Towards Scalable and Ubiquitous Millimeter-Wave Wireless Networks

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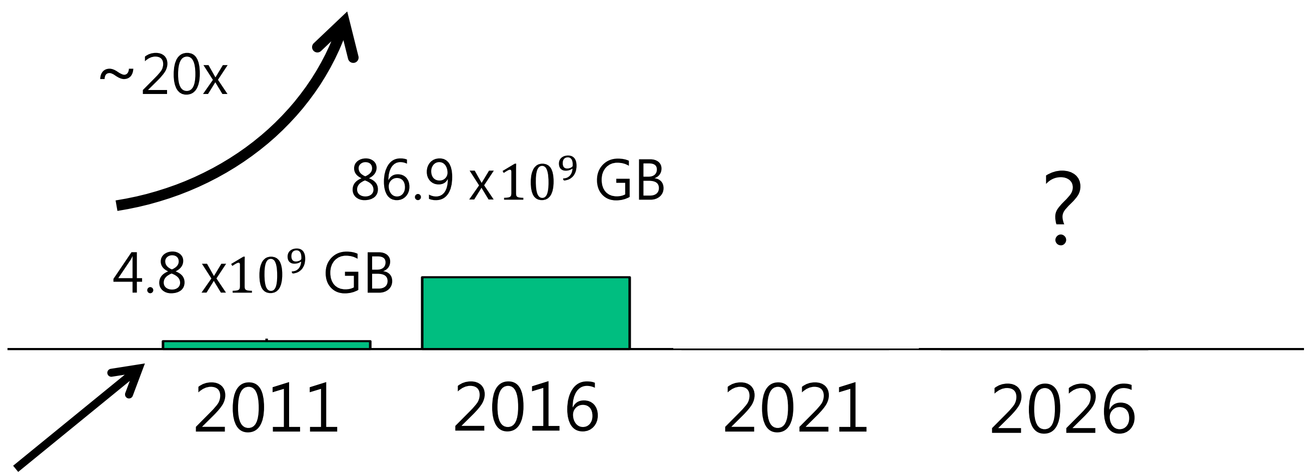
ACM MobiCom 2018

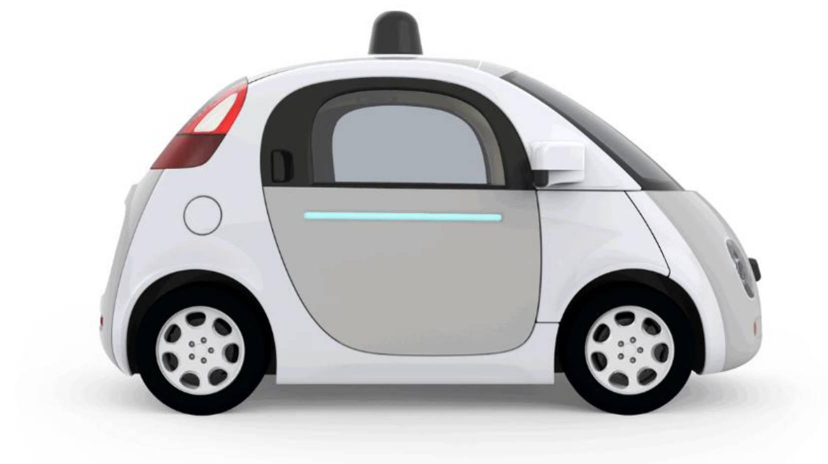
Global demand for wireless data is skyrocketing

Source: Cisco VNI,
2016 - 2021



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

Emerging devices stress wireless network



Immersive VR/AR

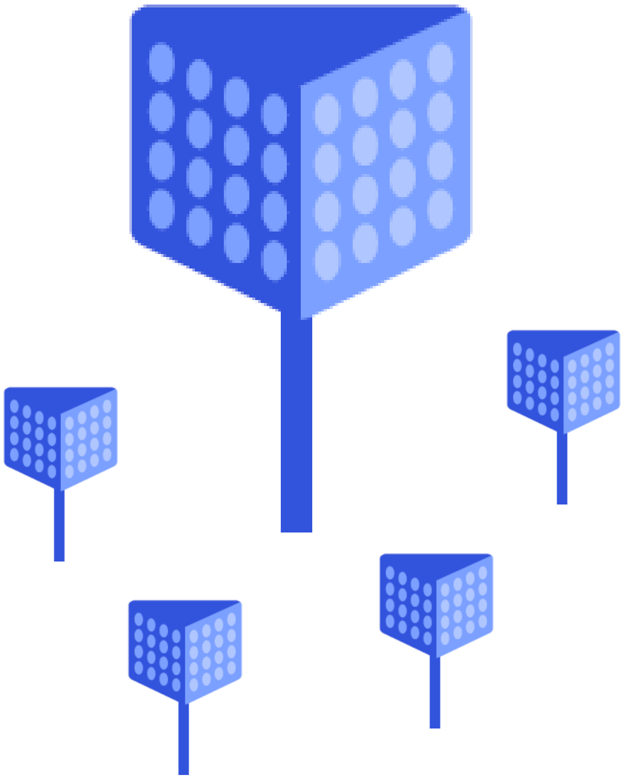
5 ~ 6 Gb/s wireless speed with sub-10 millisecond latency

Autonomous car

Locally generates more than 10 Gb/s *

* https://datacenterfrontier.com/autonomous-cars-could-drive-a-deluge-of-data-center-demand/

IMT's vision: Minimum capability of radios by the year 2020



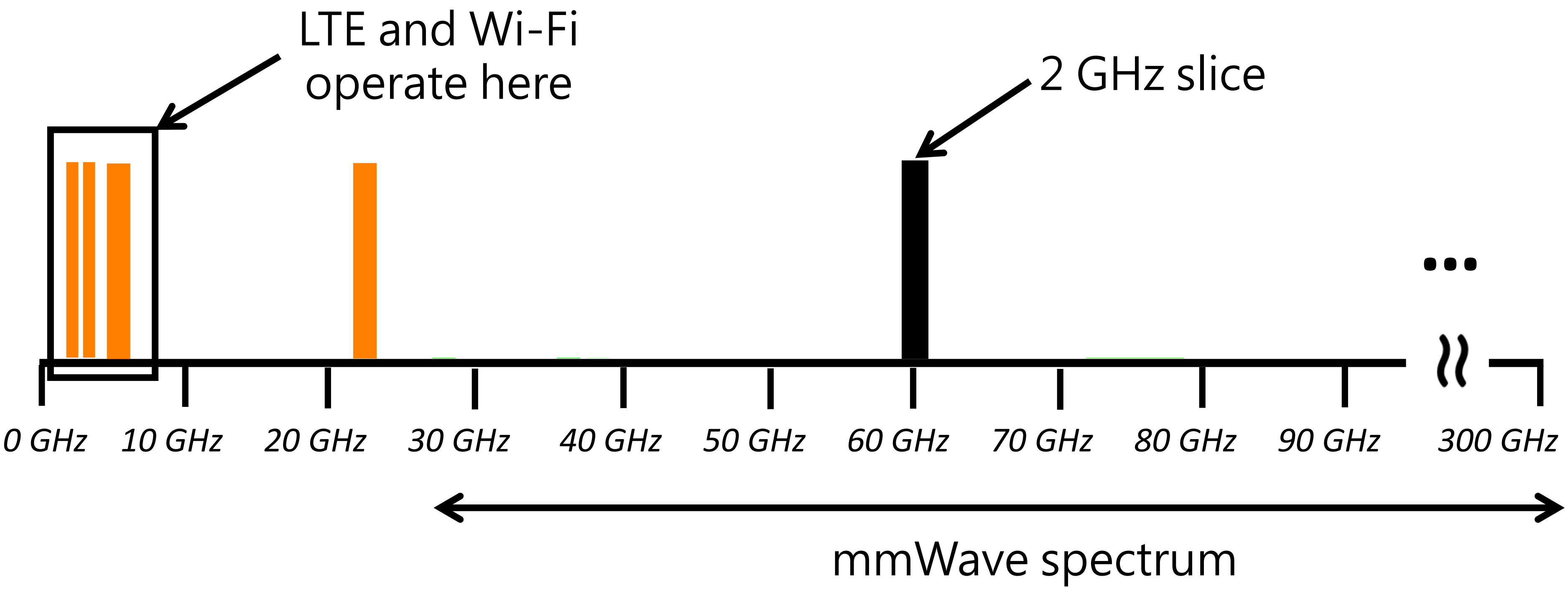
- Peak capacity > 20 Gbps
- Connection density
  - > 1 million devices/km^2
- Last-mile latency
  - < 4 ms for mobile broadband
  - < 1 ms for ultra low-latency

- > 3x spectral efficiency; > 100x area traffic capacity; > 100x network energy efficiency; > 300 Mph mobility support; … *

* ITU towards "IMT for 2020 and beyond": https://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-2020

Millimeter-wave (mmWave) spectrum

Large unlicensed spectrum at mmWave

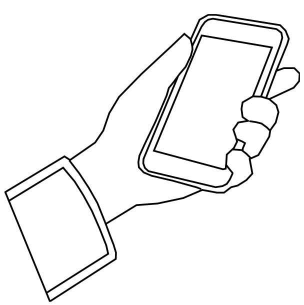


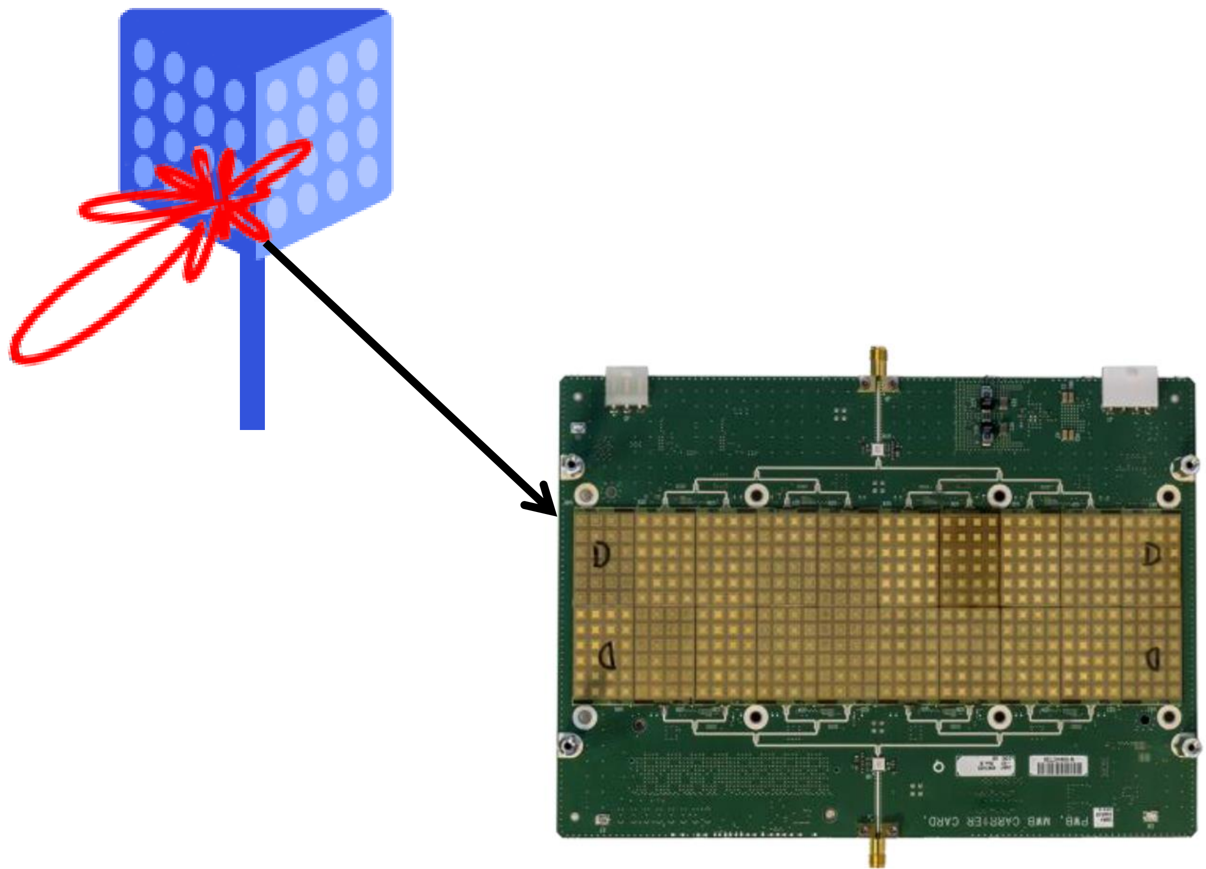
Off-the-shelf devices offer up to 7 Gbps of wireless bit-rate!

mmWave link challenges
Link adaptation

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

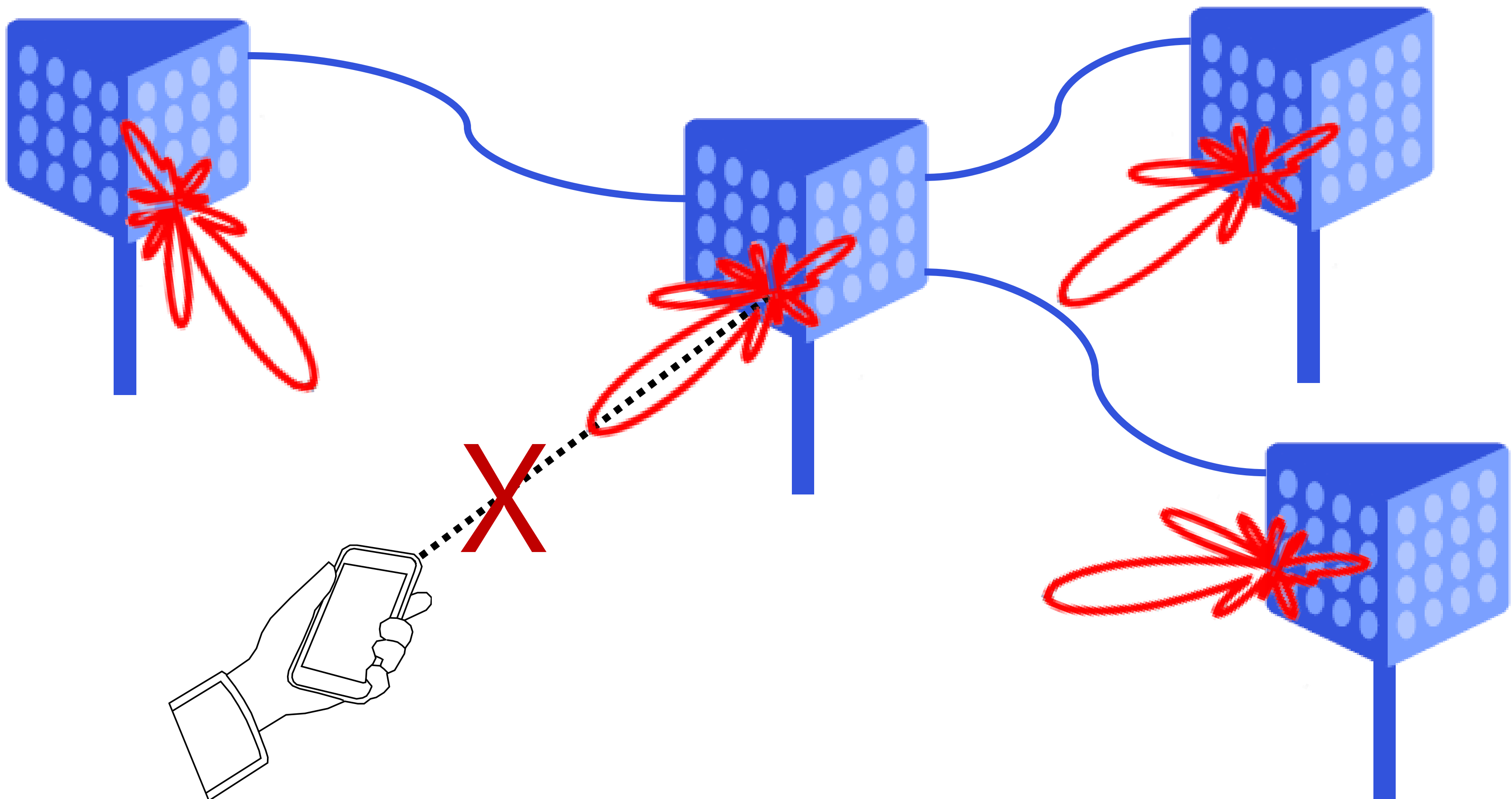
Large latency for link recovery



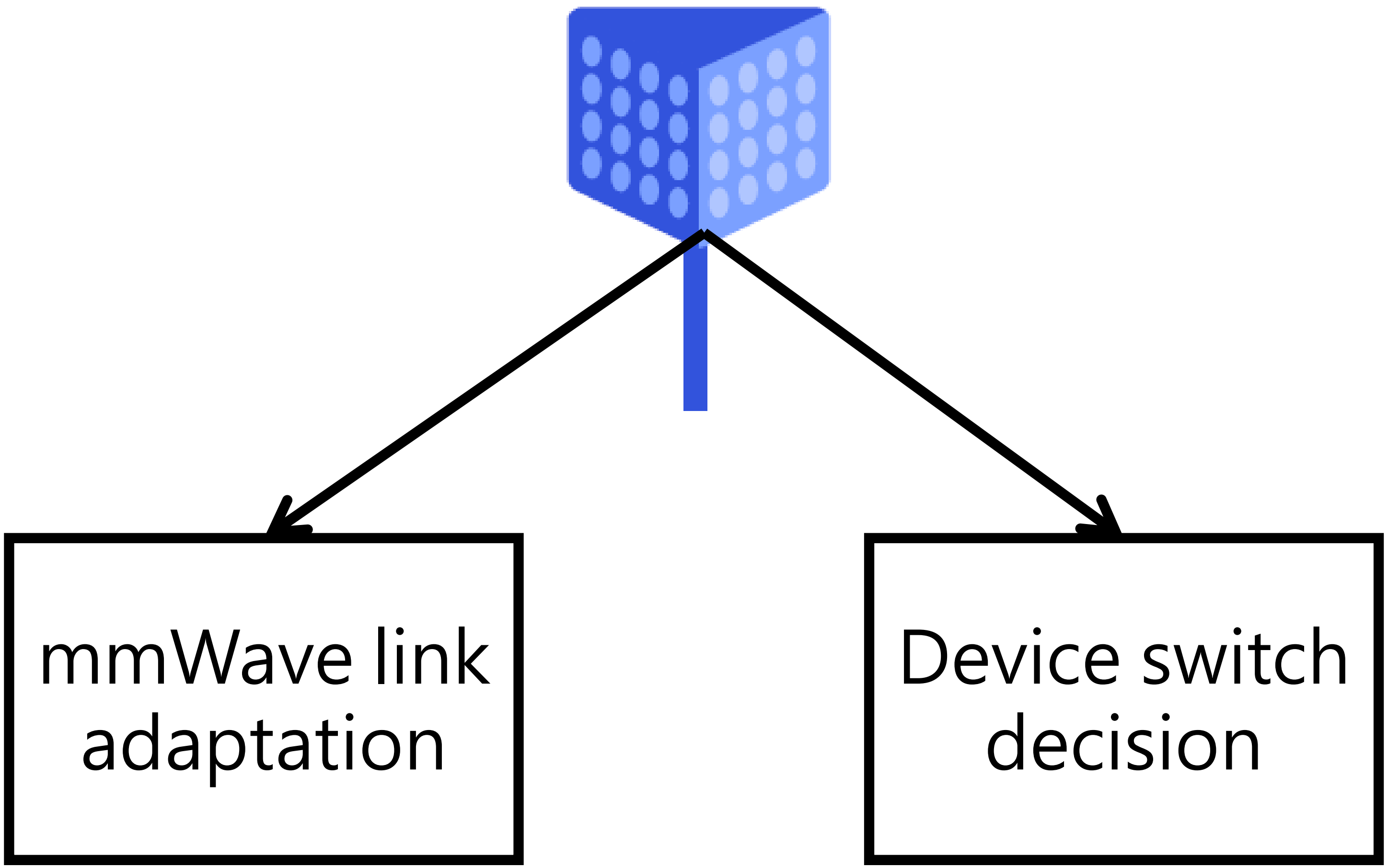


mmWave link challenges
Blockage

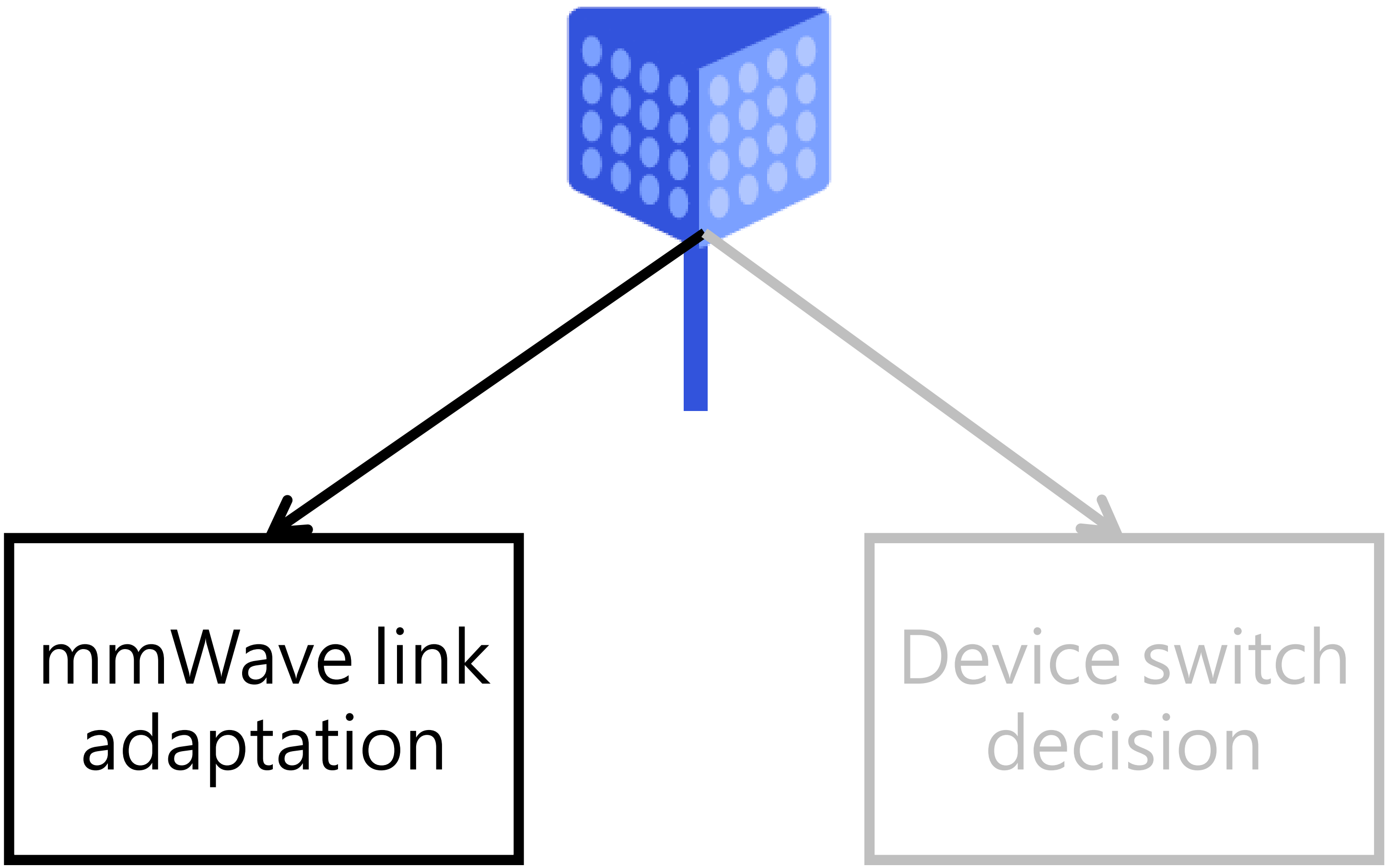
Even aligning the beam does not guarantee link connectivity



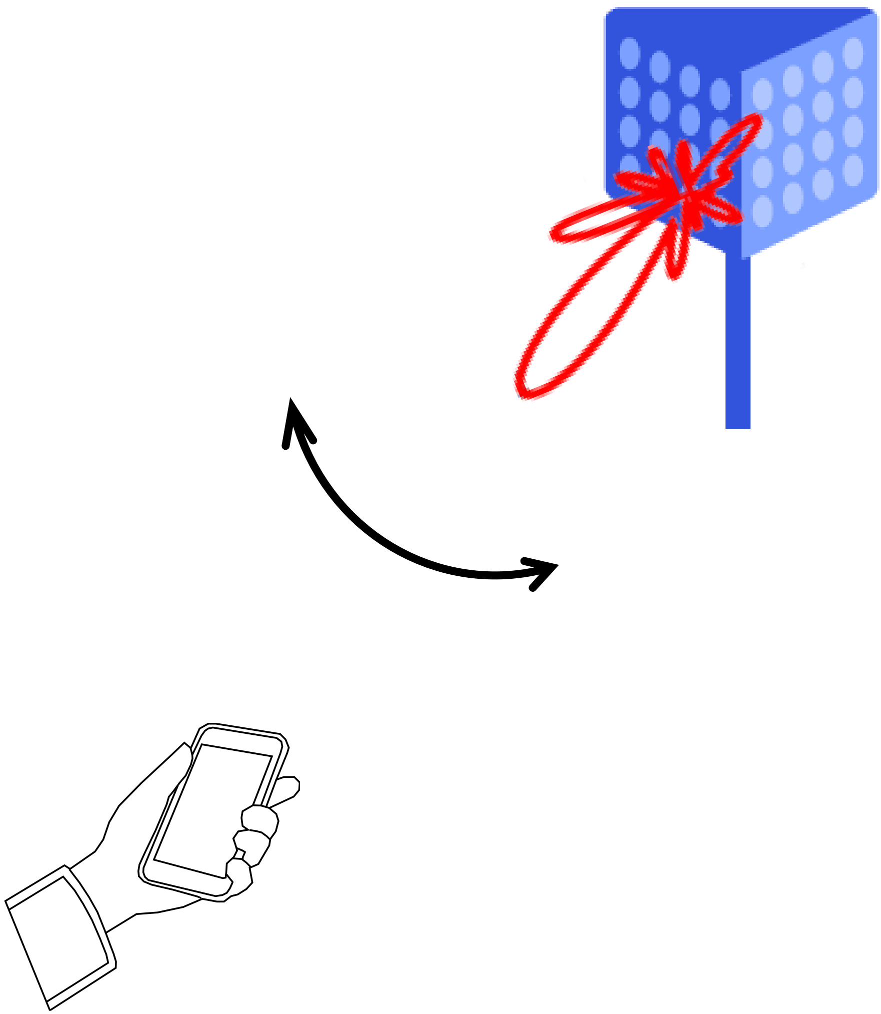
Challenges



Challenges



Challenge: mmWave link adaptation

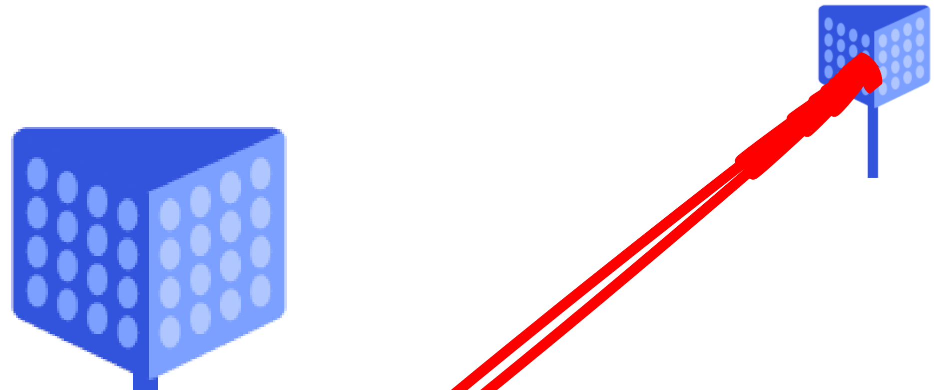


10 ms – 1000 ms

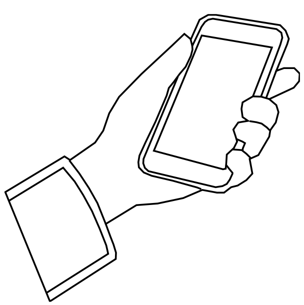
beam alignment latency *

* Even for 64 beams: [SIGMETRICS'15, NSDI'16, MobiCom'17]

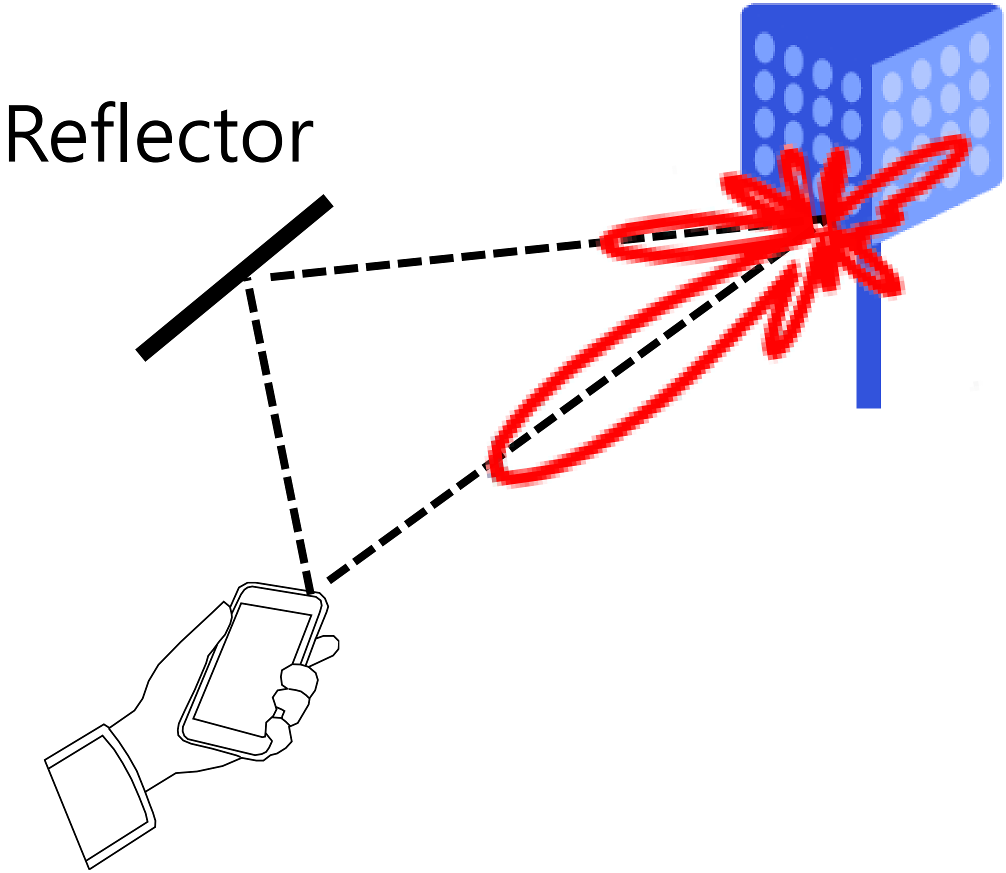
Challenge: mmWave link adaptation



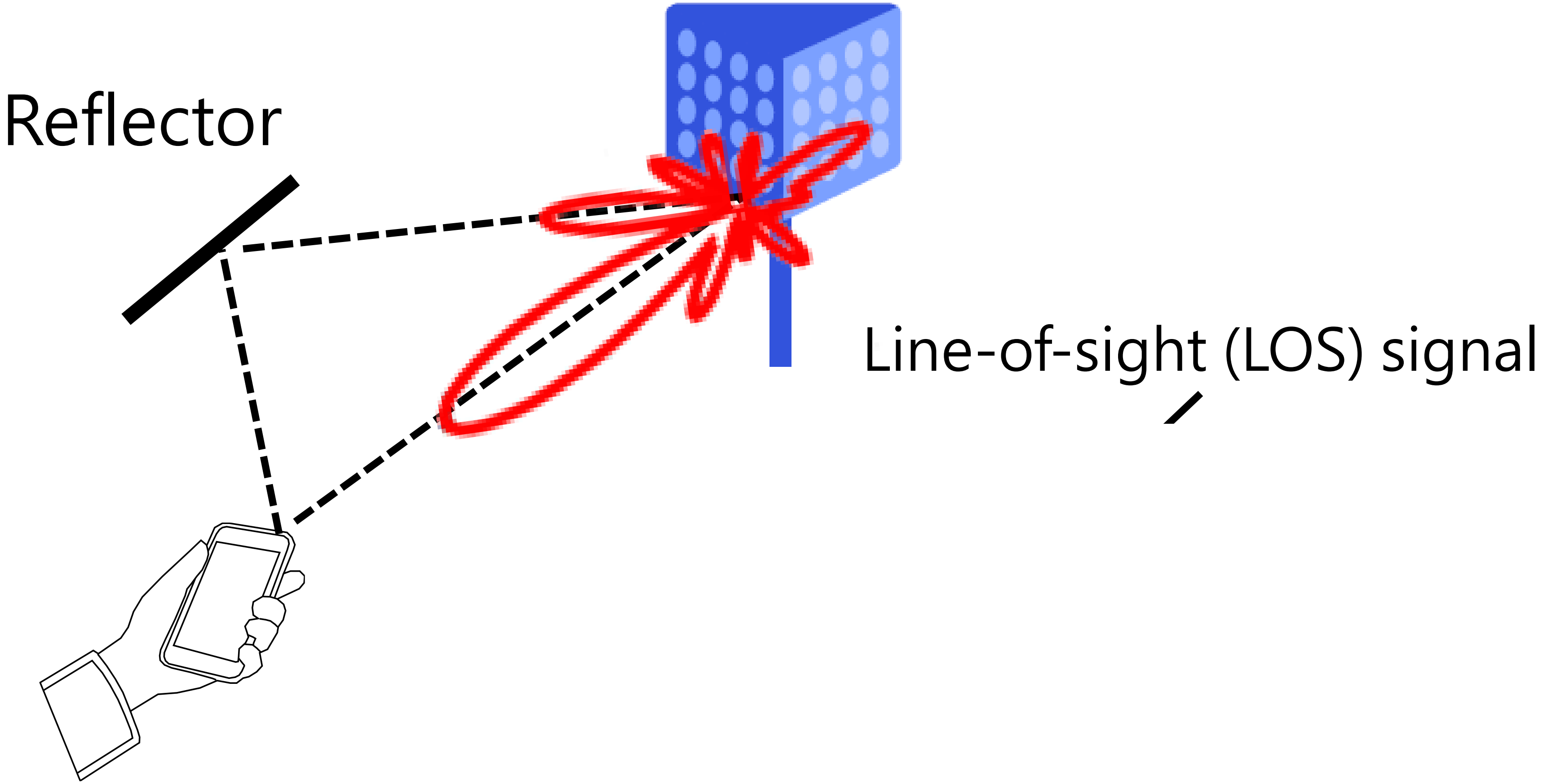
How to scale up beam alignment for large number of beams?



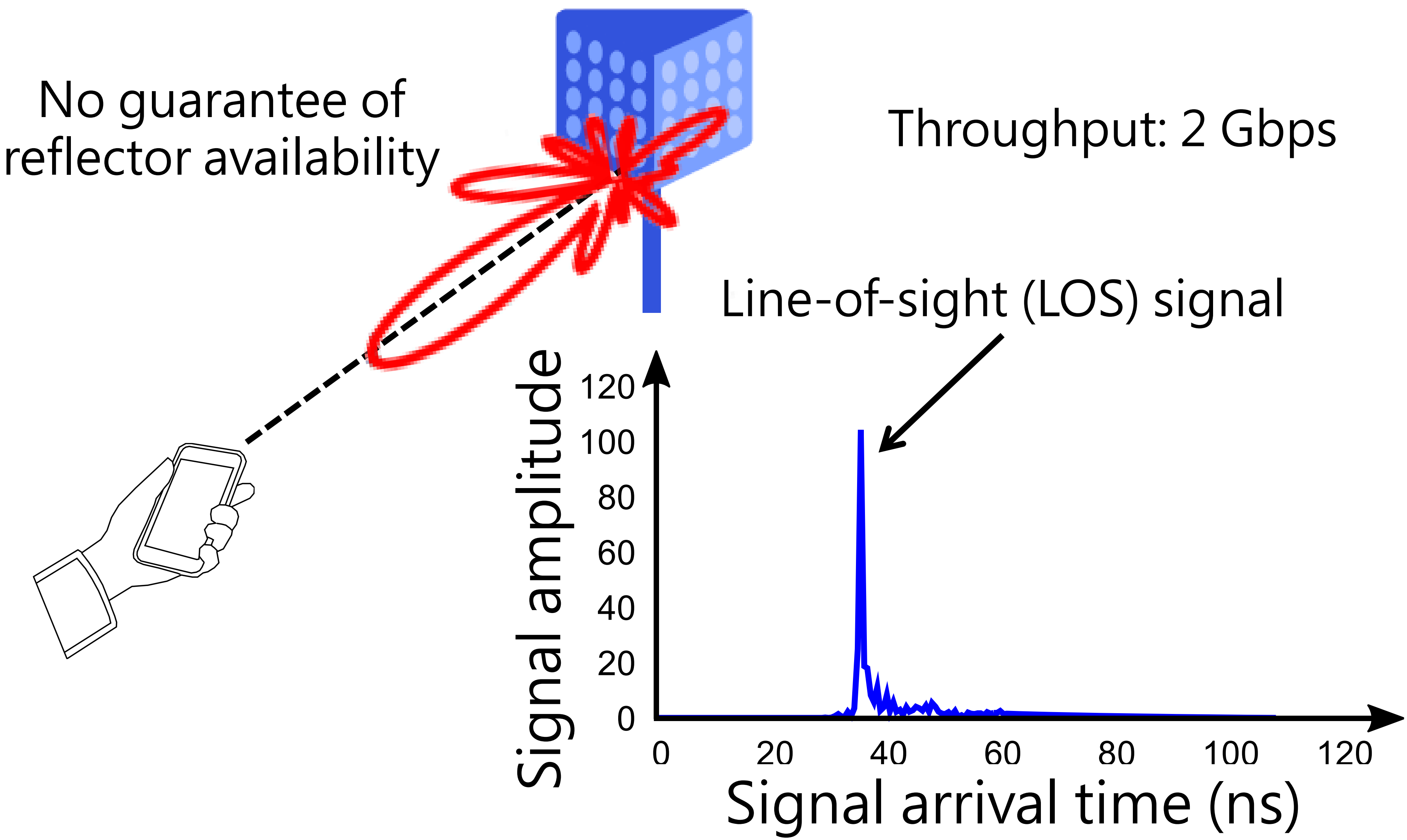
Fast beam alignment



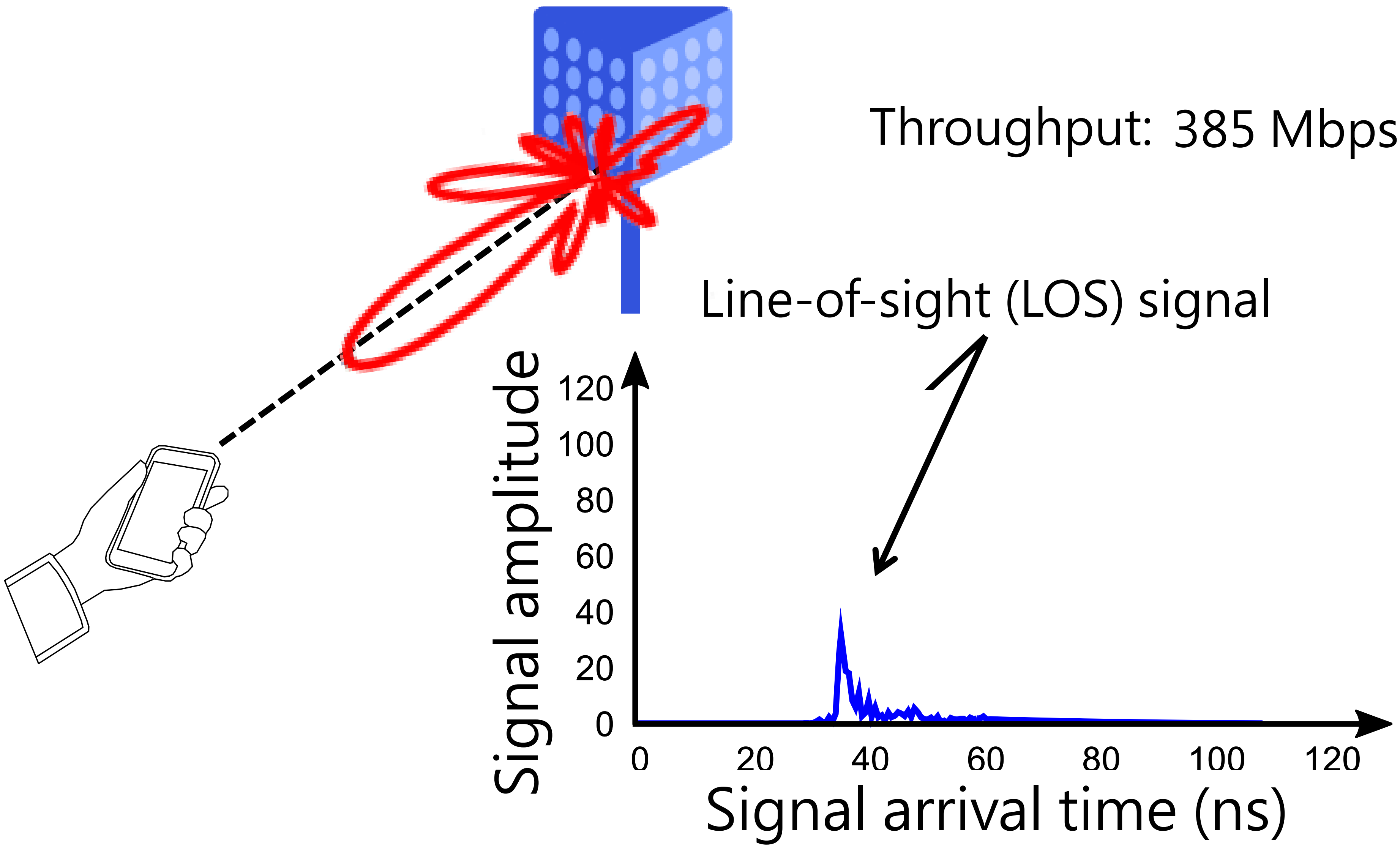
Fast beam alignment



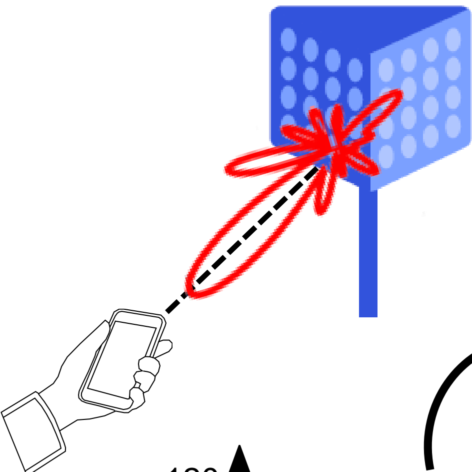
Fast beam alignment



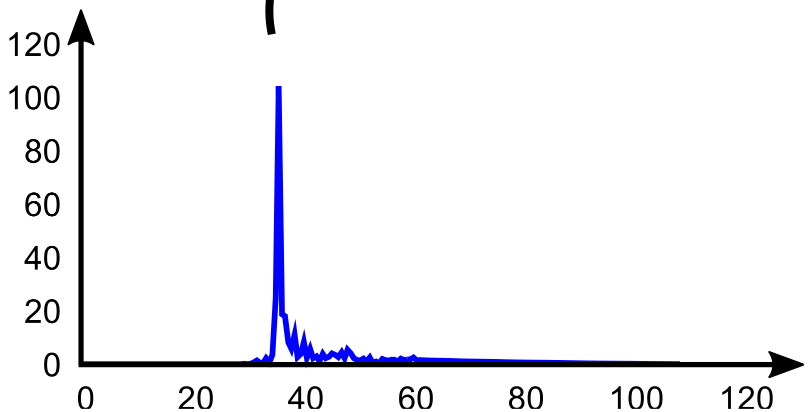
Fast beam alignment

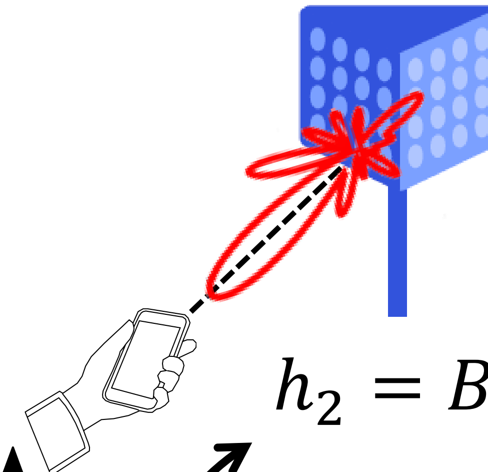


Finding common dominant path

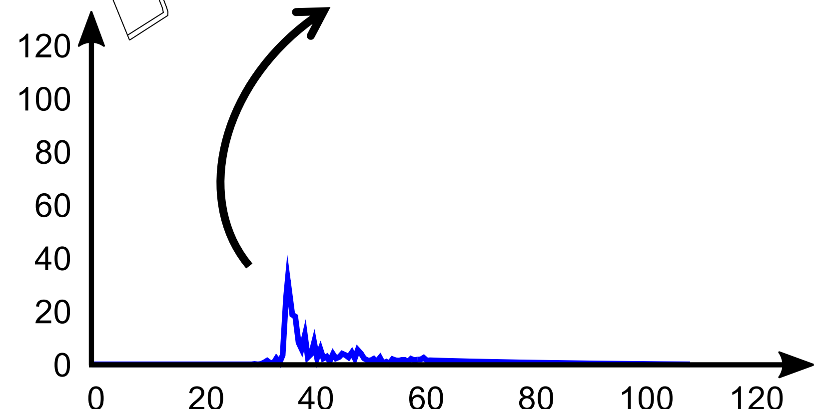


$$h_1 = B_1(\theta) * a$$



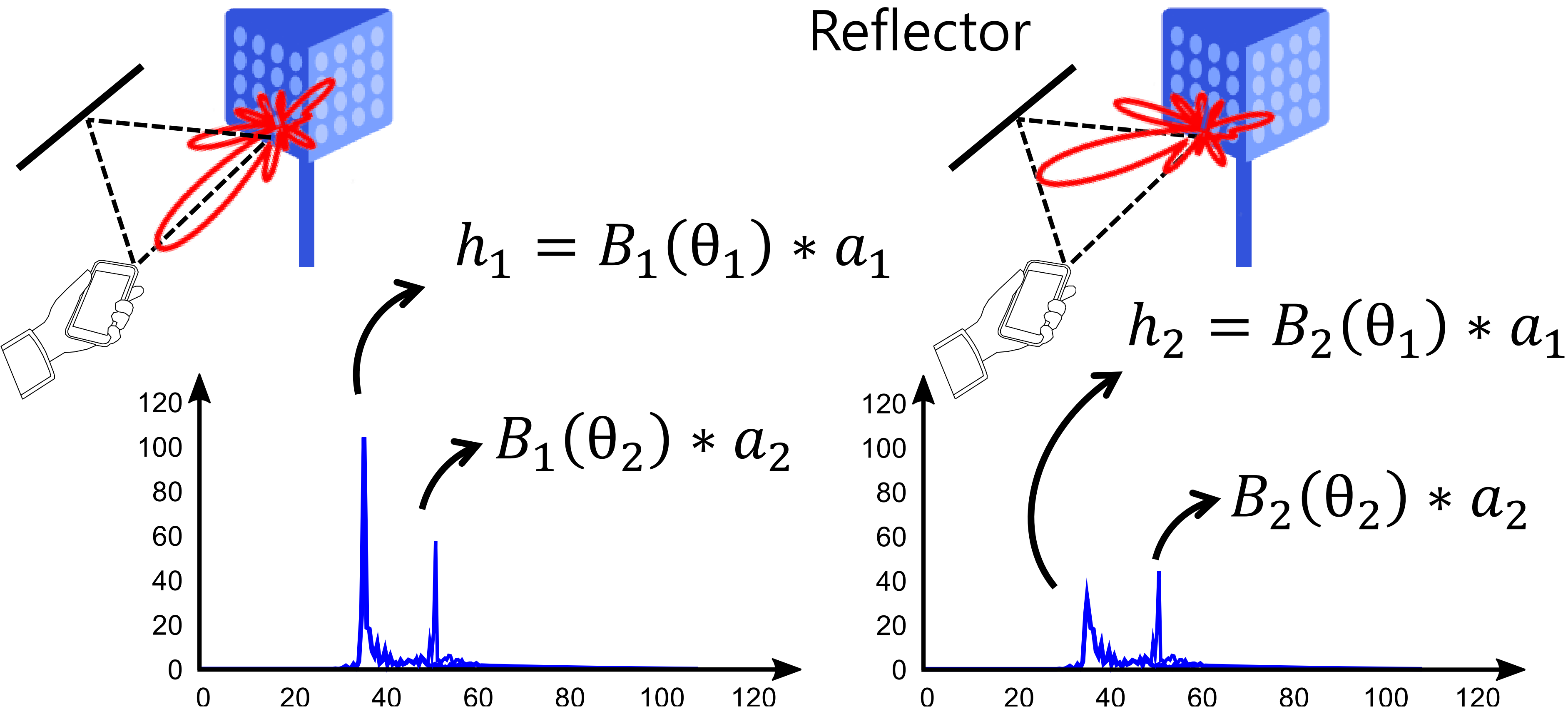


$$h_2 = B_2(\theta) * a$$



$$(a^*, \theta^*) = argmin\ |\underbrace{B_i(\theta) * a}_{\text{Impulse model}} - \underbrace{h_i}_{\text{Measurement}}|^2$$

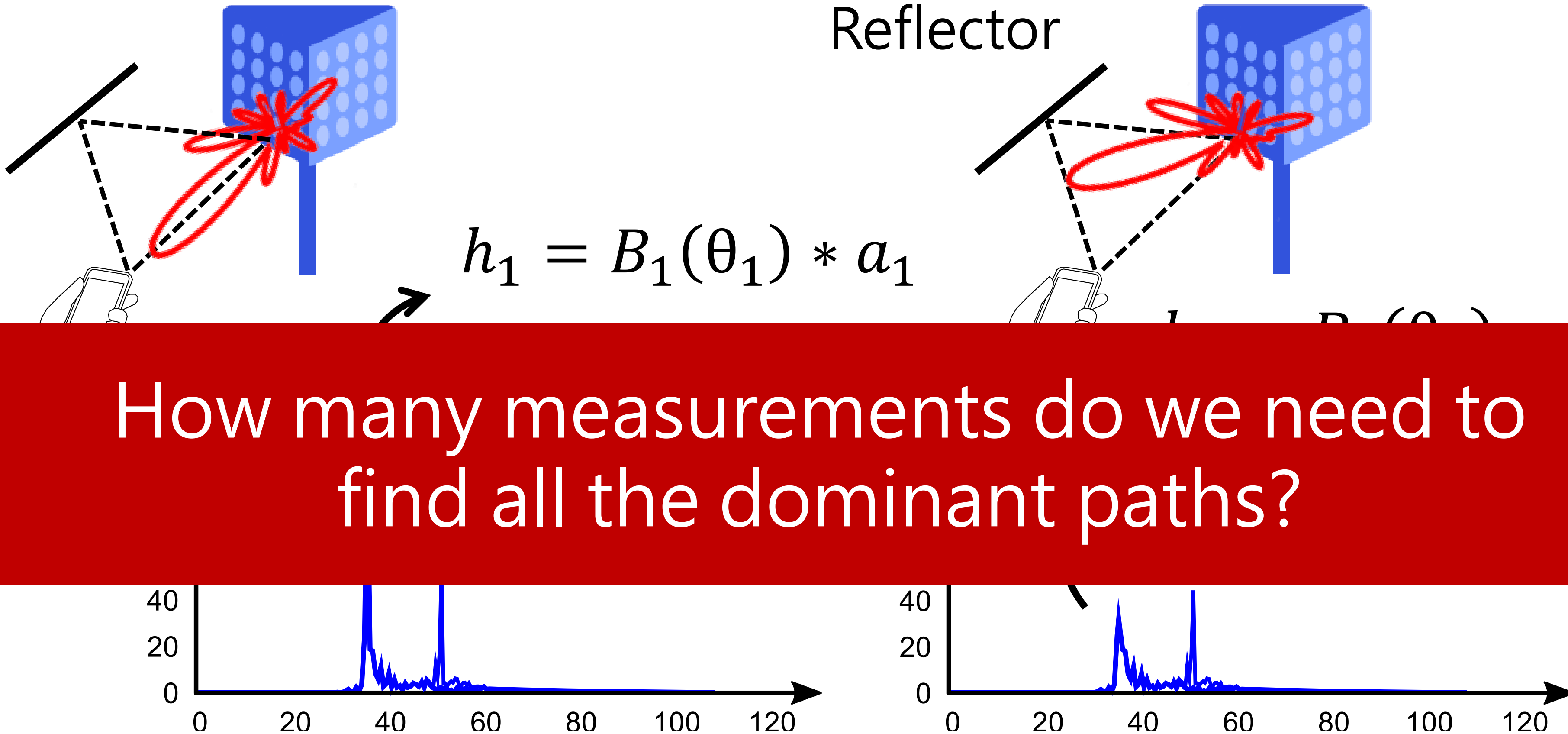
Finding multiple dominant paths



$$(a_1{}^*, \theta_1{}^*) = argmin \ |B_i(\theta_1) * a_1 - h_i|^2$$

$$(a_2{}^*, \theta_2{}^*) = argmin \ |B_i(\theta_2) * a_2 - h_i|^2$$

Finding multiple dominant paths

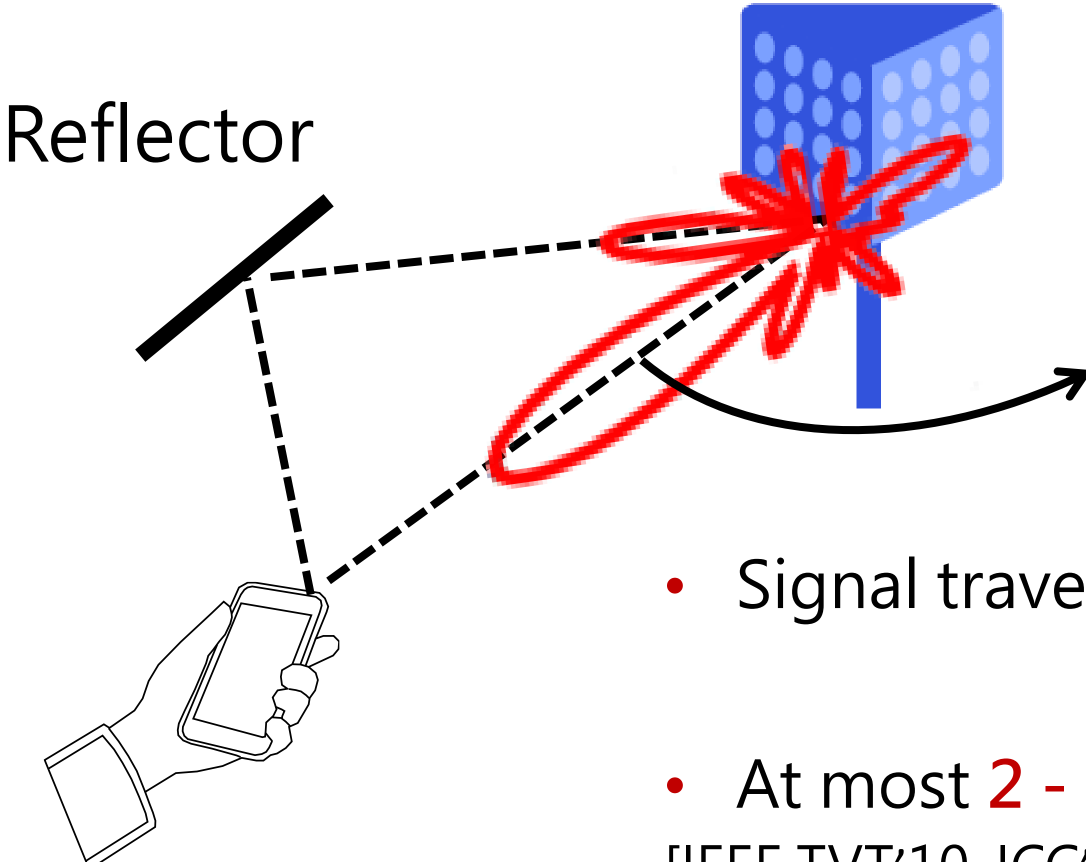


How many measurements do we need to find all the dominant paths?

$$(a_1^*, \theta_1^*) = argmin\ |B_i(\theta_1) * a_1 - h_i|^2$$

$$(a_2^*, \theta_2^*) = argmin\ |B_i(\theta_2) * a_2 - h_i|^2$$

Path sparsity at mmWave



Path variables:
$(a, \theta_{az}, \theta_{el}, \varphi)$

- Signal travels along a few paths only
- At most **2 - 3 paths** exist in practice
[IEEE TVT'10, ICC'14, SIGMETRICS'15, NSDI'16, …]

Upper bound K on the number of paths

Path sparsity at mmWave

We need 4K measurements
to find all the dominant paths

- Signal travels along a few paths only

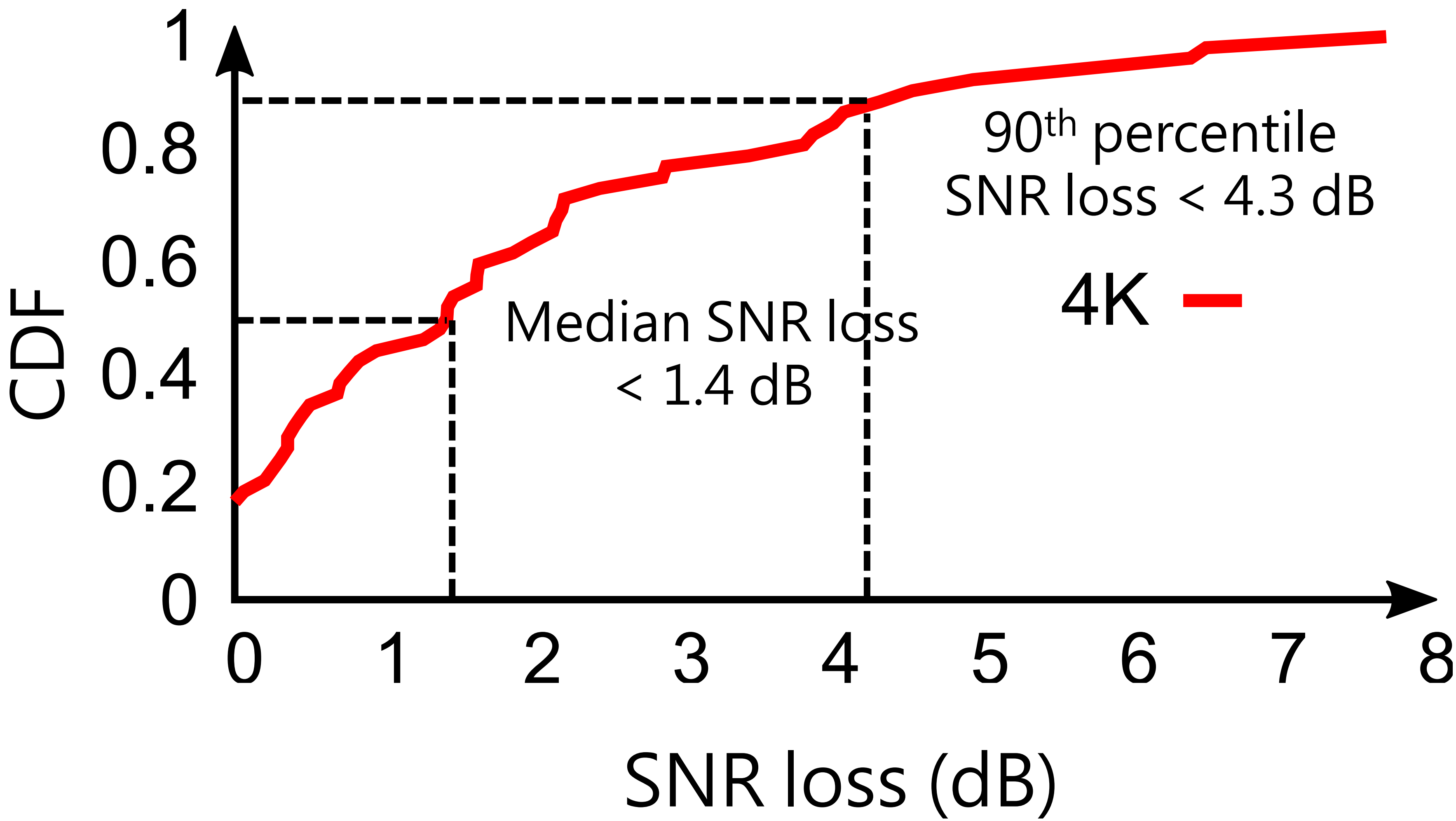
- At most 2 - 3 paths exist in practice
[IEEE TVT’10, ICC’14, SIGMETRICS’15, NSDI’16, …]

Upper bound K on the number of paths

SNR loss from fast beam alignment

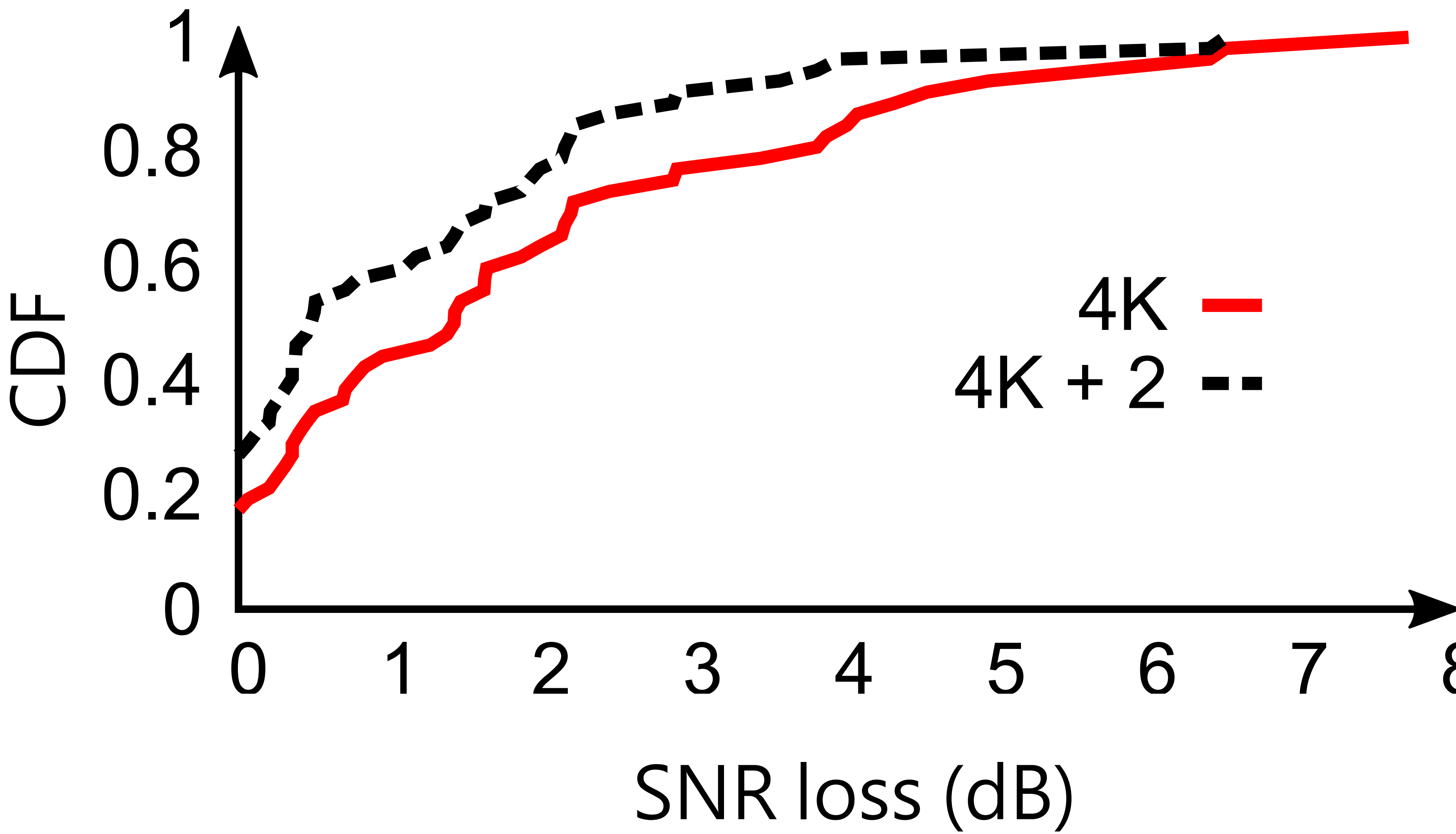
On a COTS testbed with 64 beams

SNR loss from fast beam alignment



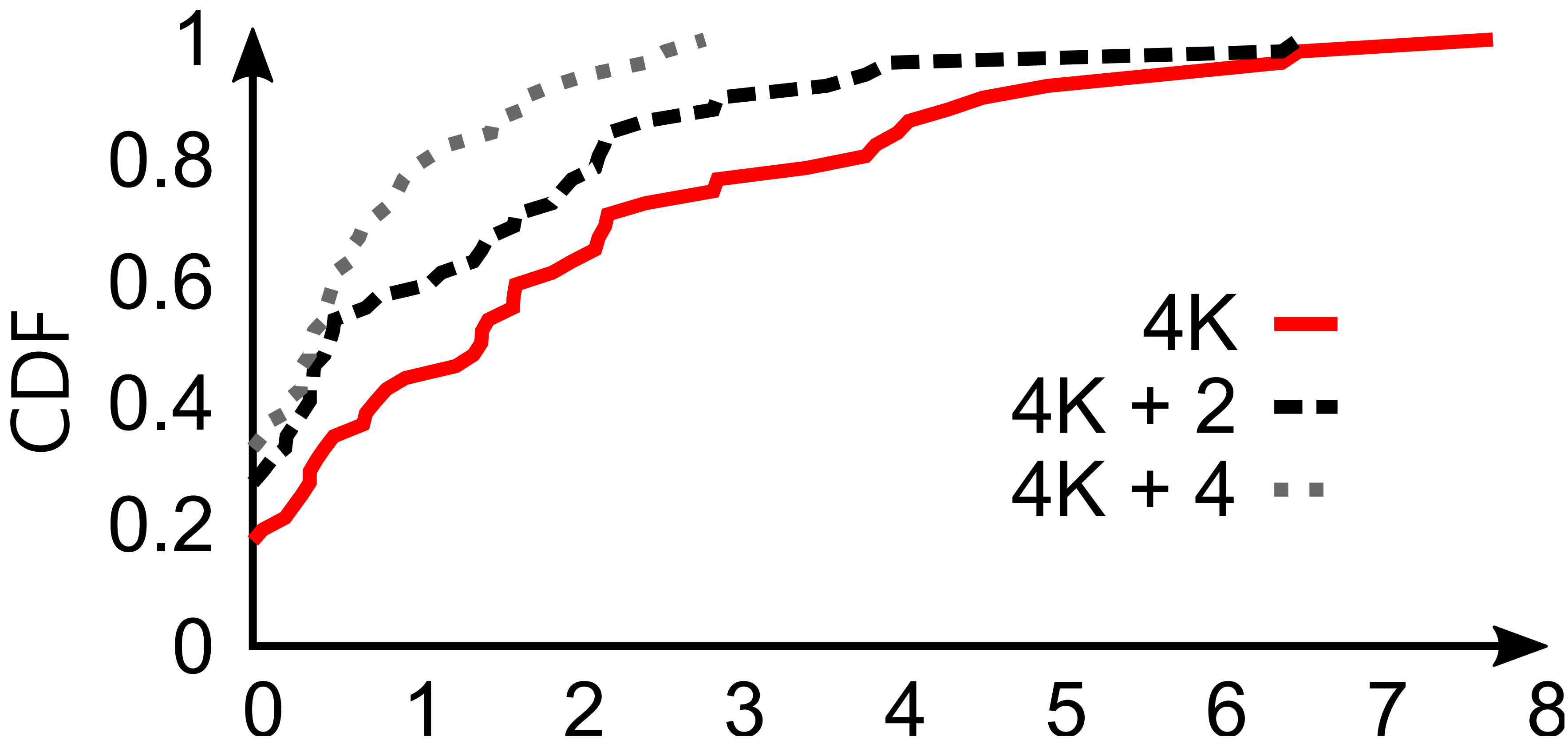
On a COTS testbed with 64 beams

SNR loss from fast beam alignment



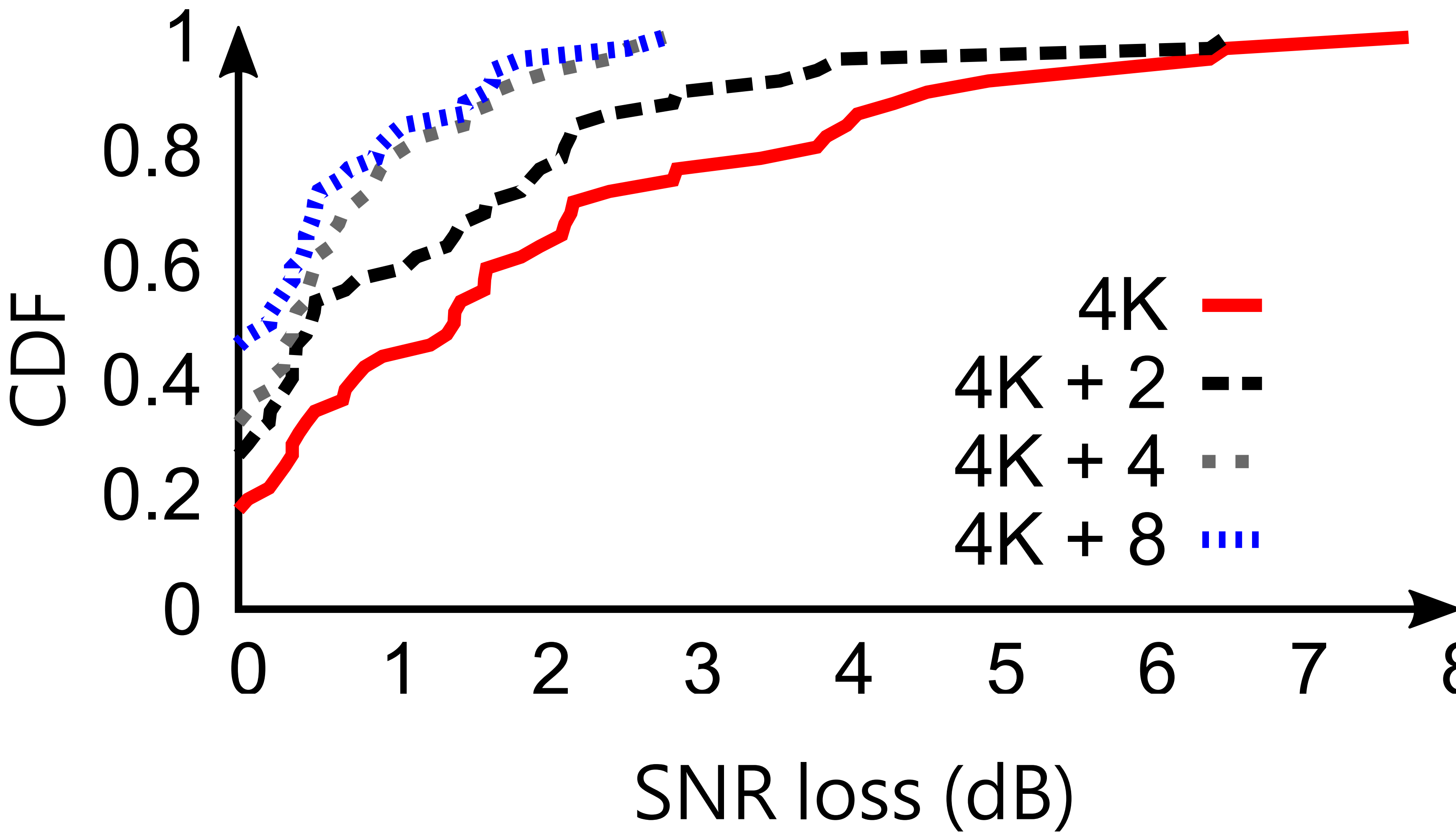
On a COTS testbed with 64 beams

SNR loss from fast beam alignment



On a COTS testbed with 64 beams

SNR loss from fast beam alignment



On a COTS testbed with 64 beams

Beam alignment latency

Beam directions	IEEE 802.11ad	Compressed sensing	Our design (4K + 8)
16			
32			
64			
128			
256			
512			
1024			

Beam alignment latency

Beam directions	IEEE 802.11ad	Compressed sensing	Our design (4K + 8)
16	0.51 ms		
32	1.01 ms		
64	2.03 ms		
128	4.04 ms		
256	106.07 ms		
512	310.11 ms		
1024	775.76 ms		

Beam alignment latency

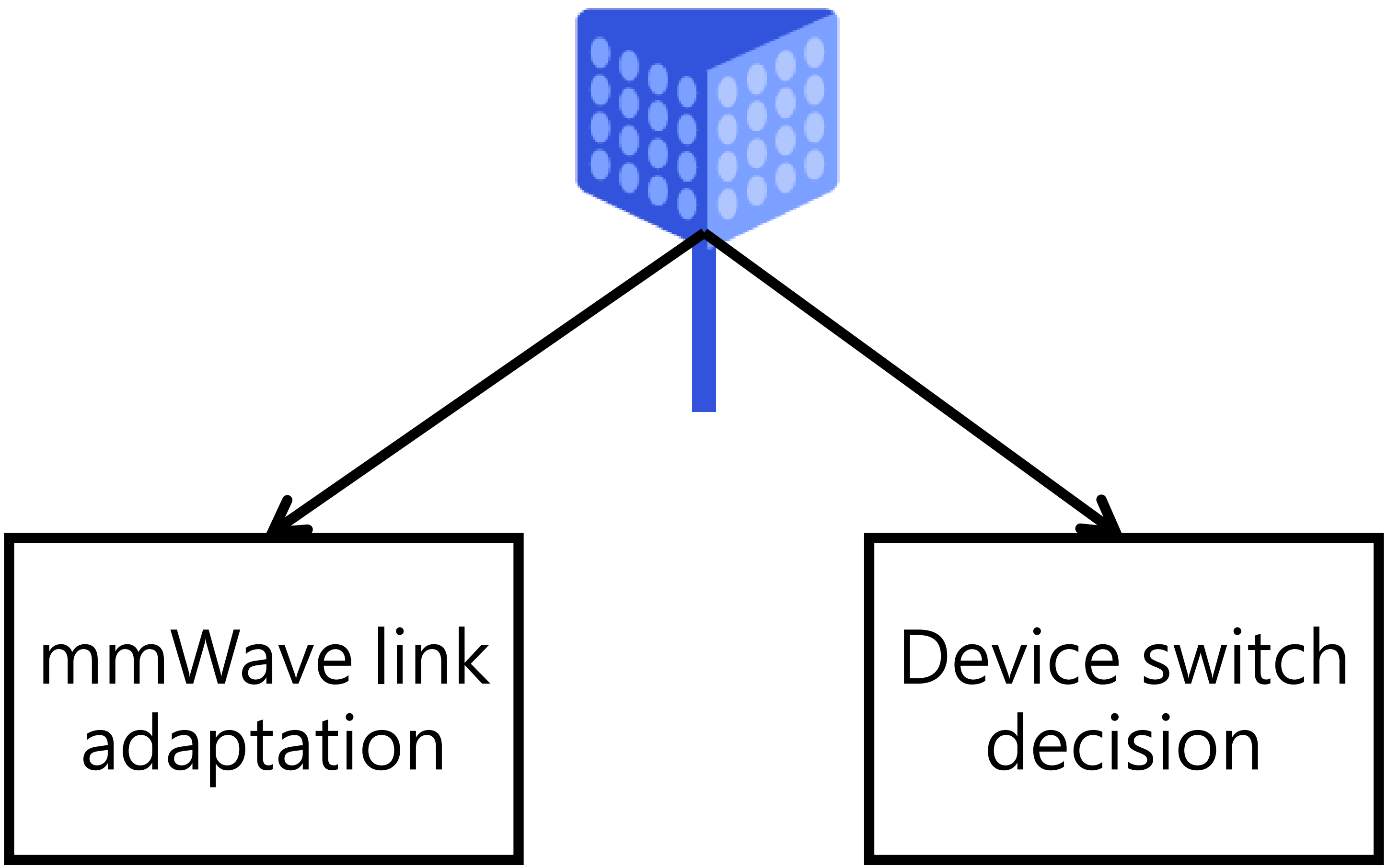
Beam directions	IEEE 802.11ad	Compressed sensing	Our design (4K + 8)
16	0.51 ms	1.32 ms	
32	1.01 ms	1.53 ms	
64	2.03 ms	2.01 ms	
128	4.04 ms	2.67 ms	
256	106.07 ms	2.85 ms	
512	310.11 ms	3.03 ms	
1024	775.76 ms	3.36 ms	

Beam alignment latency

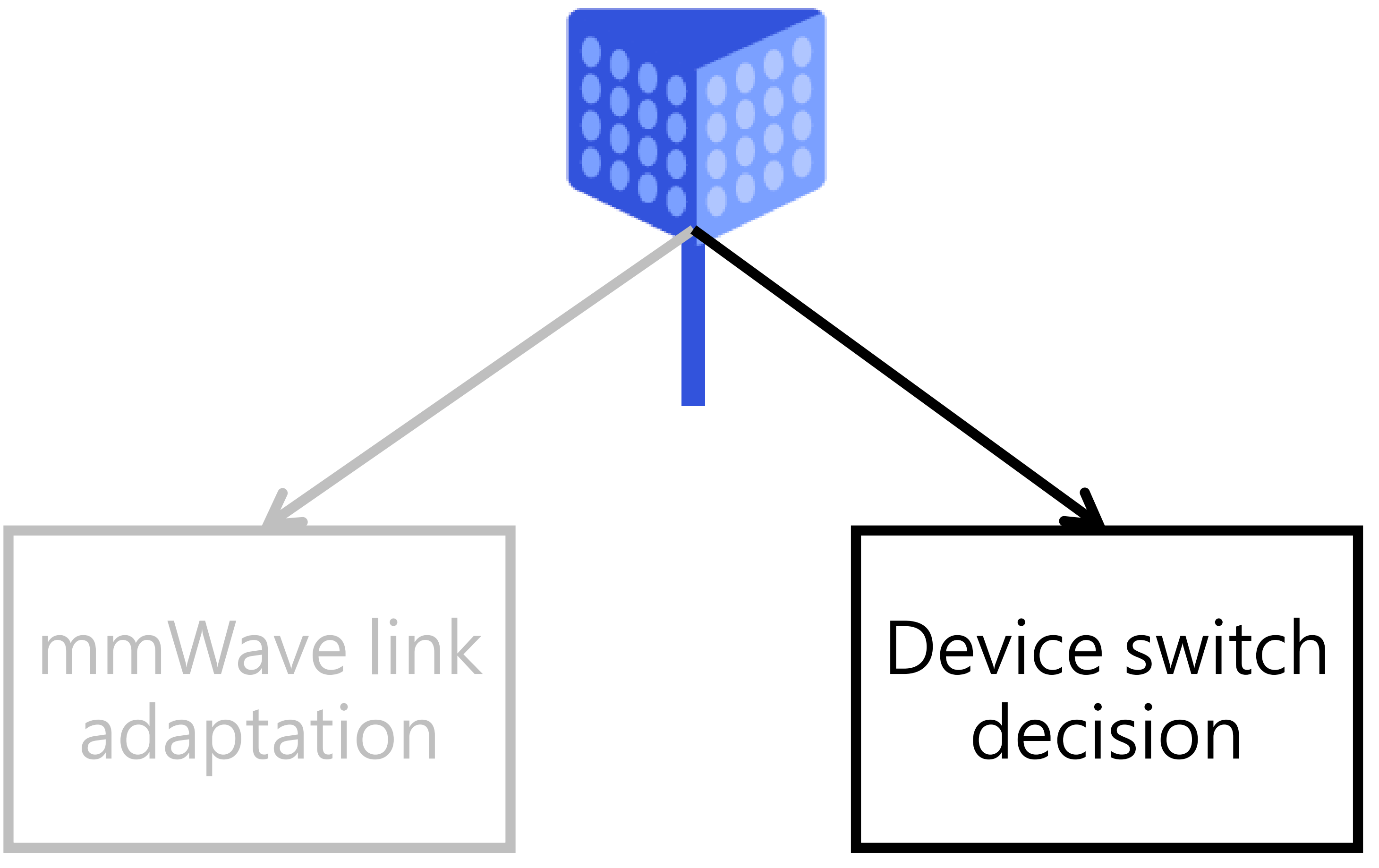
Beam directions	IEEE 802.11ad	Compressed sensing	Our design (4K + 8)
16	0.51 ms	1.32 ms	0.3 ms*
32	1.01 ms	1.53 ms	
64	2.03 ms	2.01 ms	
128	4.04 ms	2.67 ms	
256	106.07 ms	2.85 ms	
512	310.11 ms	3.03 ms	
1024	775.76 ms	3.36 ms	

* 90^{th} percentile SNR loss is below 1.5 dB (SNR range: 5 ~ 15 dB)

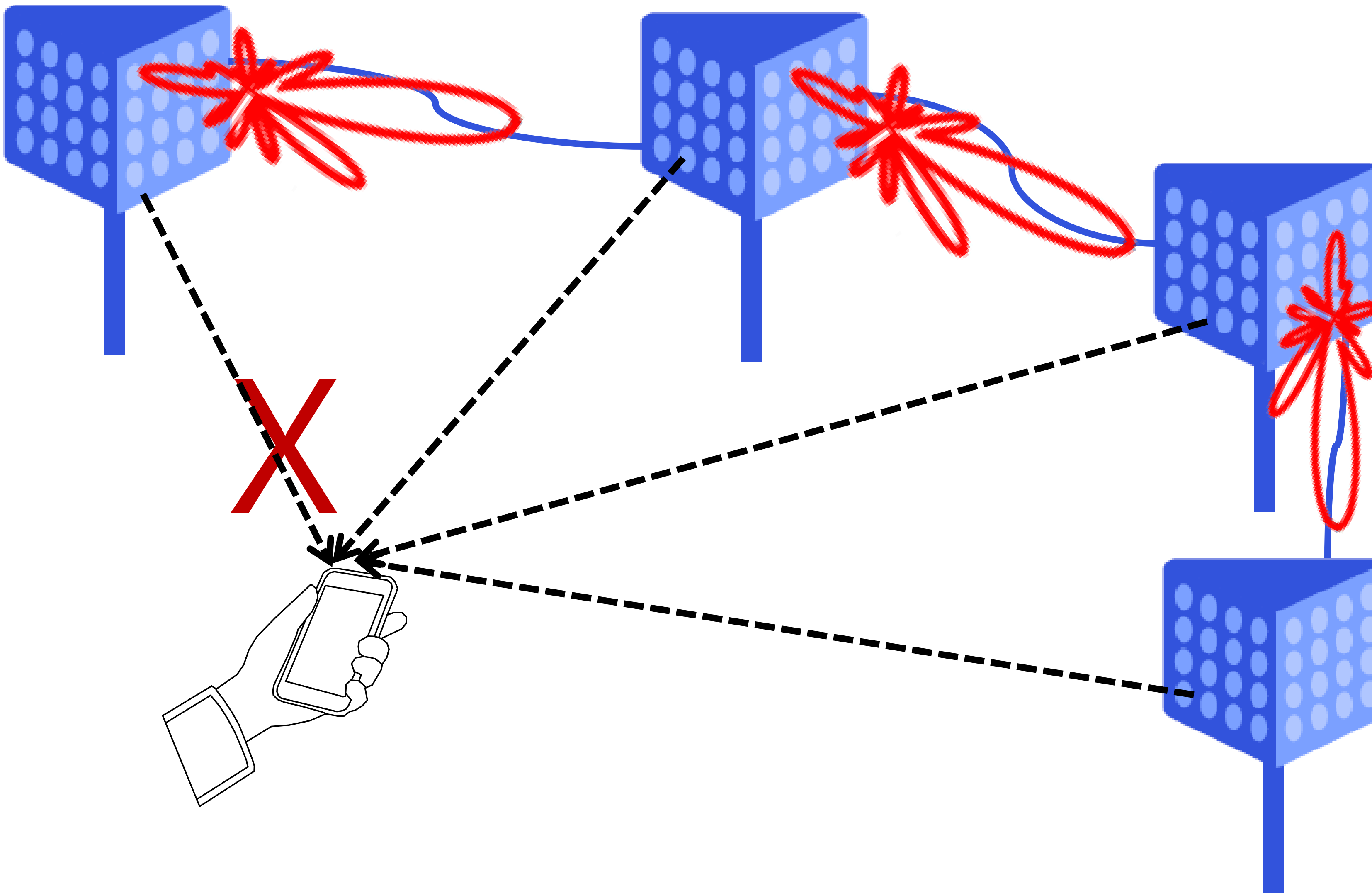
Challenges



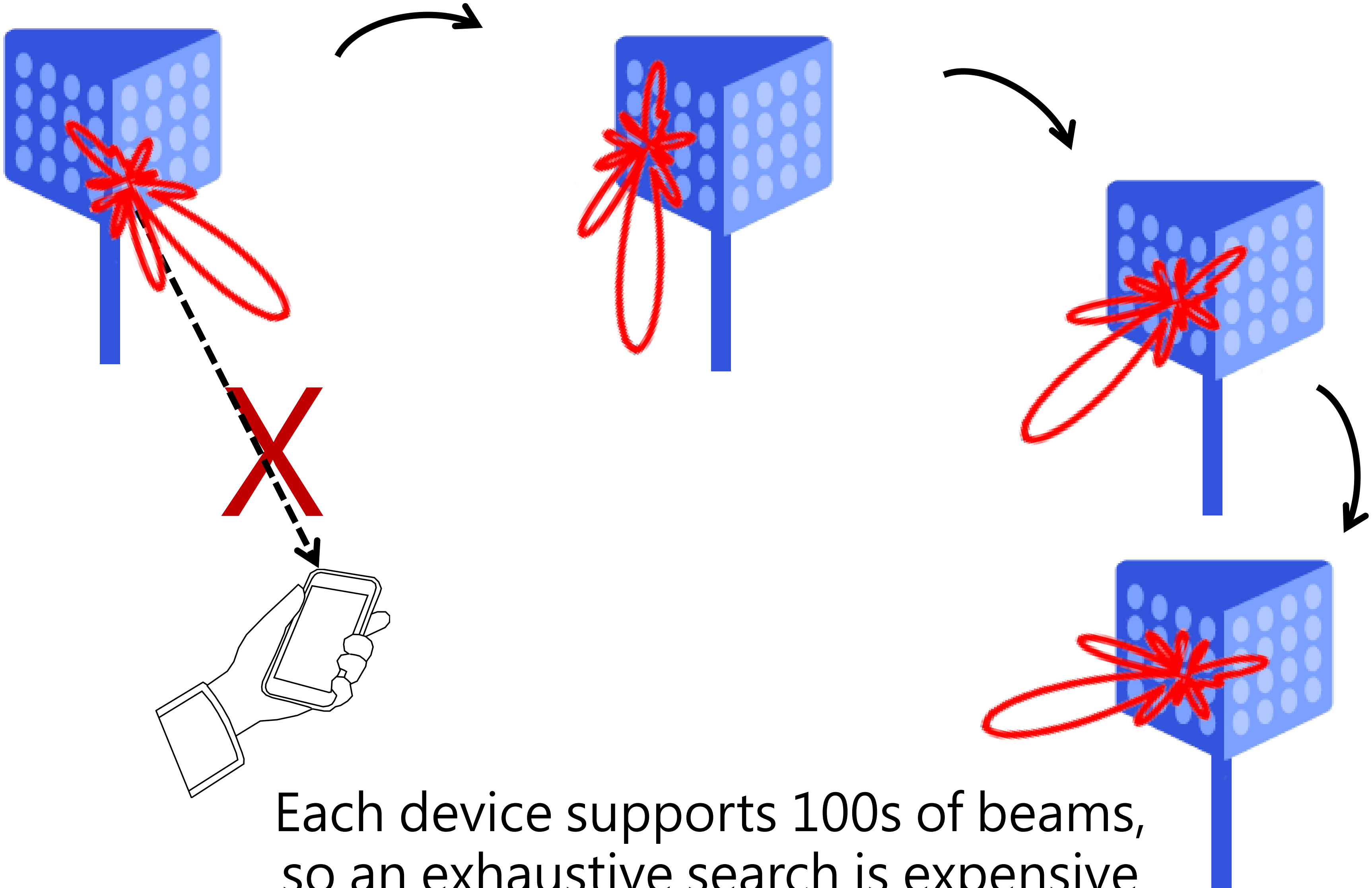
Challenges



mmWave device switch

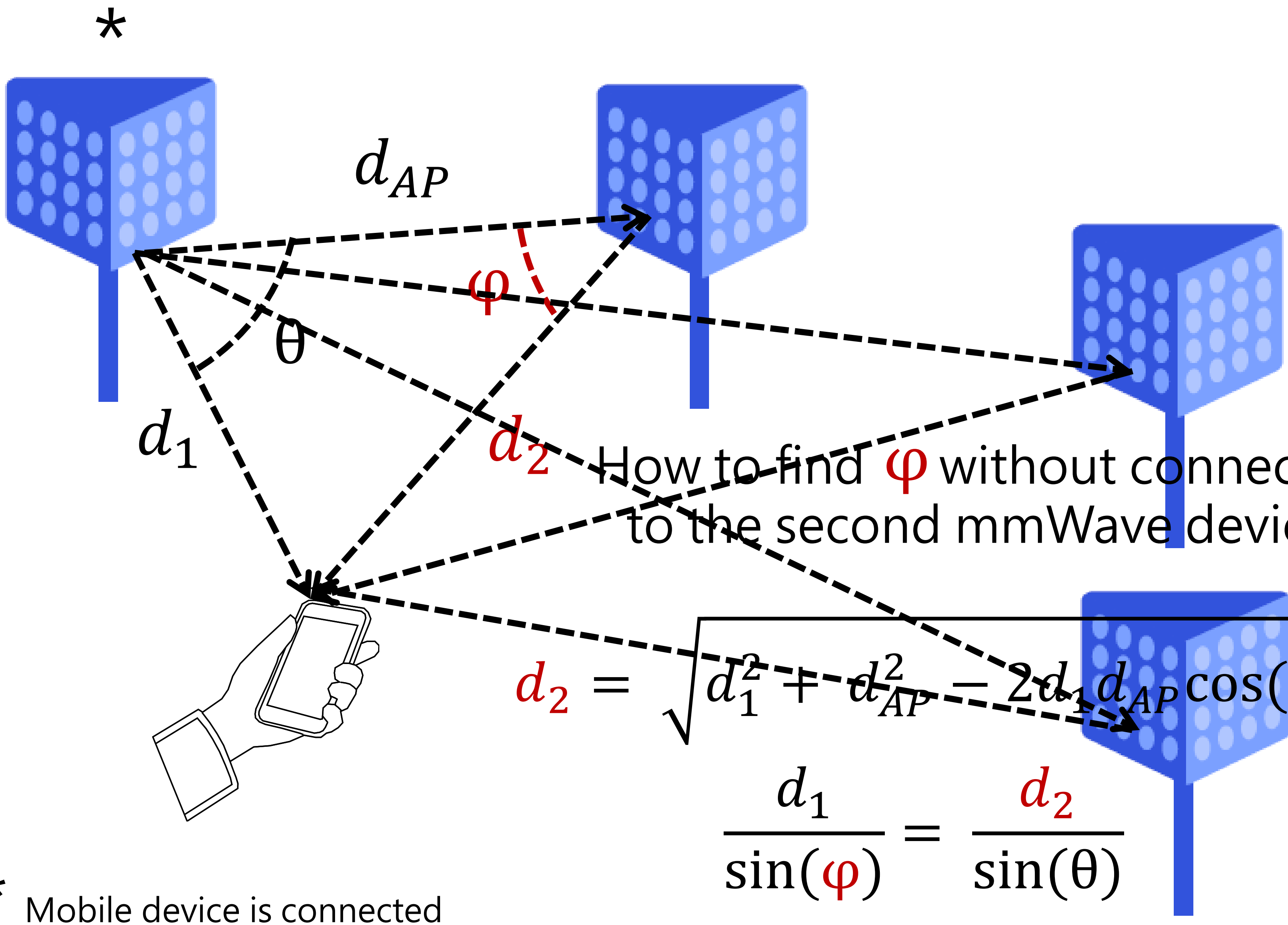


Challenge: device switch decision



Each device supports 100s of beams,
so an exhaustive search is expensive

Predictive device switch



How to find φ without connecting to the second mmWave device?

$$d_2 = \sqrt{d_1^2 + d_{AP}^2 - 2d_1 d_{AP}\cos(\theta)}$$

$$\frac{d_1}{\sin(\varphi)} = \frac{d_2}{\sin(\theta)}$$

* Mobile device is connected

Fast device switch result

3x faster device switch time

Summary

Potentials and challenges of mmWave networks

* Wide-spectrum at mmWave enables high-throughput and low-latency applications
* Beam alignment & blockage are key-barriers for mass adoption
* System design needs optimizations across link, protocol, and system stack

System summary

* Sub-ms scalable beam alignment at mmWave
* Sub-10 ms multi-device cooperation
* End-to-end system, real-time, and standard-compliant