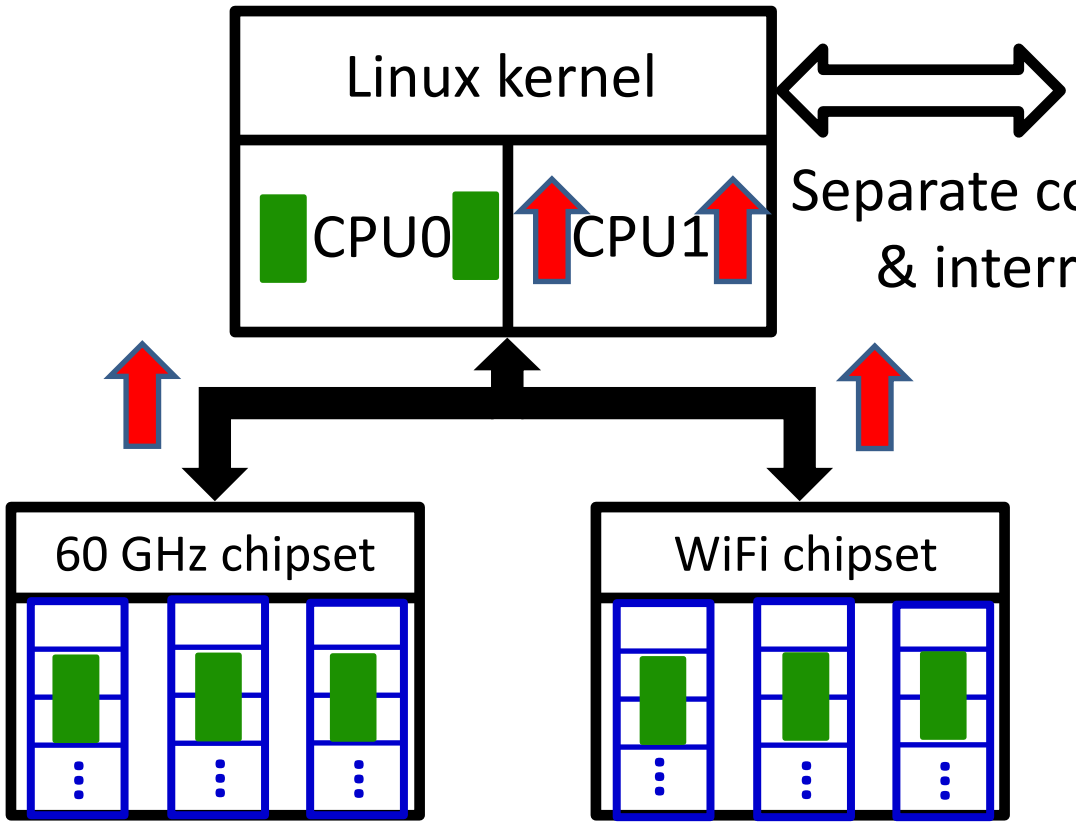
Packet



Challenge: Shared system resources

Interrupt

Packet



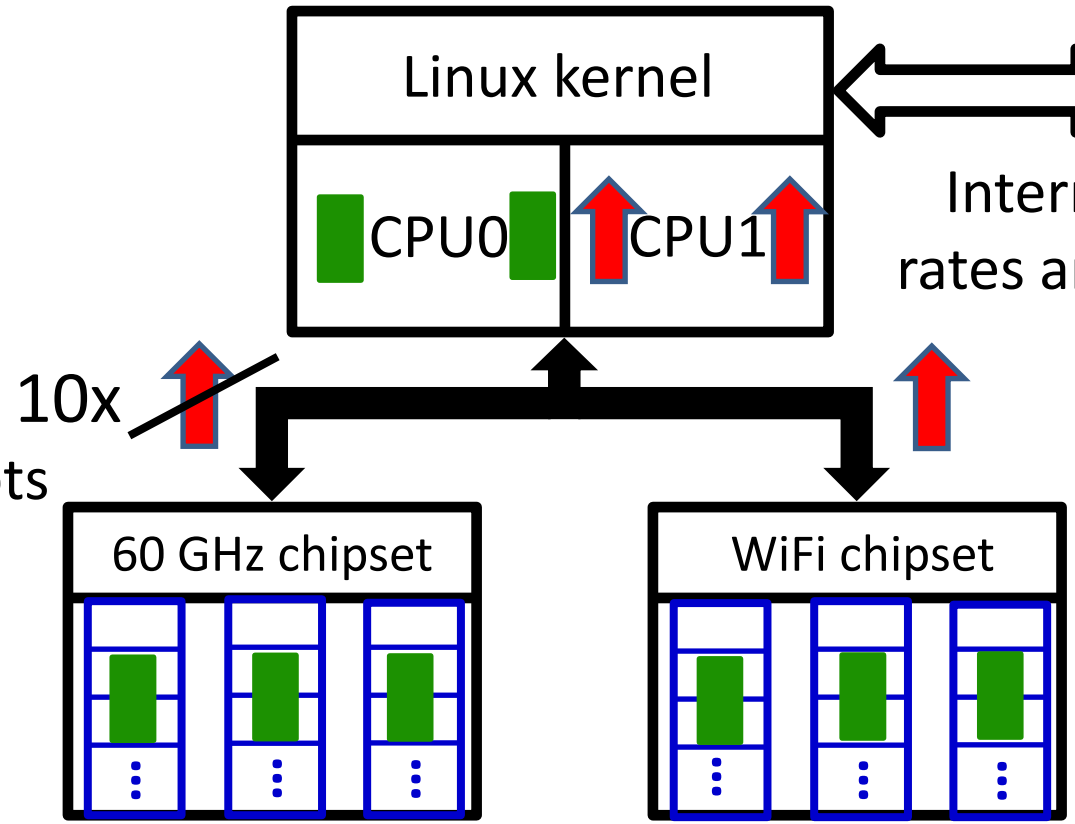
Separate cores for packet & interrupt service

Challenge: Shared system resources

Interrupt

Packet

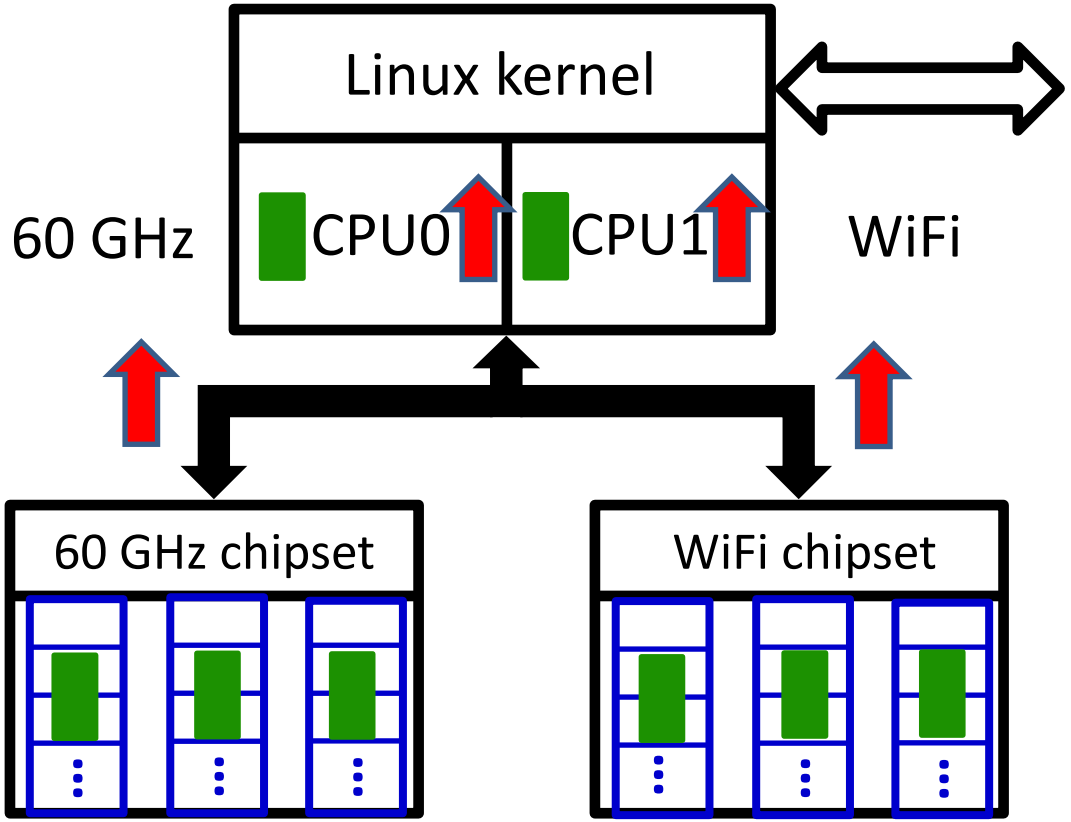
More interrupts are stalled



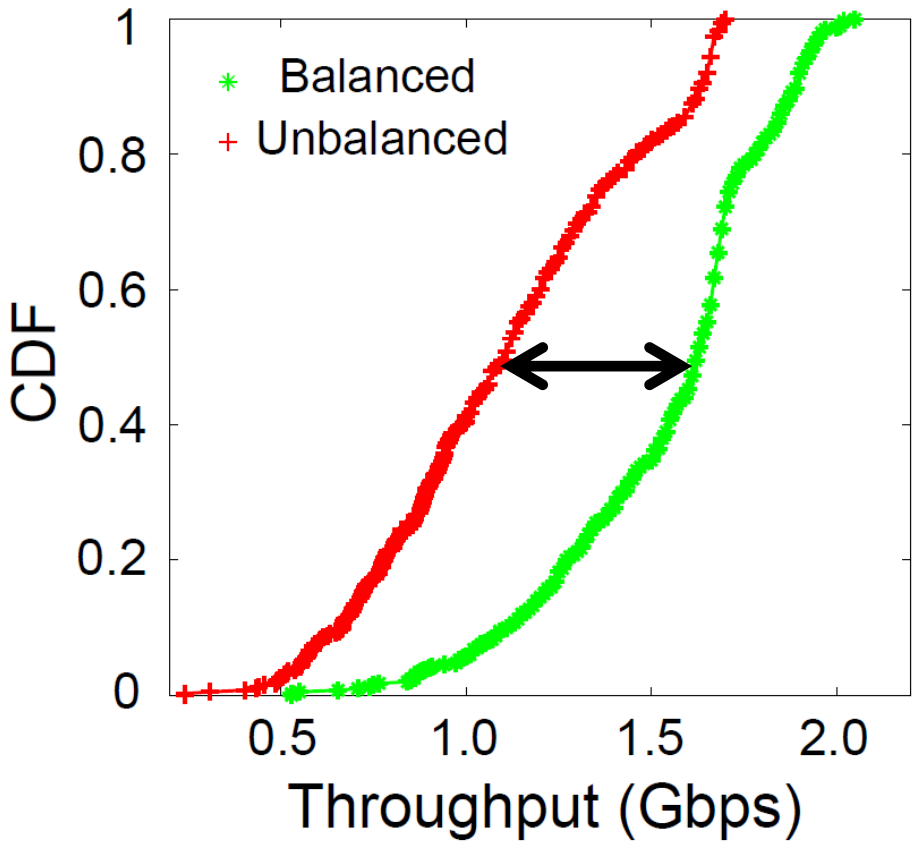
Balanced assignment: Interface to core

Interrupt

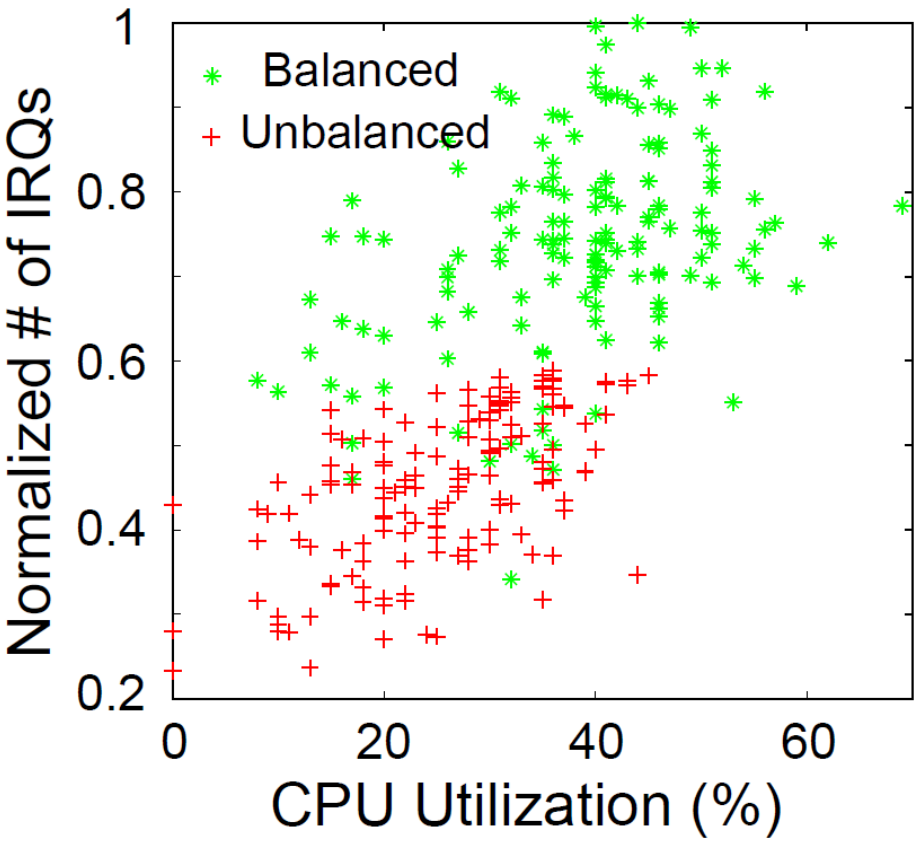
Packet



Balanced assignment improves efficiency

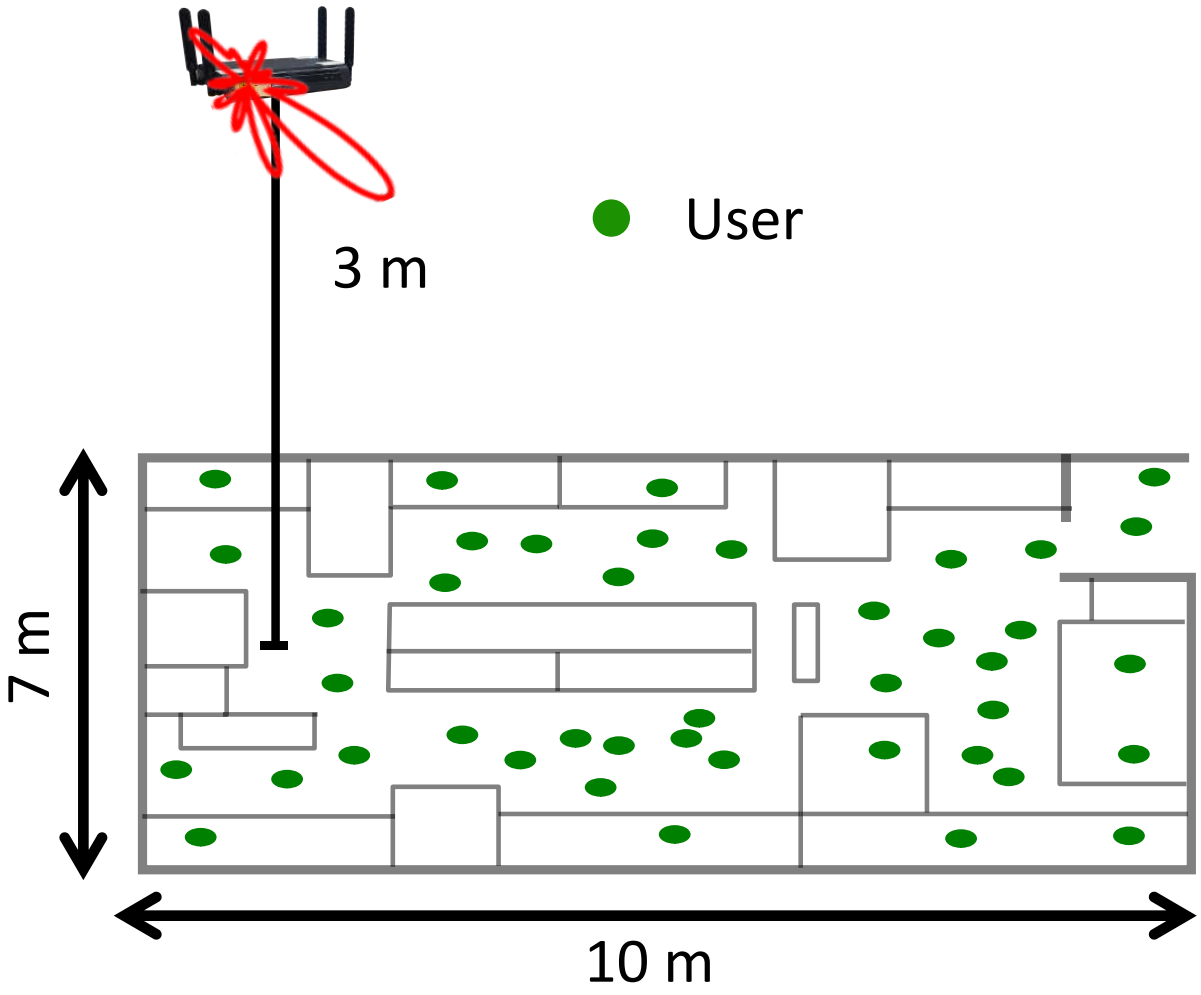


Median 0.5 Gbps throughput increase



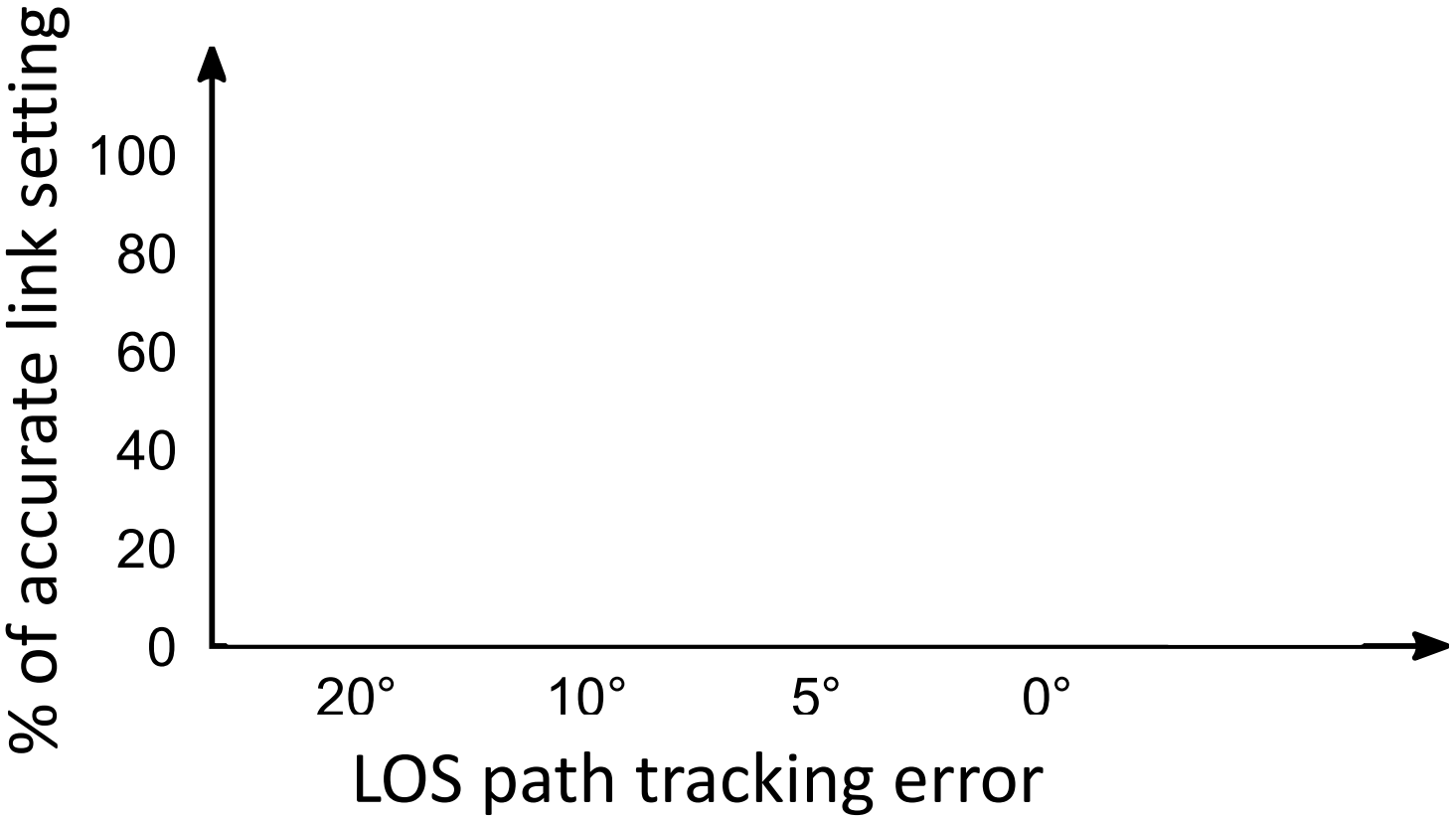
2x increase in CPU utilization & interrupt servicing

Experimental setup and evaluation



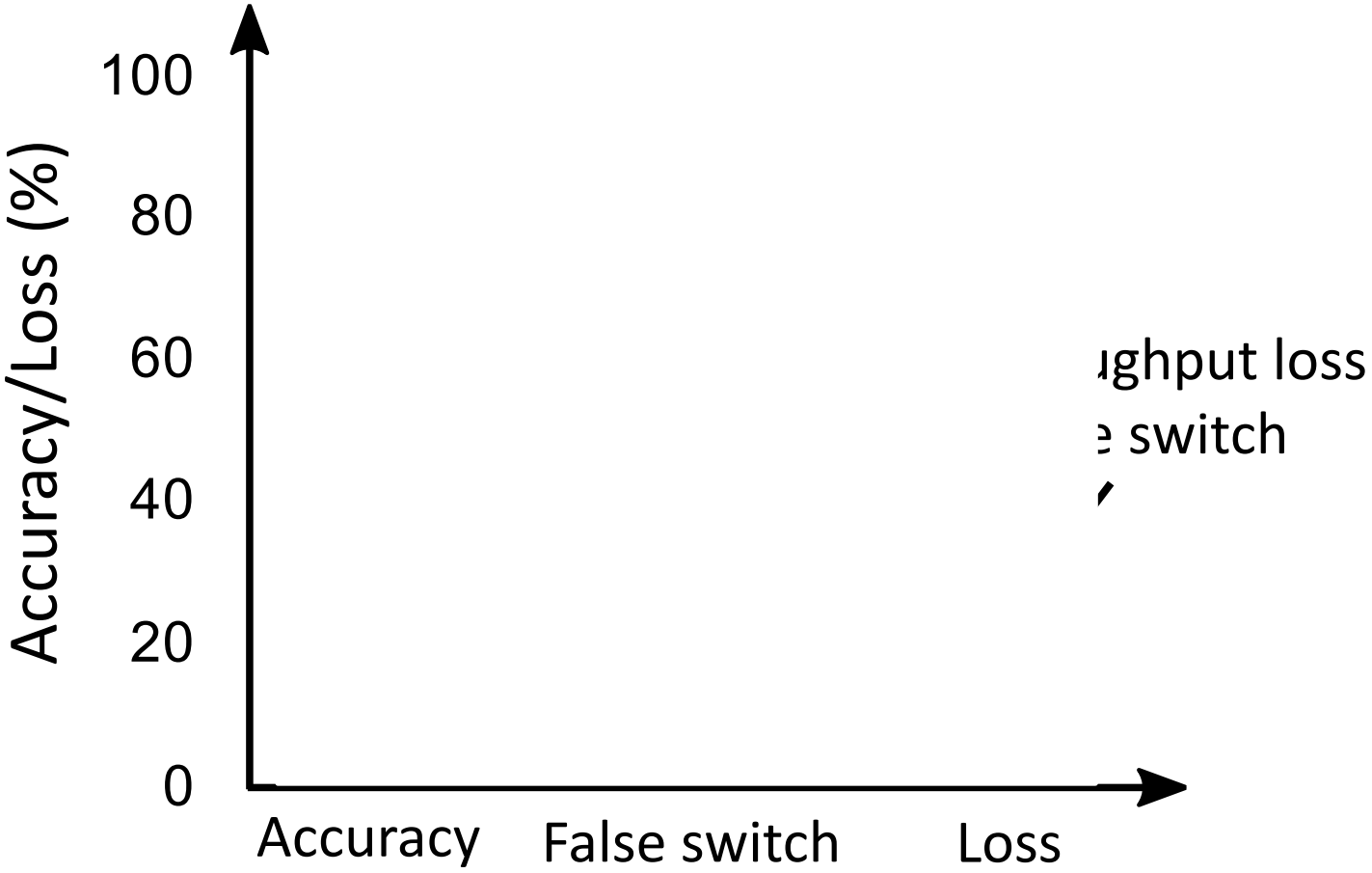
- 60 GHz follows IEEE 802.11ad
- 32 antenna array, up to 64 beams
- WiFi follows IEEE 802.11ac MU-MIMO

WiFi-assisted LOS path tracking



71% accuracy with 1~2 ms measurement overhead

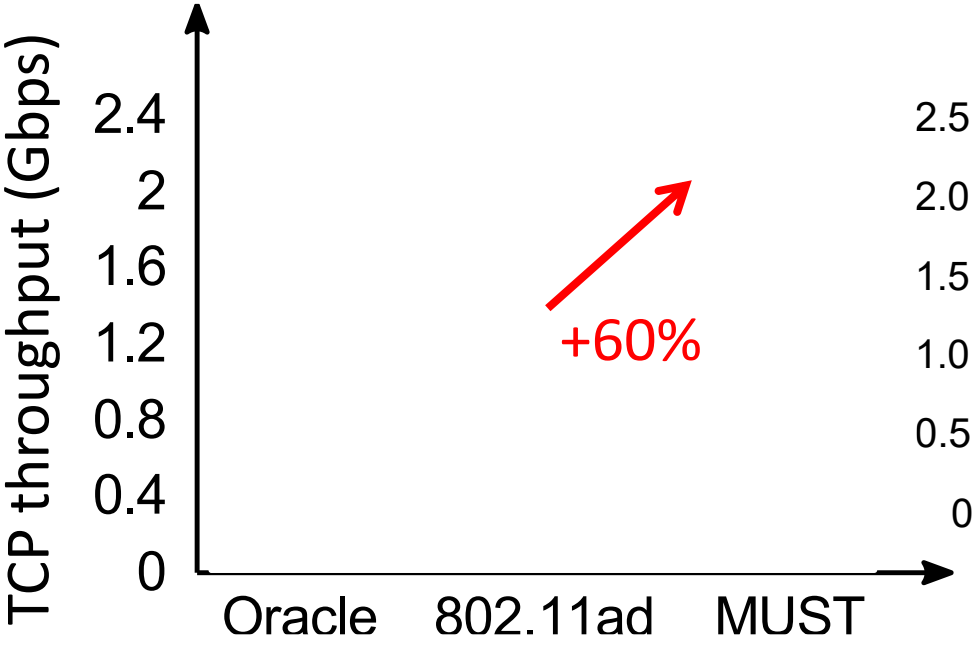
Switching accuracy and latency

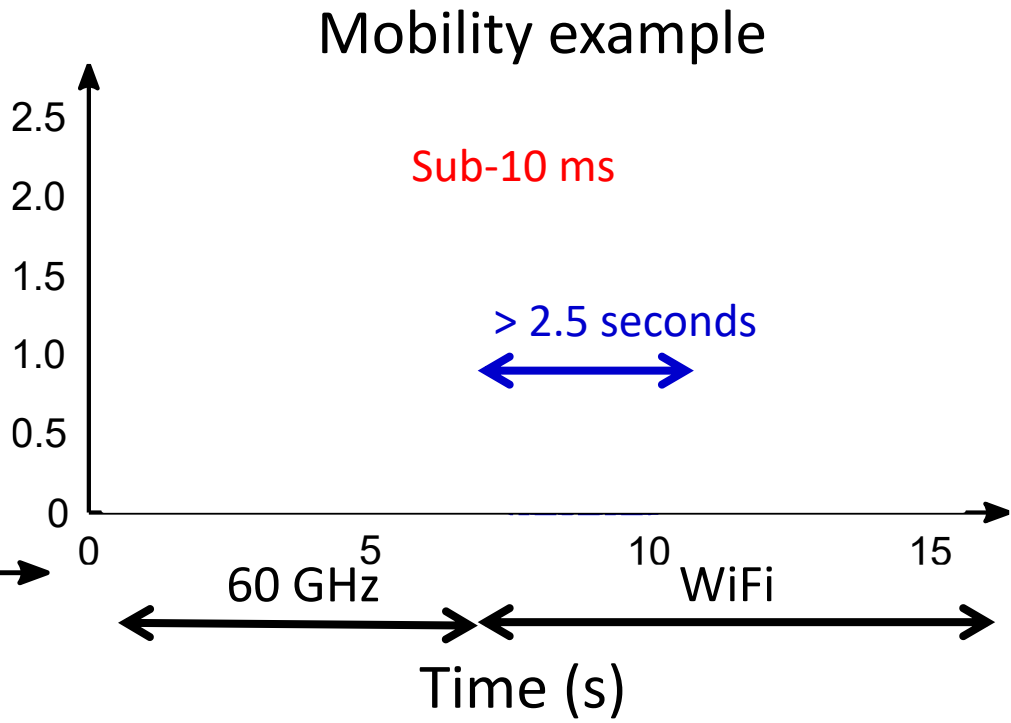


Accuracy & loss of identifying the best interface

Sub-10 ms switching latency

MUST gains





Average 60% throughput gain with two orders of magnitude switching latency improvement

Takeaways

Implications of MUST

Multi-band architecture is must to deploy 60 GHz/millimeter-wave in the wild

MUST introduces optimizations across link, protocol and system stack for potential immediate deployment

MUST in summary

A multi-band cooperation to make 60 GHz stable

* Faster adaptation at 60 GHz interface
* Sub-10 ms 60 GHz to WiFi coordination
* Real-time and standard-compliant