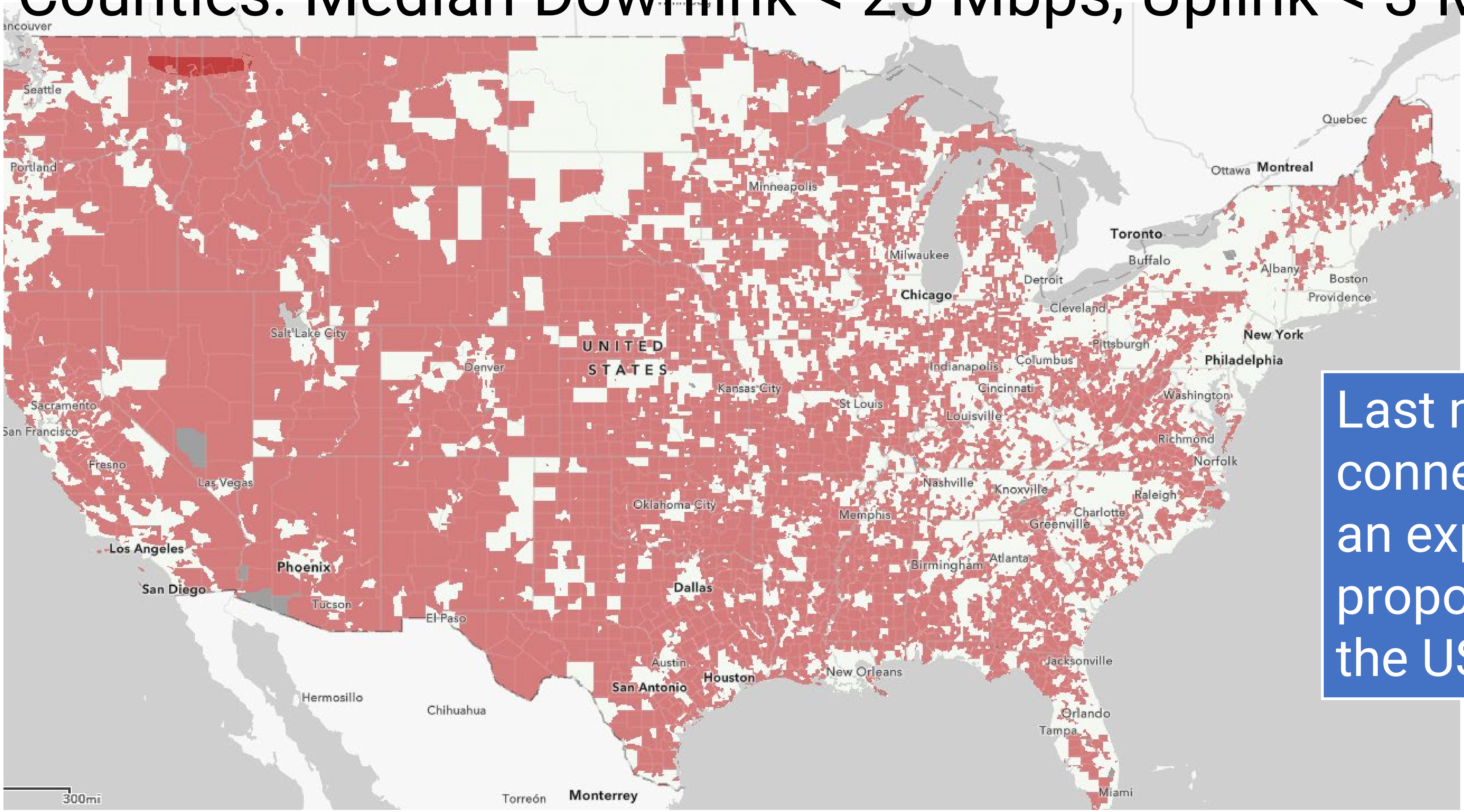
Minimalistic Beam Management Protocols

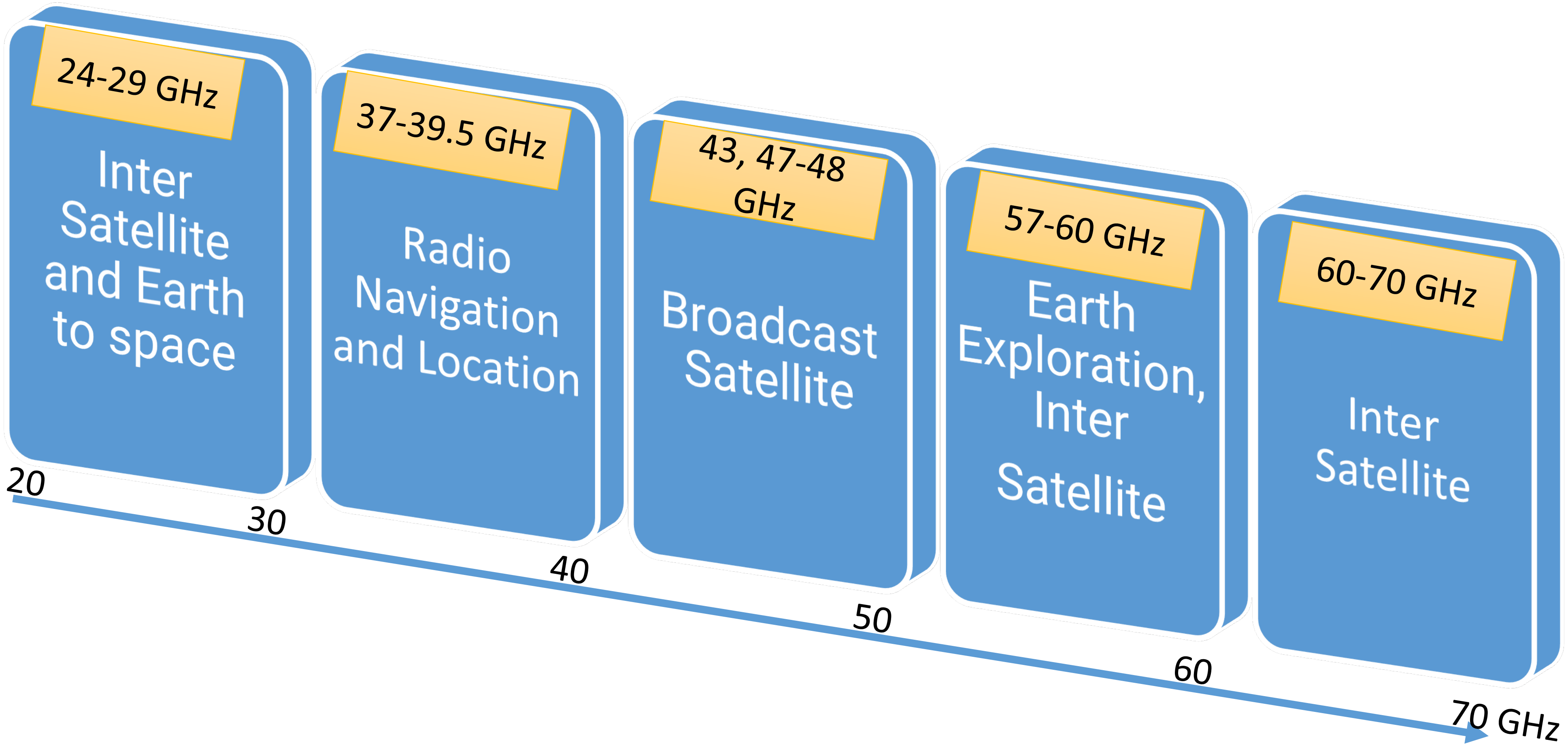
Counties: Median Downlink < 25 Mbps, Uplink < 3 Mbps



Last mile fiber connectivity is an expensive proposition in the US

https://broadbandusa.maps.arcgis.com/apps/webappviewer/index.html?id=e2b4907376b548f892672ef6afbc0da5

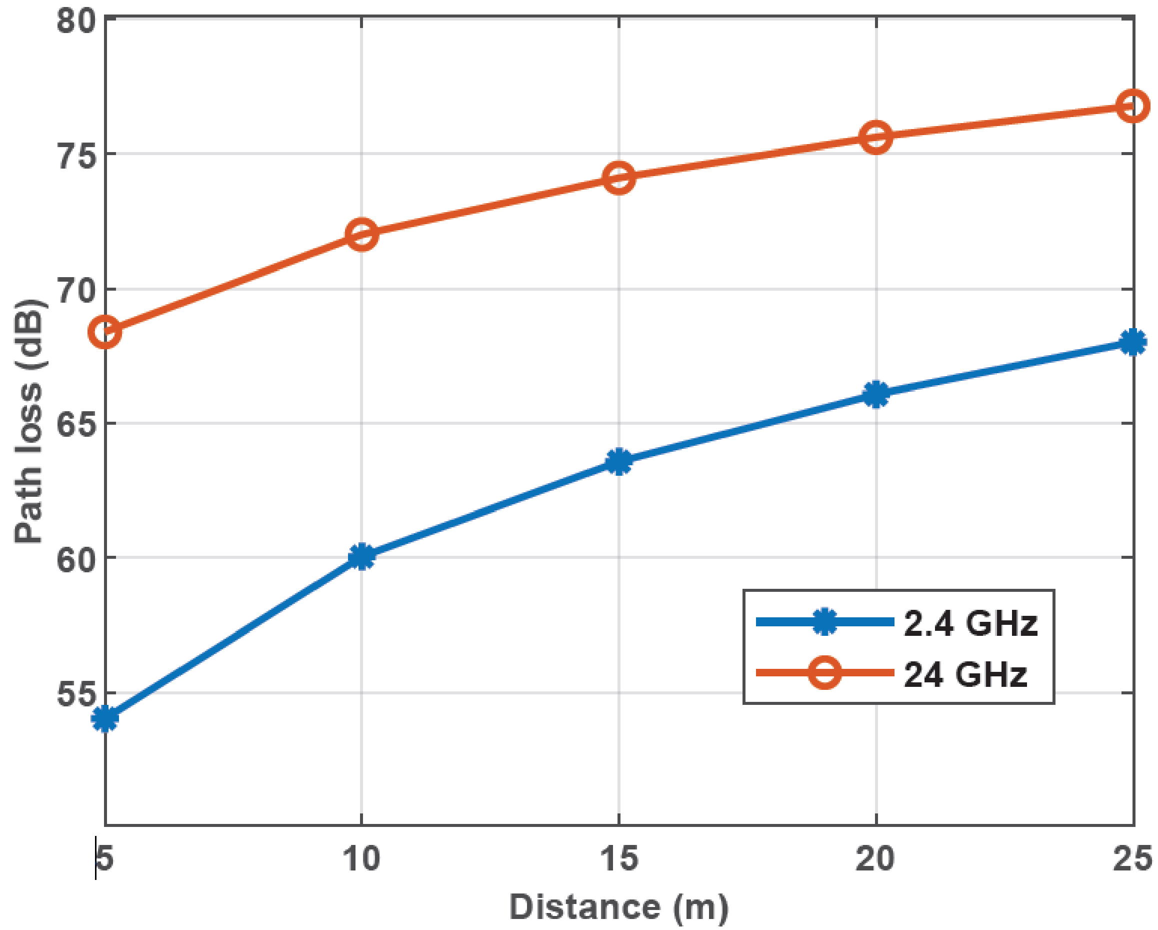
mm-Wave Spectrum



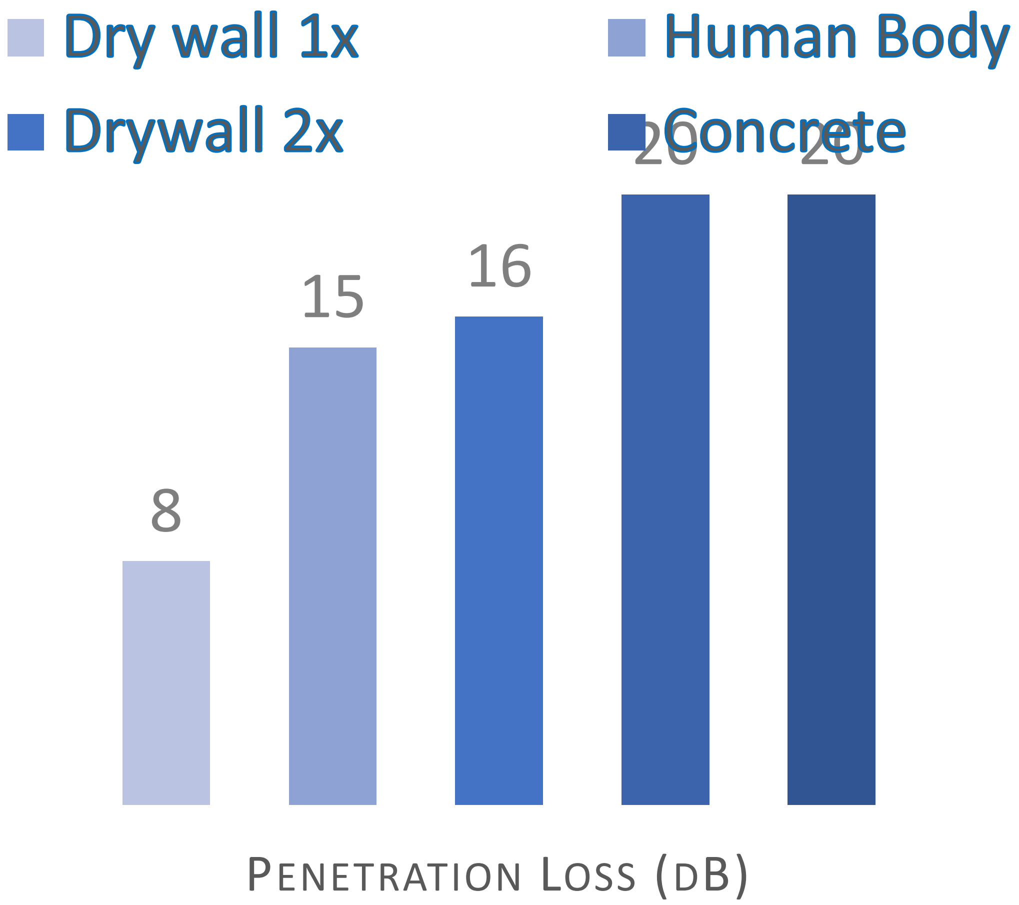
https://www.ntia.doc.gov/files/ntia/publications/january_2016_spectrum_wall_chart.pdf

mmWave Propagation

- Path Loss



- Penetration Loss



Overcoming Loss

Traditionally communication systems operate omni-directionally

Naïve way - increase transmit power to increase range

But mobile devices are power limited

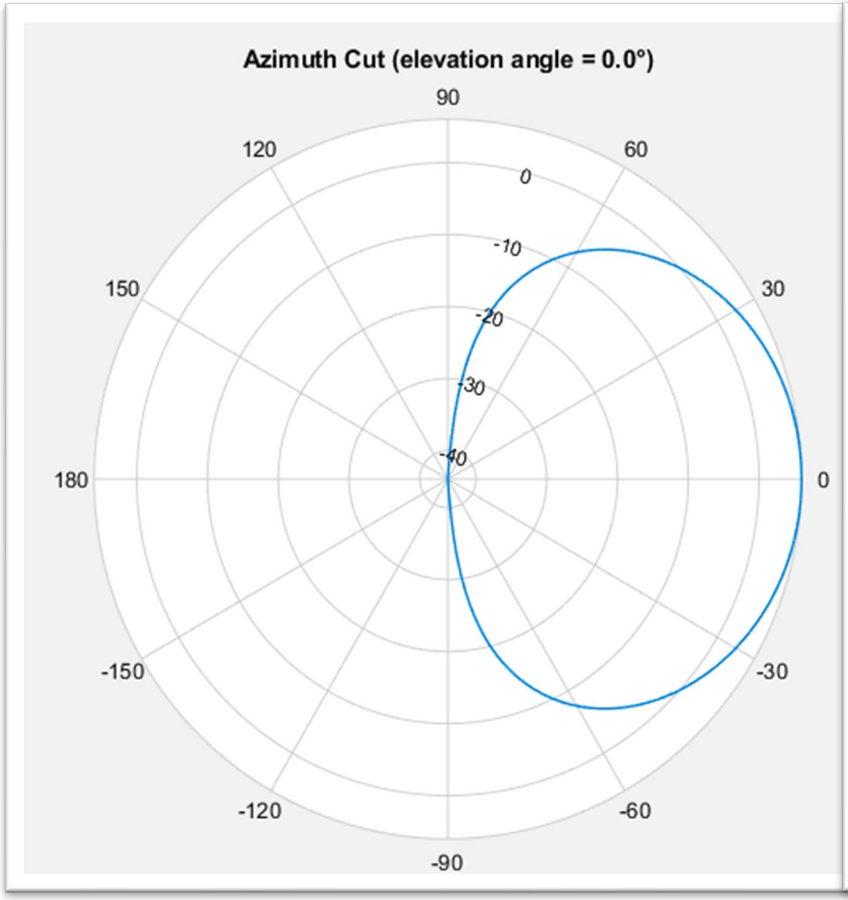
Garner substantial gains with directional communication through phased arrays

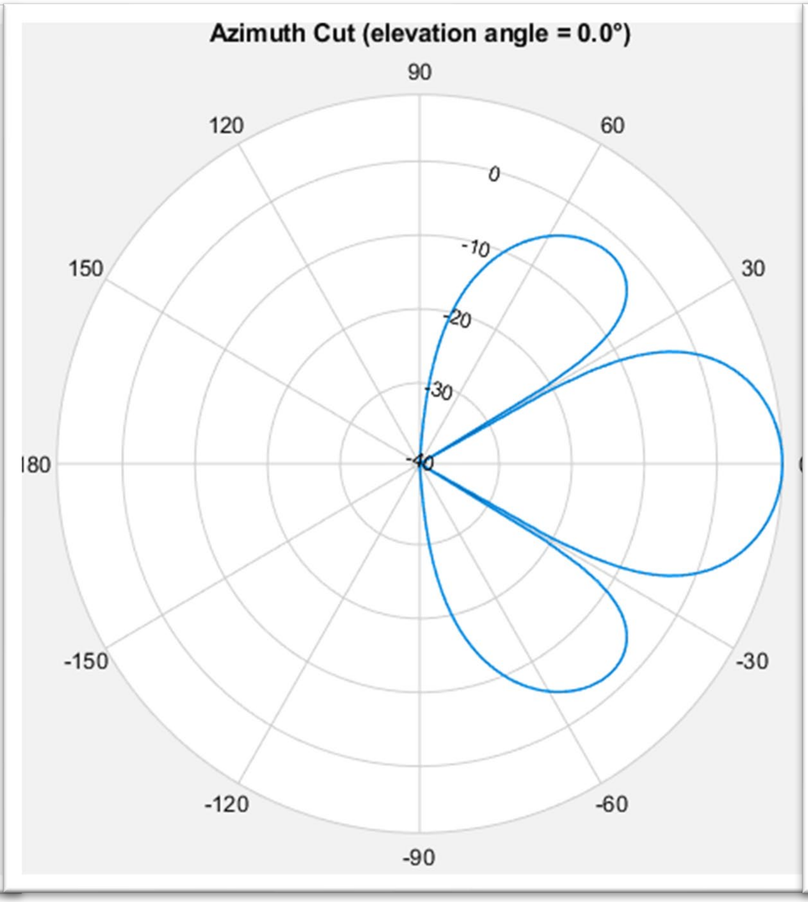
Phased Arrays

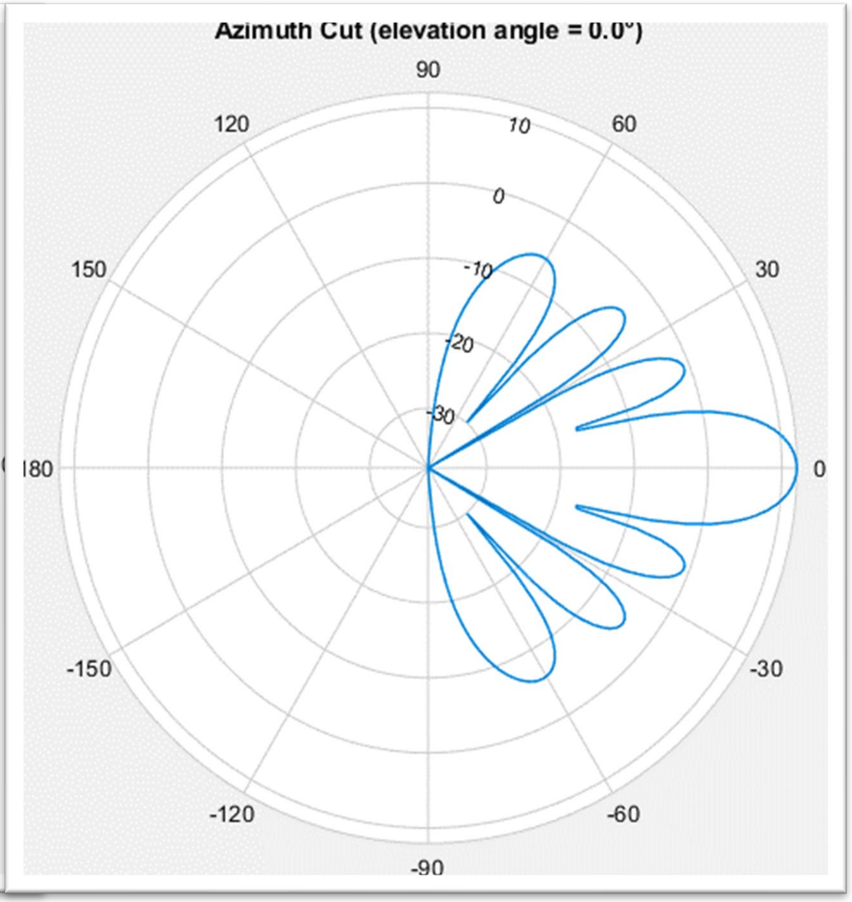
Gain = 6 dBi HPBW=60 deg

Gain = 9 dBi HPBW=26 deg

Gain = 12 dBi HPBW=12 deg







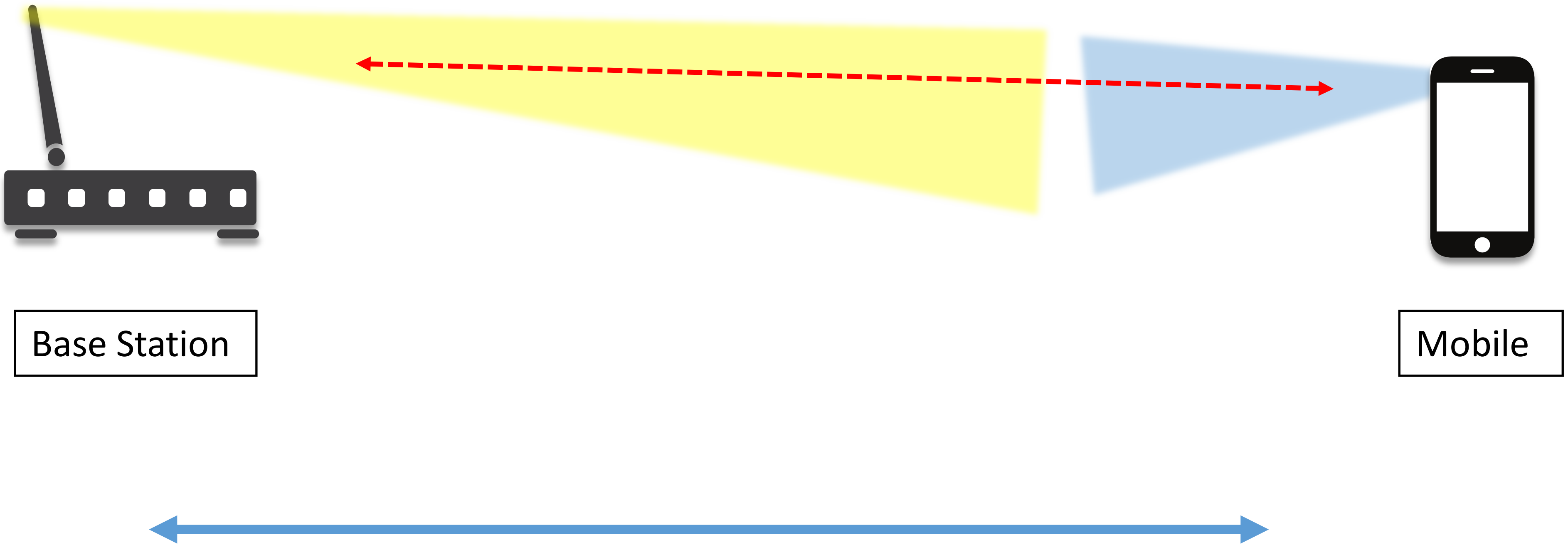
Cobra Dane,Alaska
L-Band Array, 1943

Weather Radar

Typhoon, fighter jet

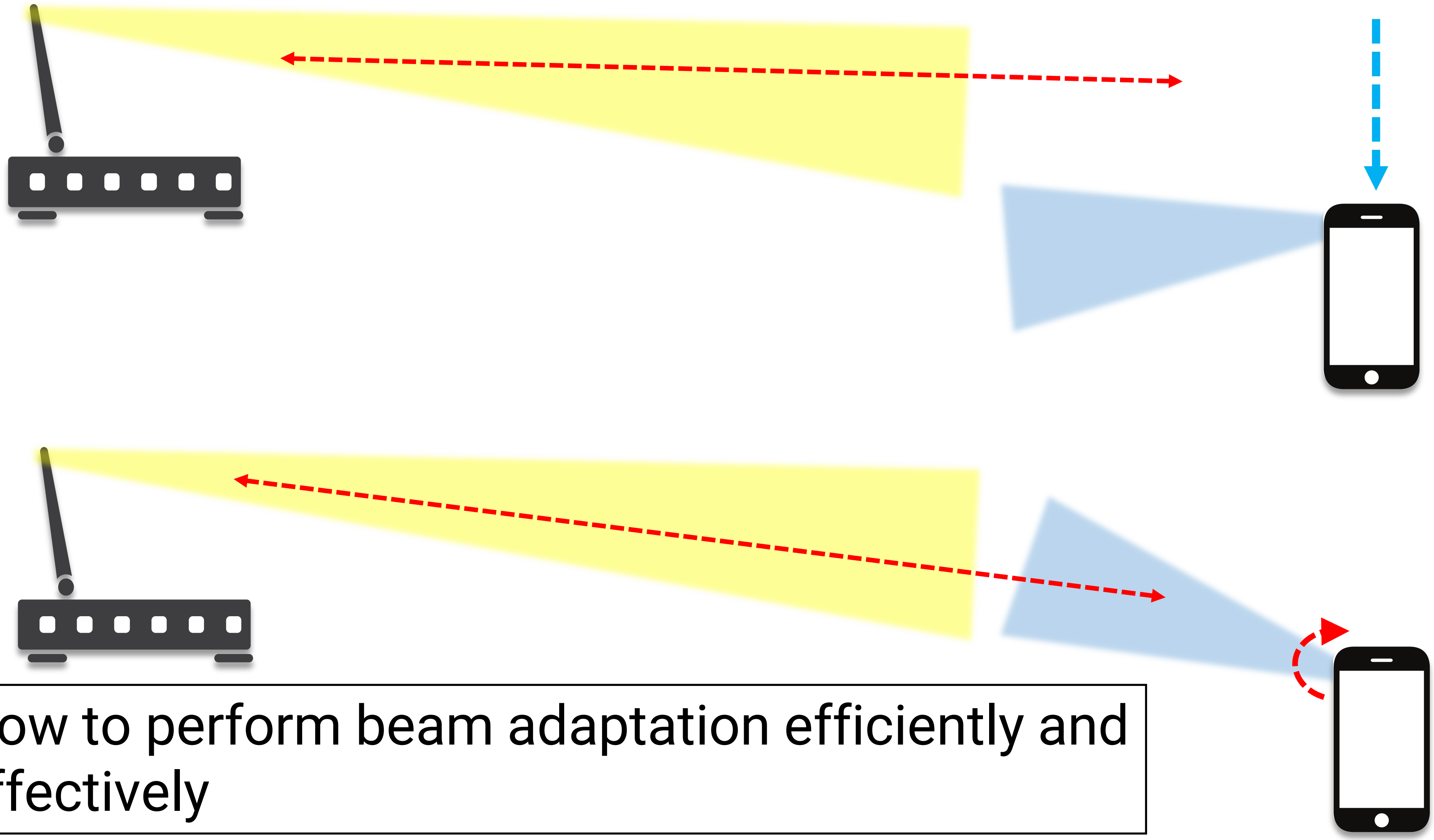
Deep space network

Directional Communication



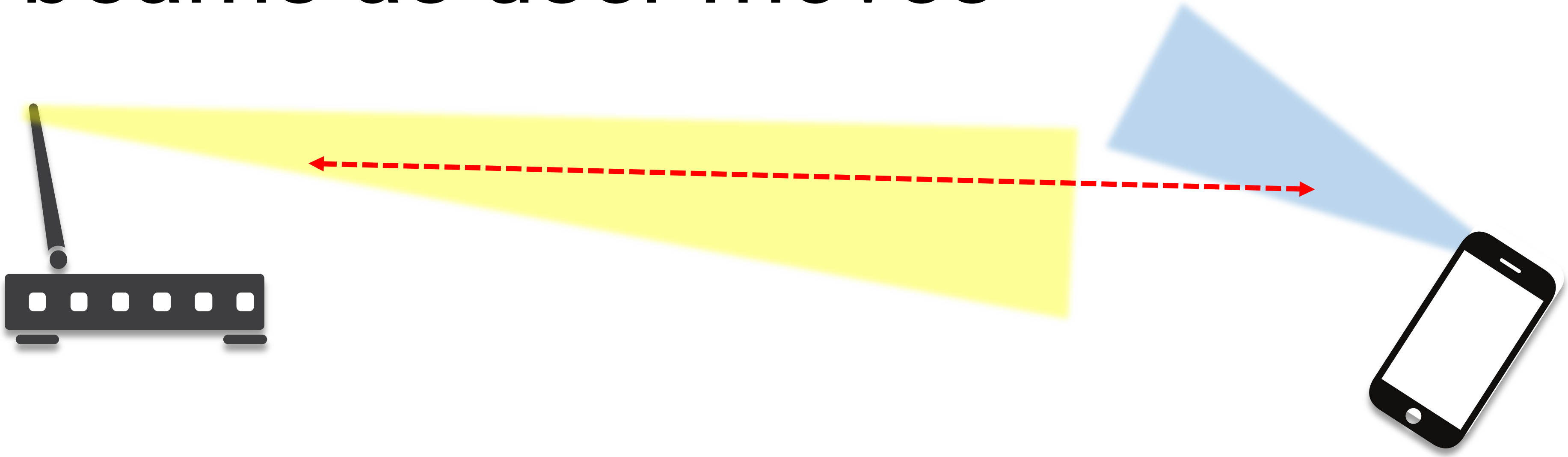
Loss = $Power_{Tx} - Power_{Rx}$

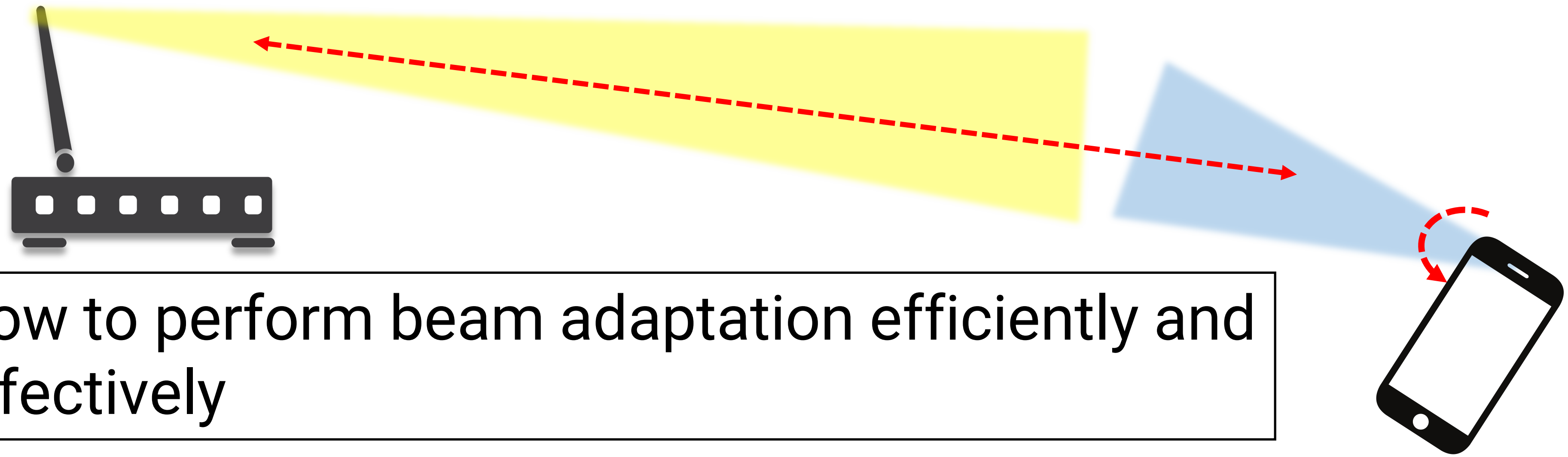
Mobility will need constant re-alignment of beams as user moves



How to perform beam adaptation efficiently and effectively

Mobility will need constant re-alignment of beams as user moves





How to perform beam adaptation efficiently and effectively

Beam Adaptation

- Without Beam Adaptation→ link fails
- User will need to be re-acquired
- Re-acquisition is time intensive
  - In 5G, Base Station transmits in 64 directions every 20ms
  - For mobile to discover a base station beam, takes up to 1.28 seconds
- Re-alignment must be quick to avoid long silent periods

Beam Adaptation in 5G NR

- 5G NR provides *mechanisms* to control beams – *not policies*
- Beam Management is a policy left for implementation

Several suggestions for policies have been made in the literature

<u>Out-of-band beam management:</u>

Motion Sensor assisted

- Accelerometer; Gyroscope; Location; Pose

Approach:

Base Station predicts user location and pose using data from sensors to switch beams

Shortcomings:

- Modem to Sensor communication latency
- Requires a reliable uplink channel to collect data
- Need complex motion prediction model for accuracy

T. Wei and X. Zhang, UCSD- MobiCom '17
Zhicheng Yang et. al, UC-Davis, MASS'15

Several suggestions for policies have been made in the literature

<u>Out-of-band beam management:</u>

Light Sensors

Approach

- Use light sensors on mobile to detect lights on Access point
- Find angle of arrival of light
- Orient radio beam

Shortcomings

- Sensor to modem communication
- Angle detection complexity

T. Nitsche, A. B. Flores, E. W. Knightly, and J. Widmer, Rice Univ, INFOCOM'15
M. K. Haider, Y. Ghasempour, D. Koutsonikolas, and E. W. Knightly, Rice Univ., MobiCom'18

Suggestions Made in The Literature

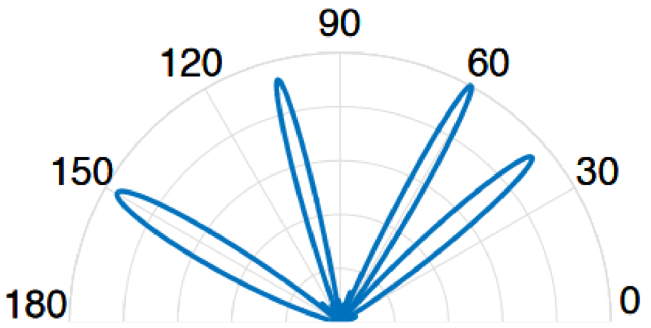
Inband beam management: Faster Beam Search

Approach:

- Use multiple arm-shaped beams to search in multiple directions at once
- Measure signal strength
- Randomize arm directions in each beam and repeat
- Vote armed beams based on measurements, find the common angular direction among the top

Shortcomings:

- Phase weights of antenna elements need careful design to produce a multi-arm radiation pattern
- No significant search reduction time when the size of the array is small, i.e <50 elements



0°, 60°, 90° or 120° Beam 1
40°, 60°, 100° or 150° Beam 2

60° is direction of client

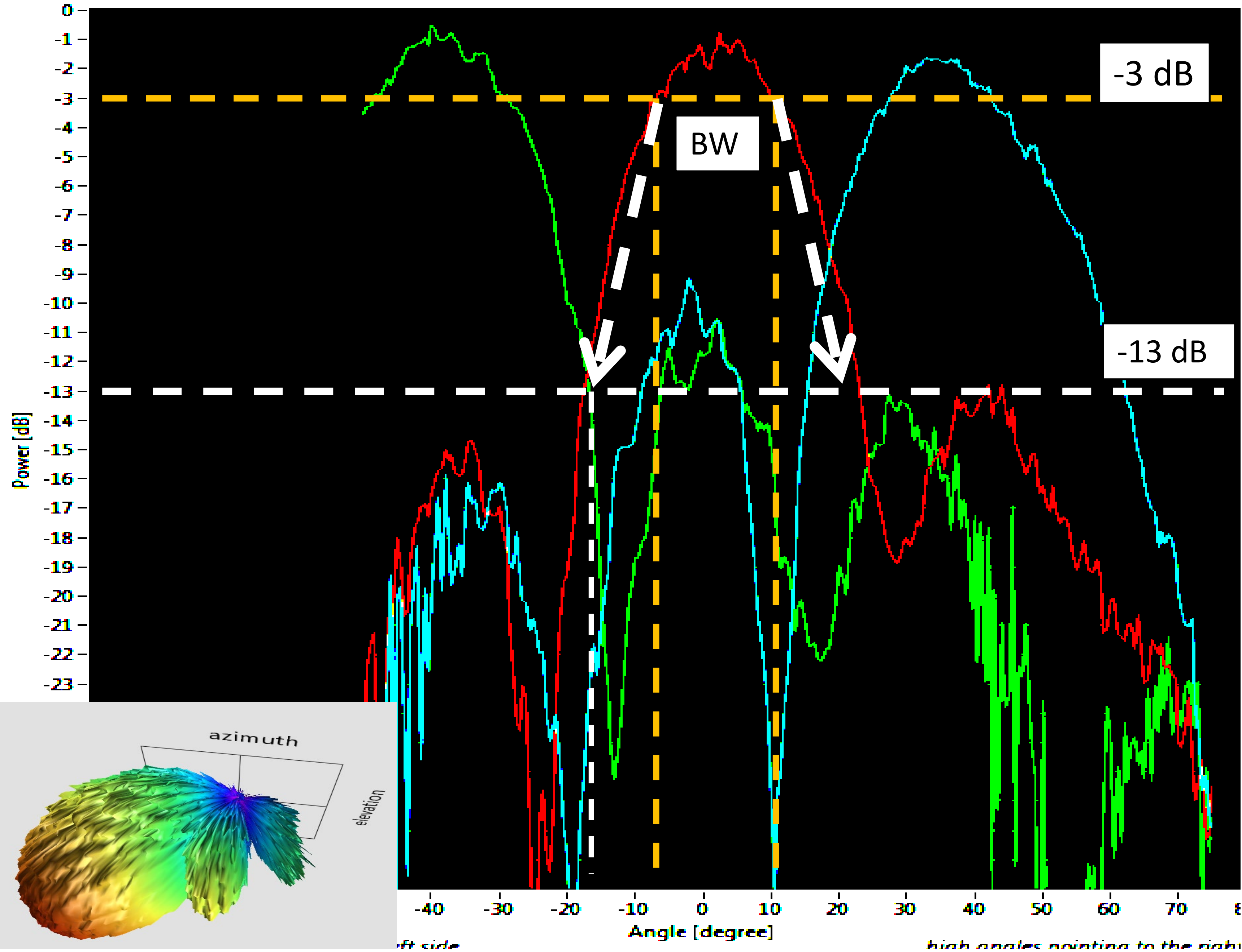
Haitham Hassanieh, Mohammed Abdelghany, Omid Abari, Dina Katabi, Michael Rodriguez, Piotr Indyk, MIT, SIGCOMM'18

BeamSurfer Protocol

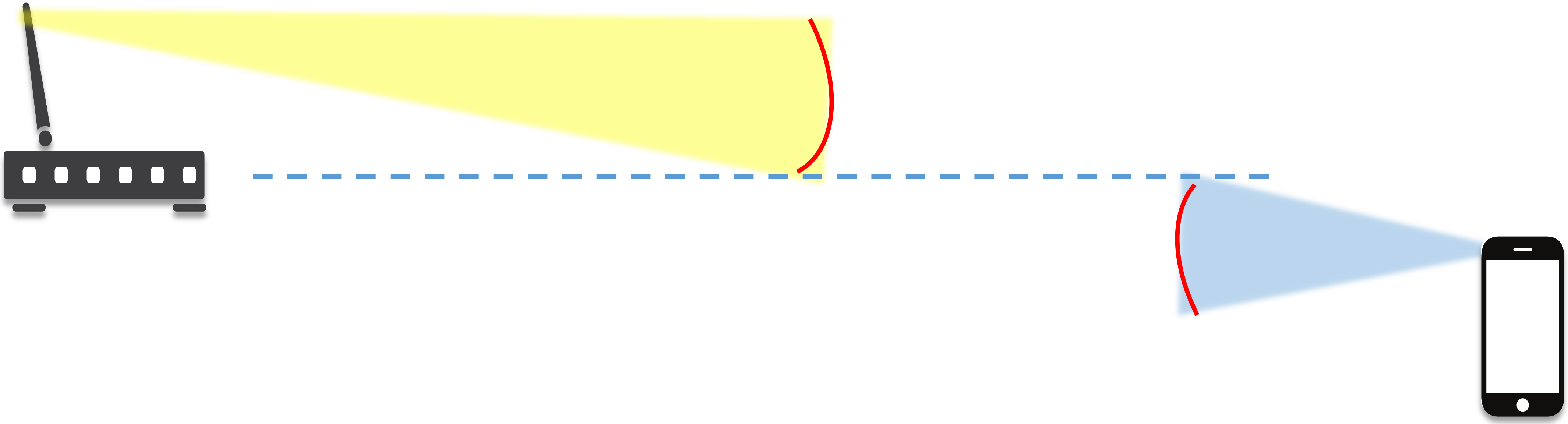
- A minimalistic beam management protocol
- In-band operation
- No need for any side information
- Signal strength within 3 dB of Omniscient Oracle choice
- Received signal strength (RSS) measurements and no need for special radiation patterns

Beam Width

- Angular width between half power/3 dB points
- Antenna gain drops steeply after beam width



Beam Width (BW)

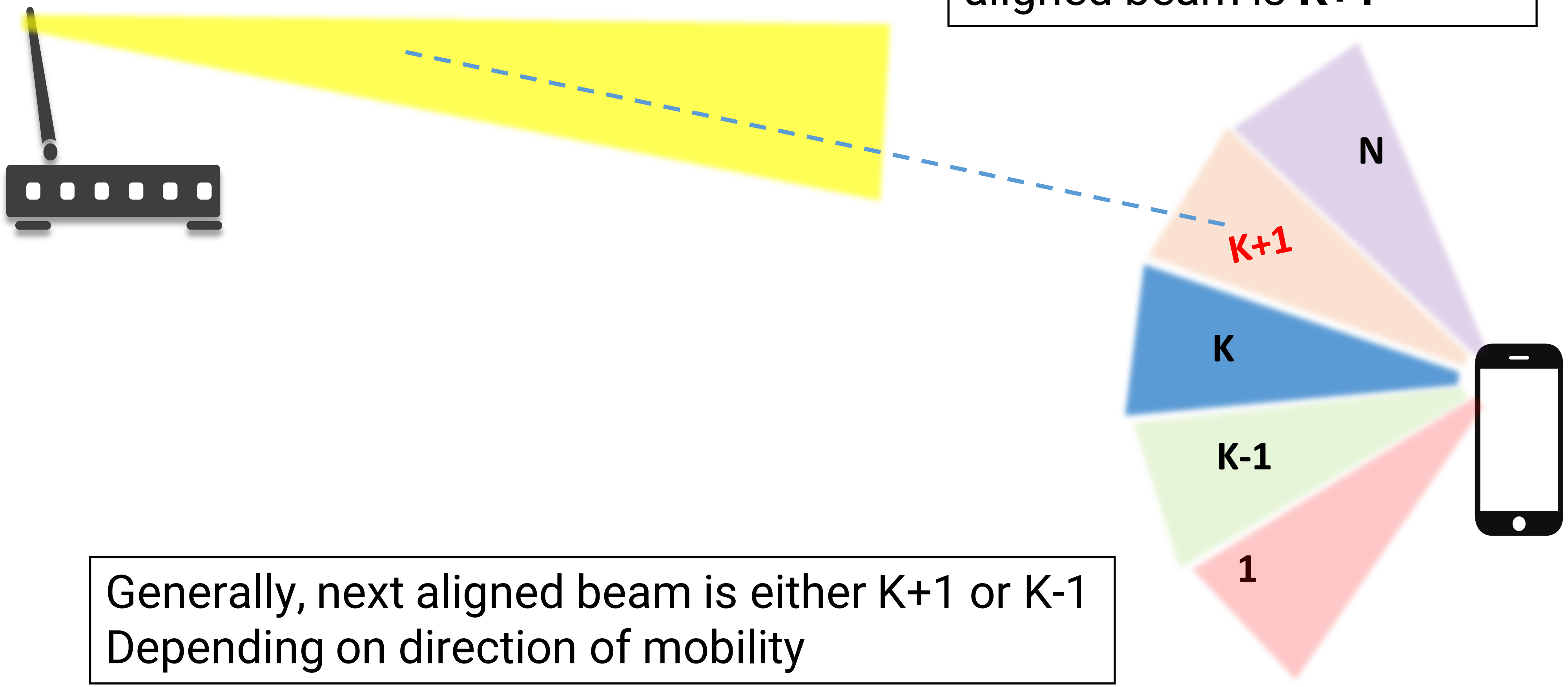


Beam needs **adaptation** when the **mobile** has moved by one BW

- received signal strength drops by **3 dB**

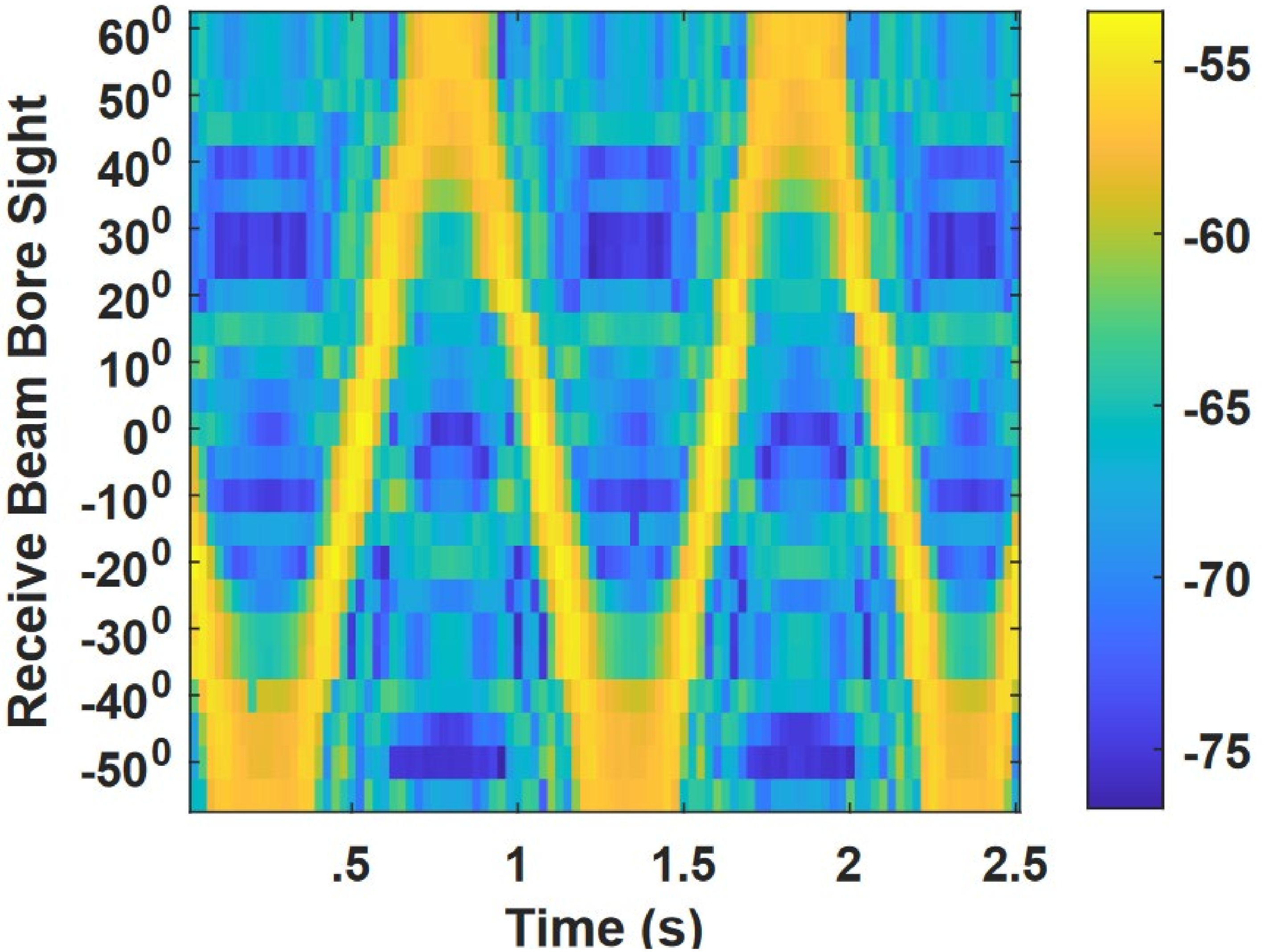
Main Idea

Suppose current beam is **K**, after mobile moves, next aligned beam is **K+1**



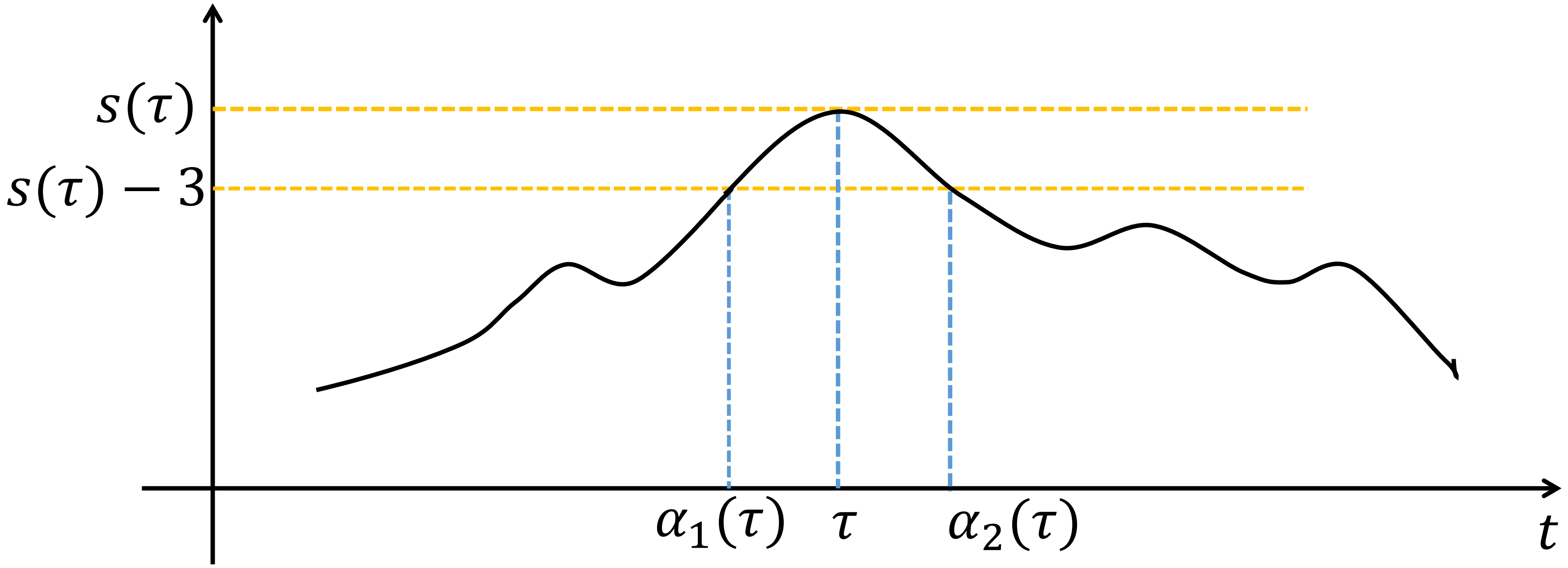
Generally, next aligned beam is either K+1 or K-1
Depending on direction of mobility

Heat map of RSS During Rotational Motion



Beam Coherence Time

- Duration after which this adaptation must take place



BCT: Measurements

- Translation Motion

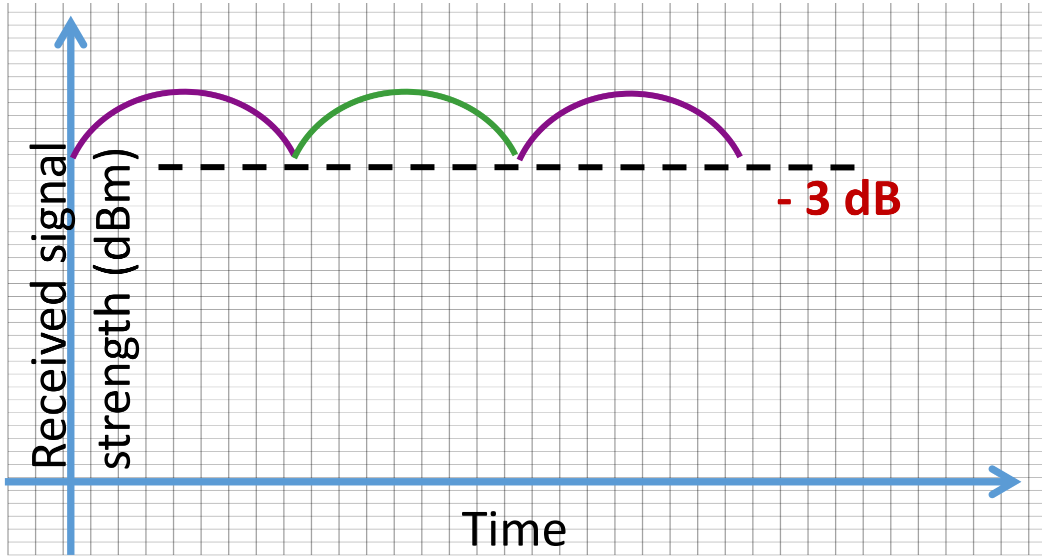
Speed (m/s)	Distance (m)	BCT (ms)
0.67	5	643
0.67	10	861
1.4	5	476
1.4	10	802

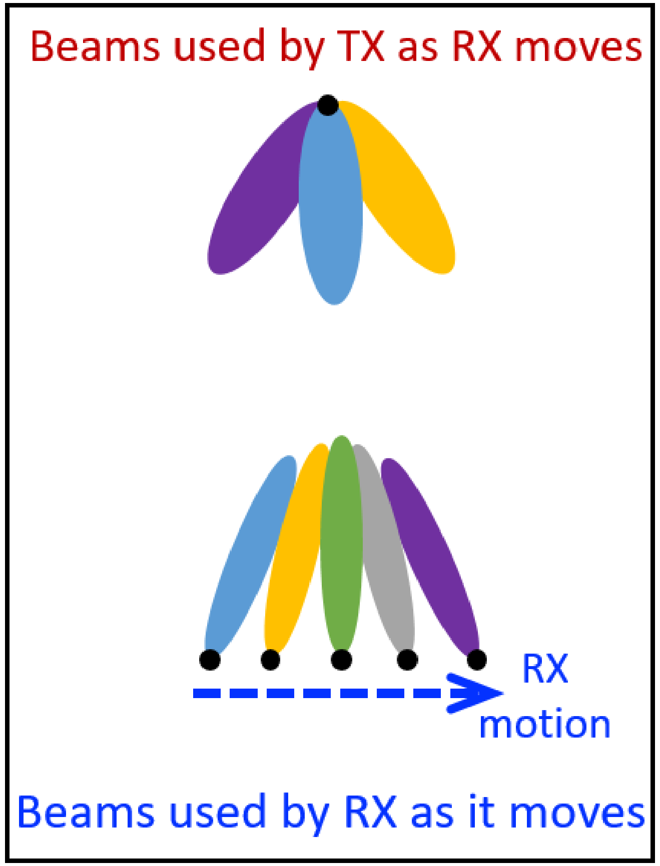
- Rotational Motion

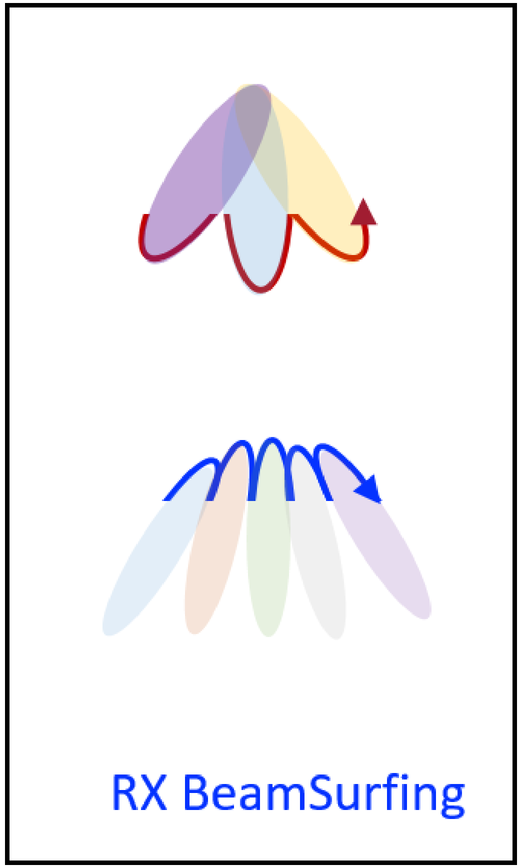
Speed (rad/s)	Distance (m)	BCT (ms)
$2\pi/9$	5	284
$\pi/3$	5	200
$2\pi/3$	5	141
$4\pi/3$	5	101

Beam Surfing

- Switch current beam to a **neighbor** beam when **RSS** drops by 3 dB

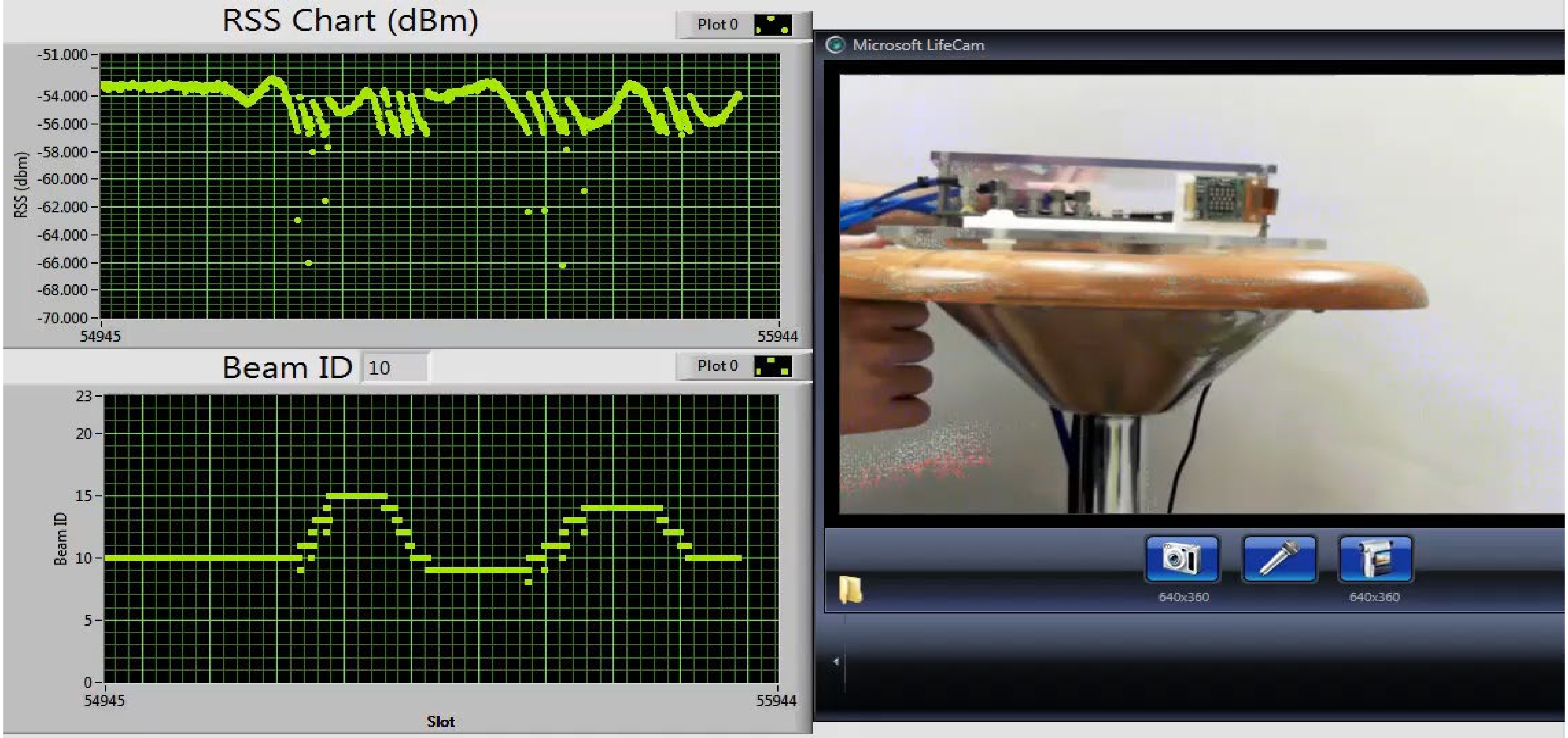






BeamSurfer : Translational Motion

BeamSurfer: Rotation Motion



Oracle’s Choice of the Best Beam

- We took measurements at each point on a trajectory to identify the beam that has the highest received signal strength

- This gives an upper bound on sub-optimality

- No real system can expect to perform as Omniscient Oracle

- But these measurements help calibrate BeamSurfer’s performance comparison

Performance Comparison With Omniscient Oracle Solution

Mobility Pattern	RMS Loss over Omniscient Oracle (dB)
Rotational Motion, $\omega = 60\ deg/s$	2.1
Rotational Motion, $\omega = 120\ deg/s$	2.3
Rotational Motion, $\omega = 240\ deg/s$	2.31
Lateral Motion, V= $1.4\ m/s$	1
User randomly walks between TX-RX	1.21

Implementation in 5G NR and Beam Correspondence

- BeamSurfer only uses available 5G NR mechanisms– RSS measurements
- Beam Correspondence exists if the same beam can be used for both uplink and downlink
- In our indoor experiments, we observed beams are reciprocal

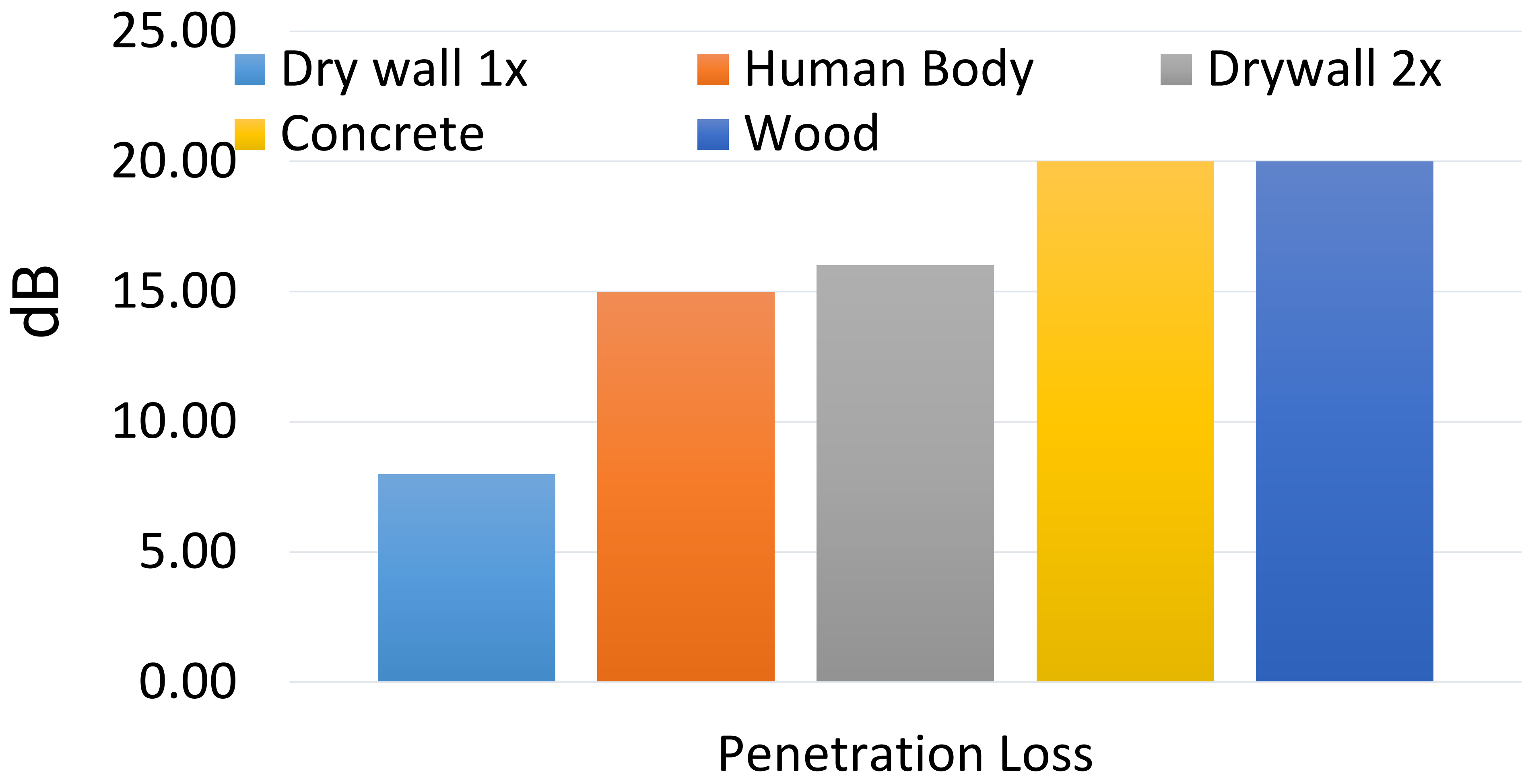
3GPP 5G NR Physical Layer Measurements, TS: 38.215
https://portal.etsi.org/webapp/workprogram/Report_WorkItem.asp?WKI_ID=65332

BeamSurfer: Summary

- Totally in band
- Minimalistic
- No need for any side channel information
- Within in 3dB of super-optimal Omniscient Oracle alignment

Blockage

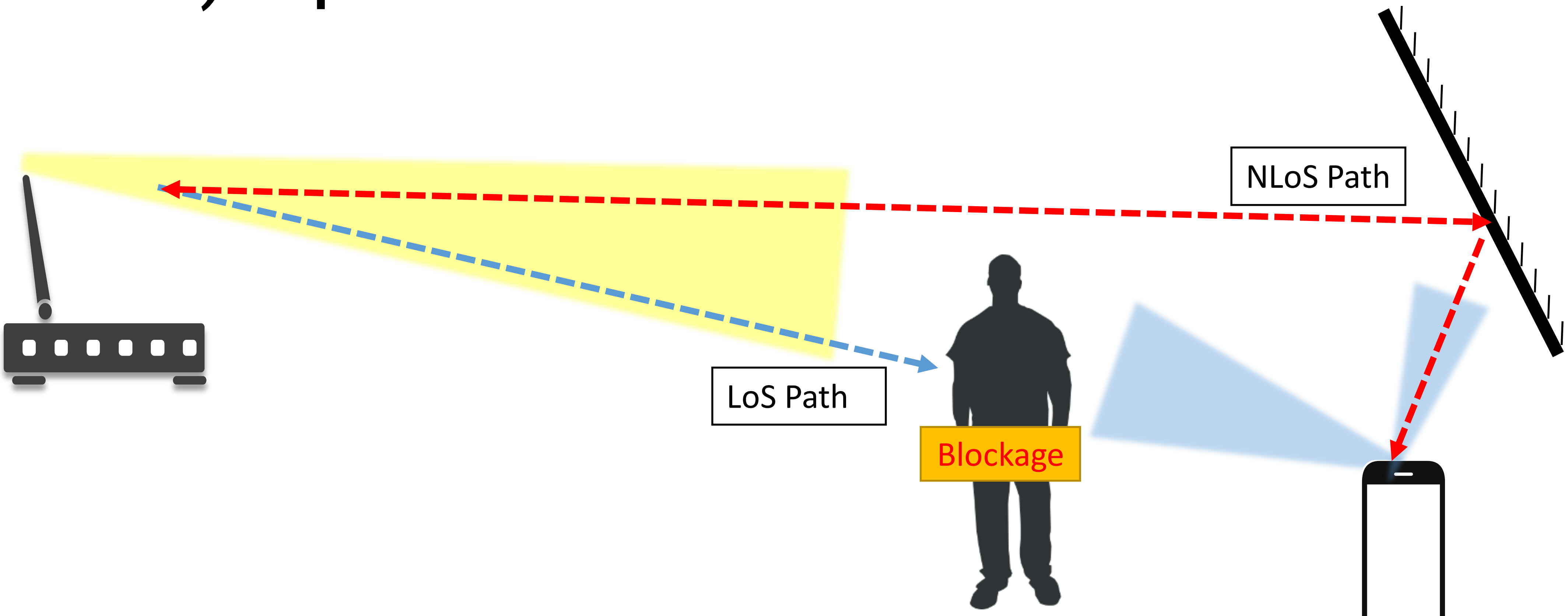
mmWaves Are Easily Blocked



Pedestrian Blockage

- Pedestrian blockages are temporary
  - 200 milli-seconds
- Unpredictable
- Immediate throughput loss due to poor RSS
- Loss of Critical control plane information
- Mobile loses timing synchronization
  - **Link is lost**
- Reconnection is a long, energy intensive process

Link adaptation by Non Line of Sight (NLoS) Operation



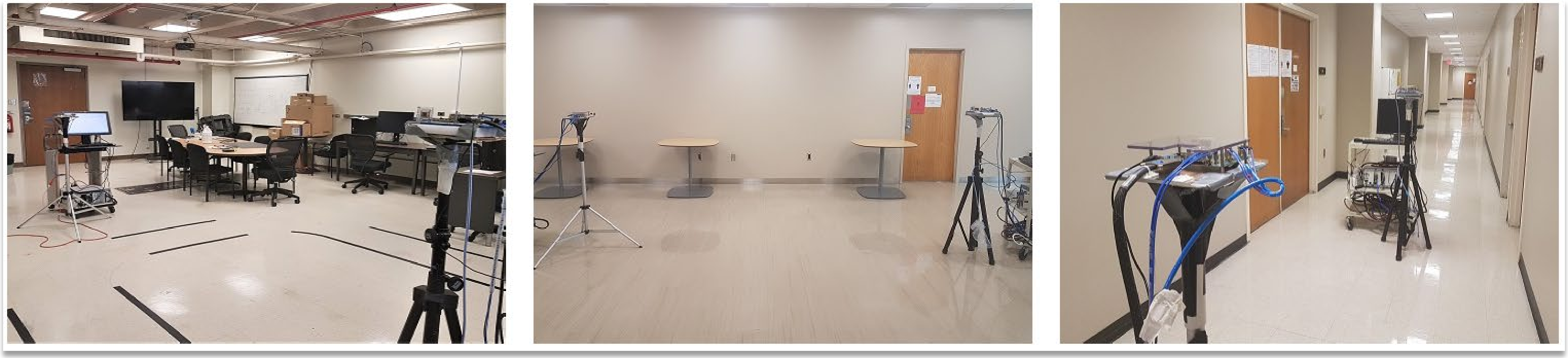
Non-Line of Sight Radiation

- RSS of reflected radiation is always less than LoS

Material	$RSS_{LoS} - RSS_{NLoS}$ (dB)
Drywall- Single Layer	10
Drywall-Double Layer	10
Wooden Door	11
Concrete Wall	13

Non-Line of Sight Communication

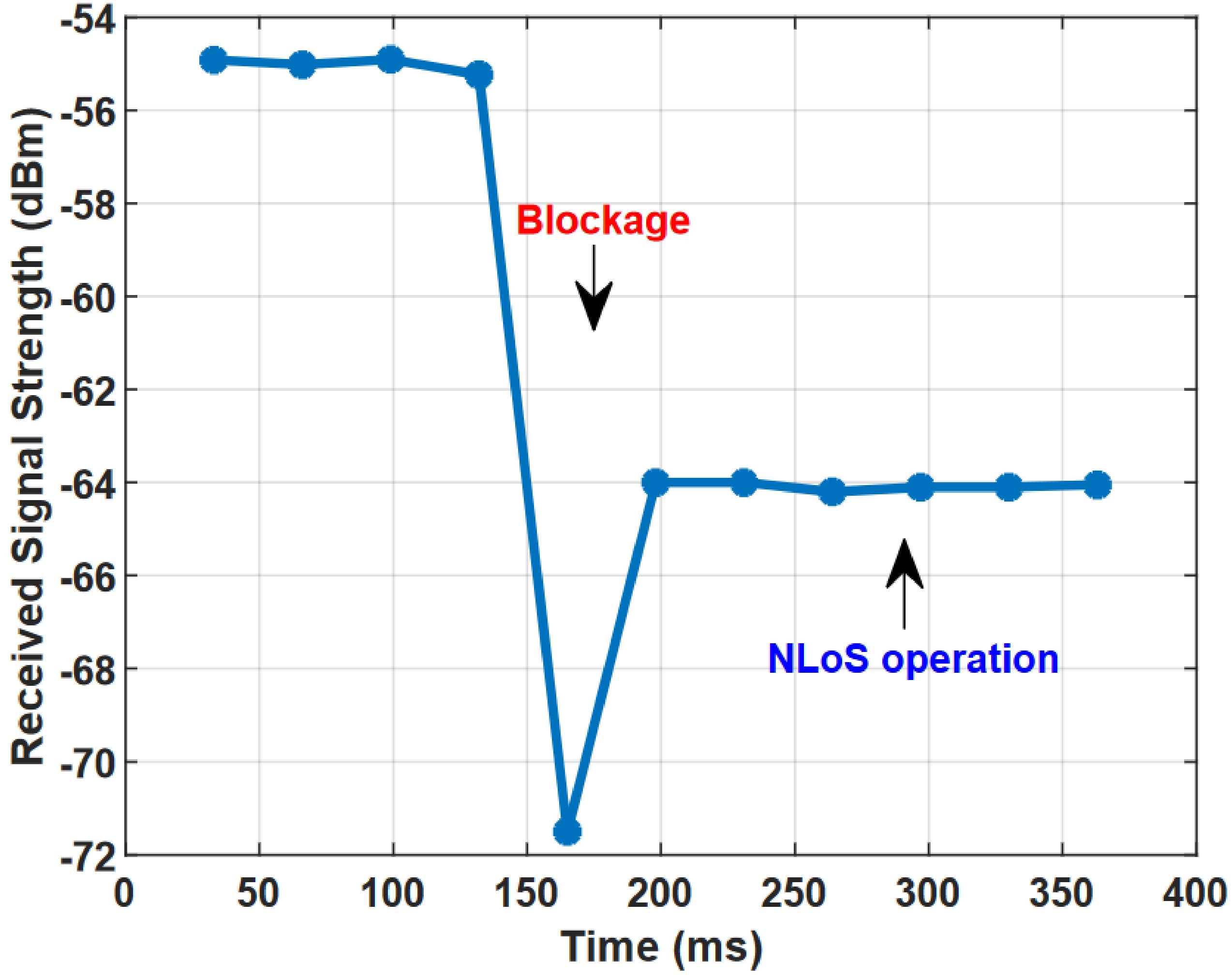
- Reflected radiation typically exists in Indoor Environments



Non-Line of Sight Communication

- May not be enough to sustain high data rate communication
- But enough to sustain Control Plane Traffic
- Averts timing synchronization failure
- Link remains connected during blockage
- Allows quick recovery to LoS communication after temporary transient blockage ends

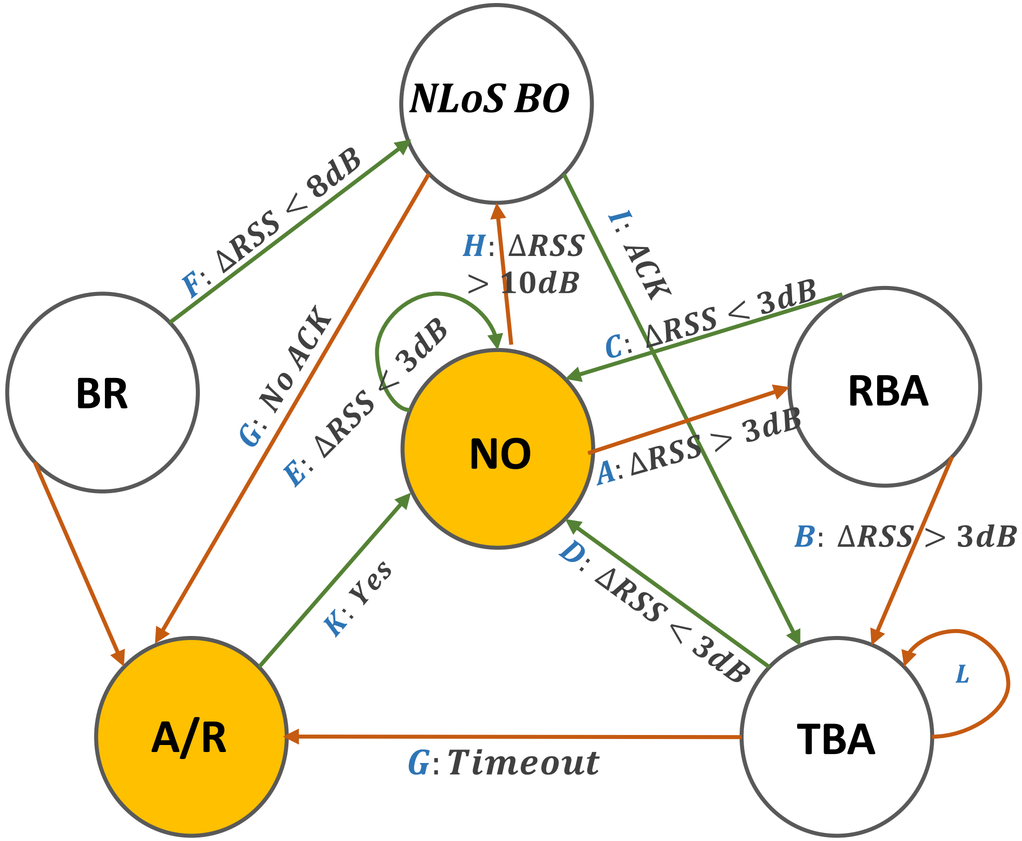
Blockage Recovery



Blockage Recovery Scheme

- Harvest reflected radiation intermittently during normal operation
  - To be ready in case sudden blockage occurs
- Sufficient to memorize just one NLoS direction
- Discover NLoS path
  - After one BCT

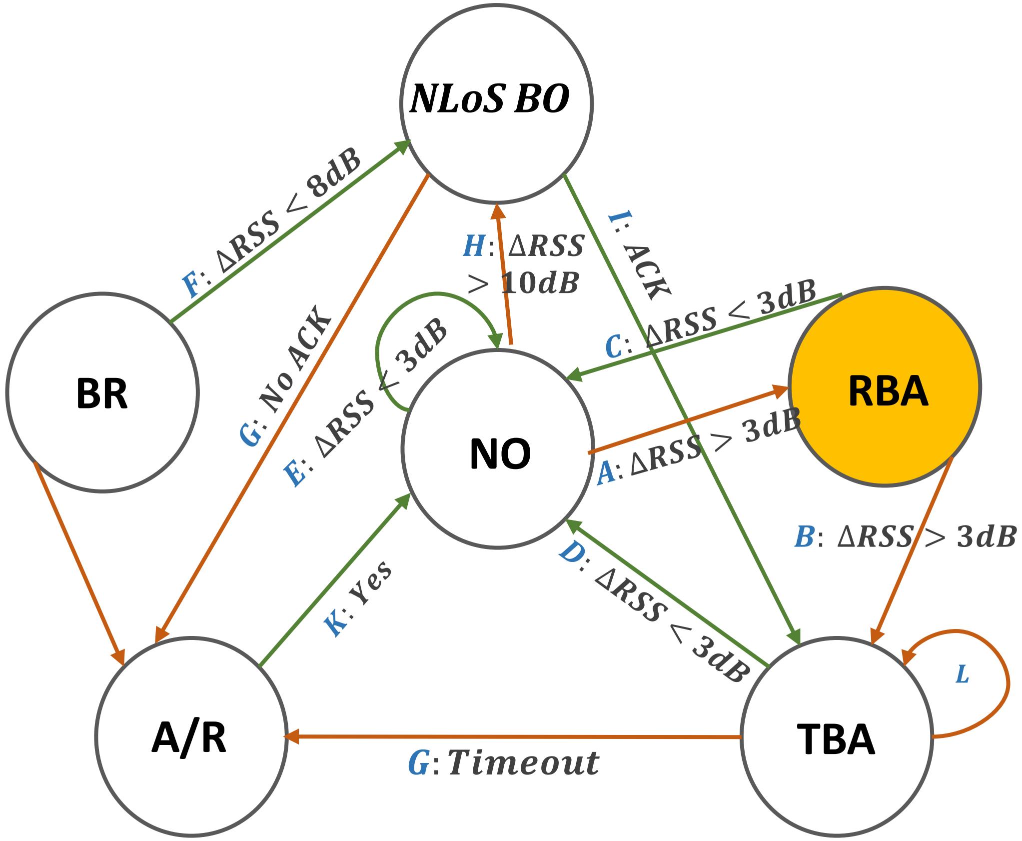
The BeamSurfer Protocol



NO : Normal Operation
RBA : Receive Beam Adaptation
TBA : Transmit Beam Adaptation
A/R : Acquisition/Re-acquisition
BR : Blockage Recovery
NLoS BO : NLoS Beam Operation

A : Determine next receive beam to surf
B : Receive beam Adaptation
C : Found receive beam to surf
D : Found transmit beam to surf
E : Surfing
F : Found reflected beam
G : User is lost
H : Blockage has happened
I : Initiate search for best TX-RX beam pair
K : User acquired
L : Search non-neighbor TX beams , since neighboring transmit beams didn't work

BeamSurfer: Beam Management



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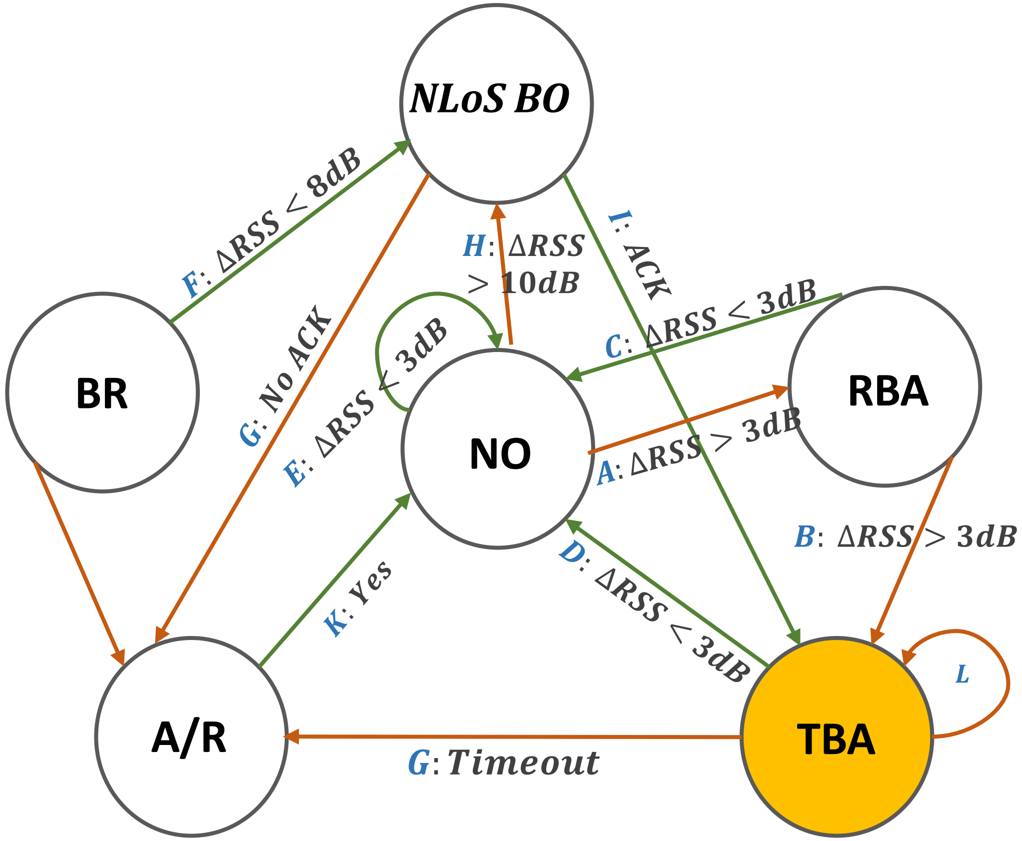
BeamSurfer



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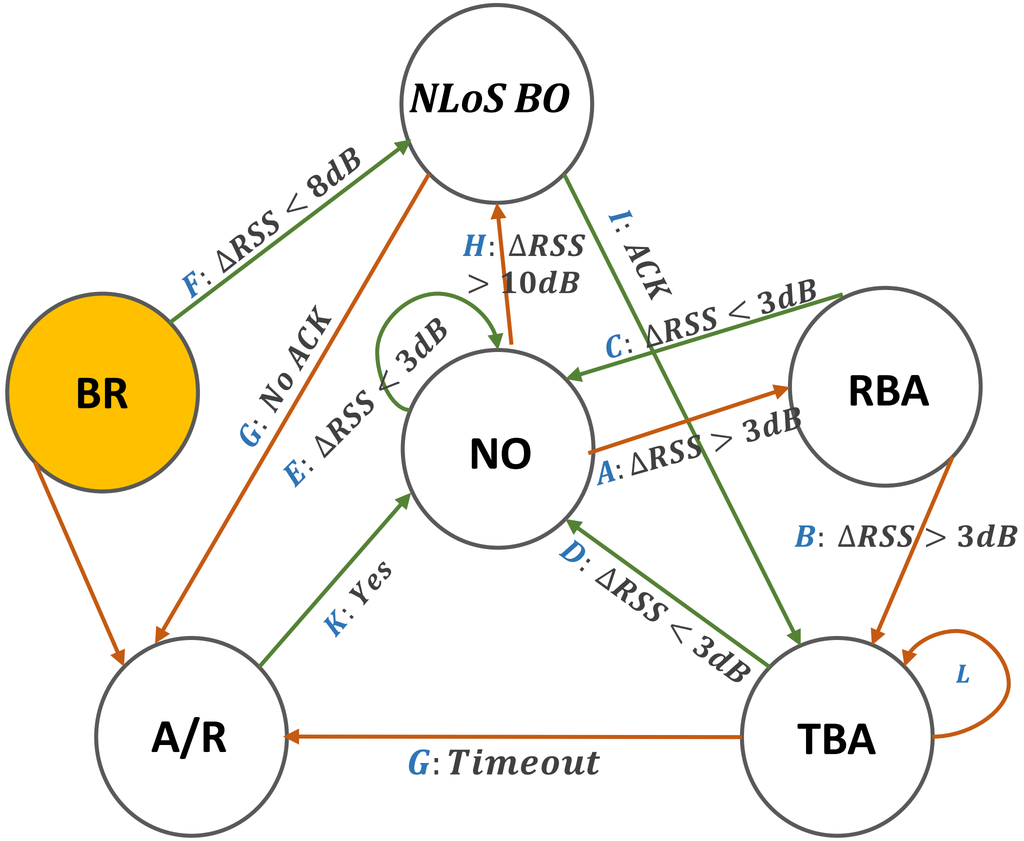

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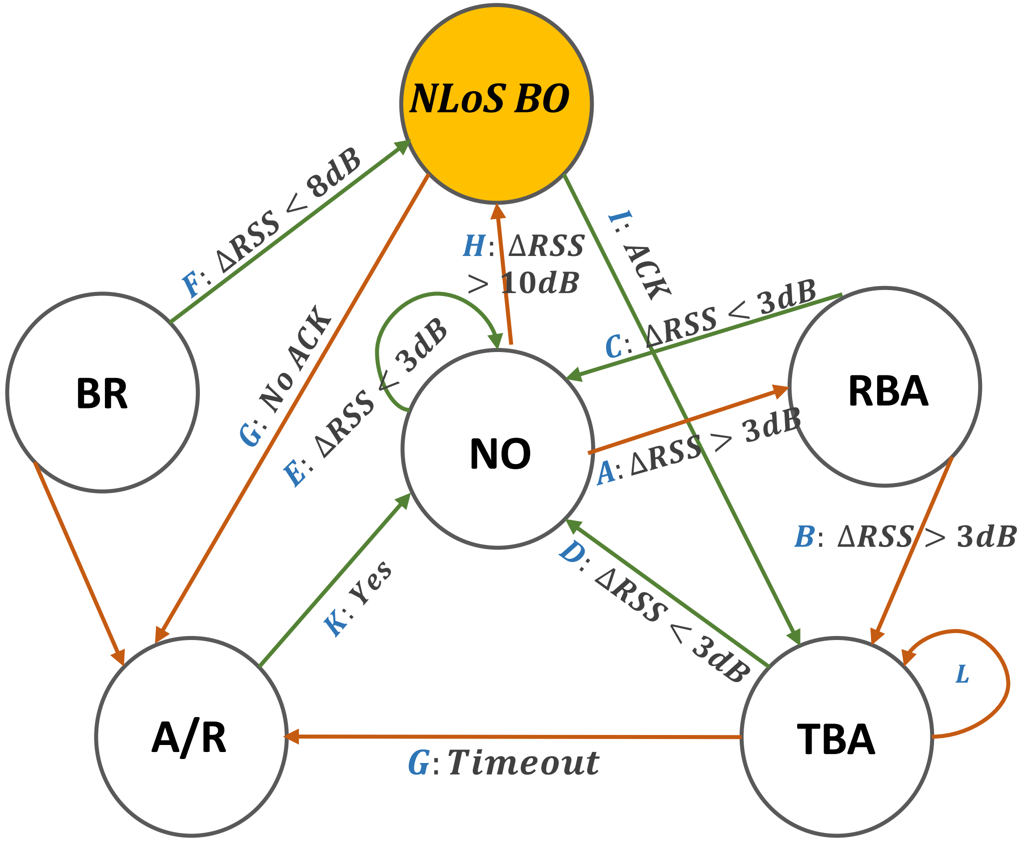

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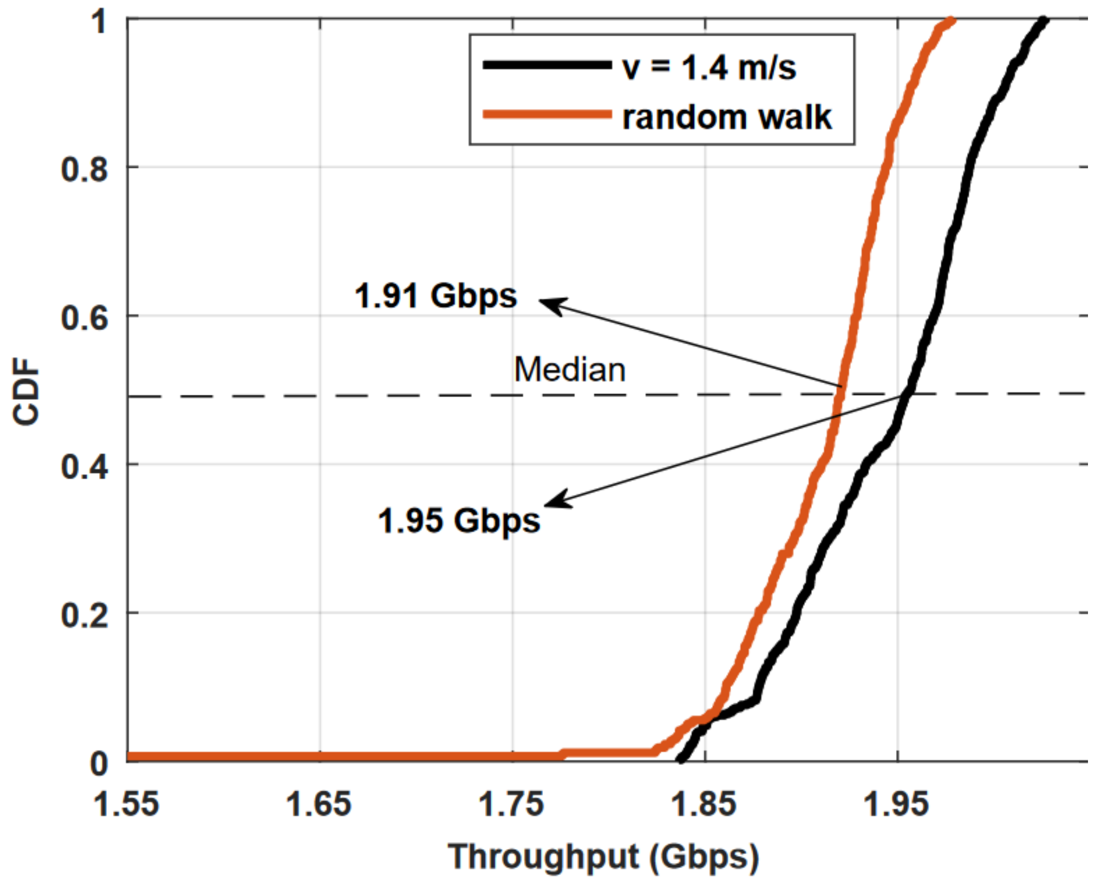
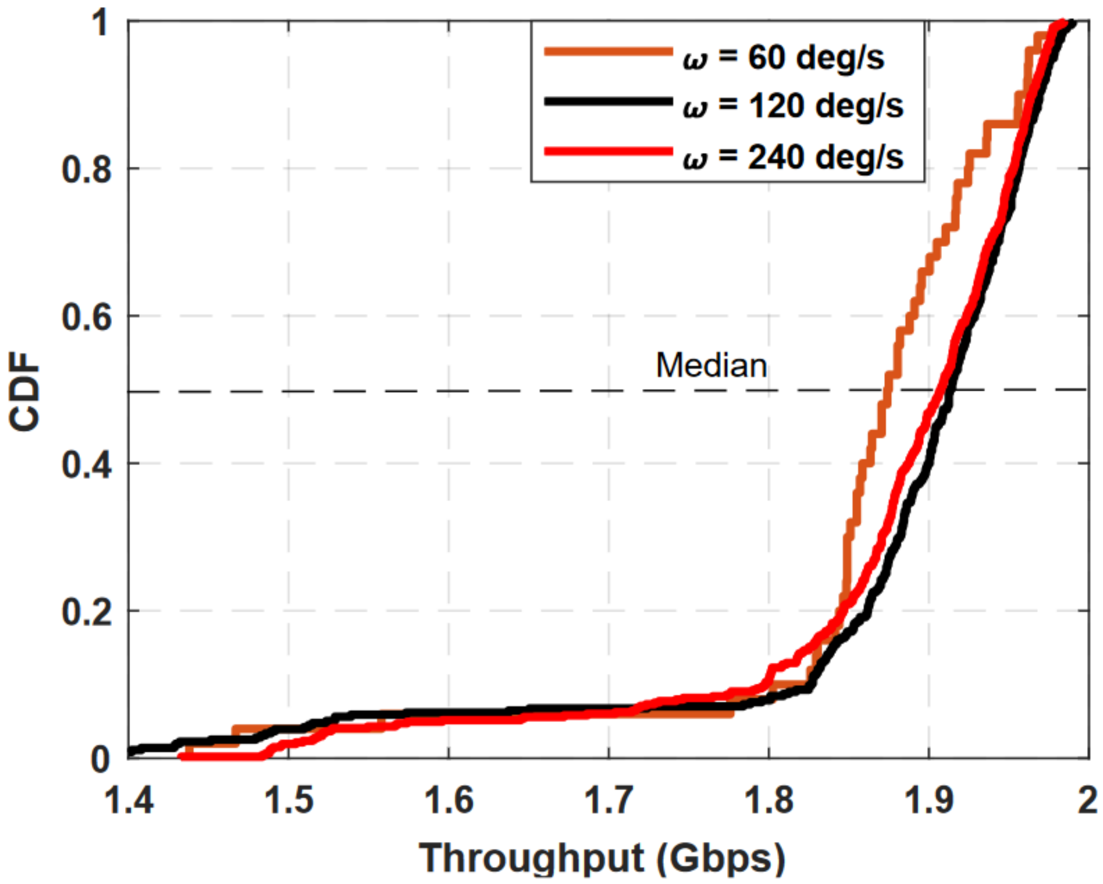
Throughput Performance of BeamSurfer Protocol



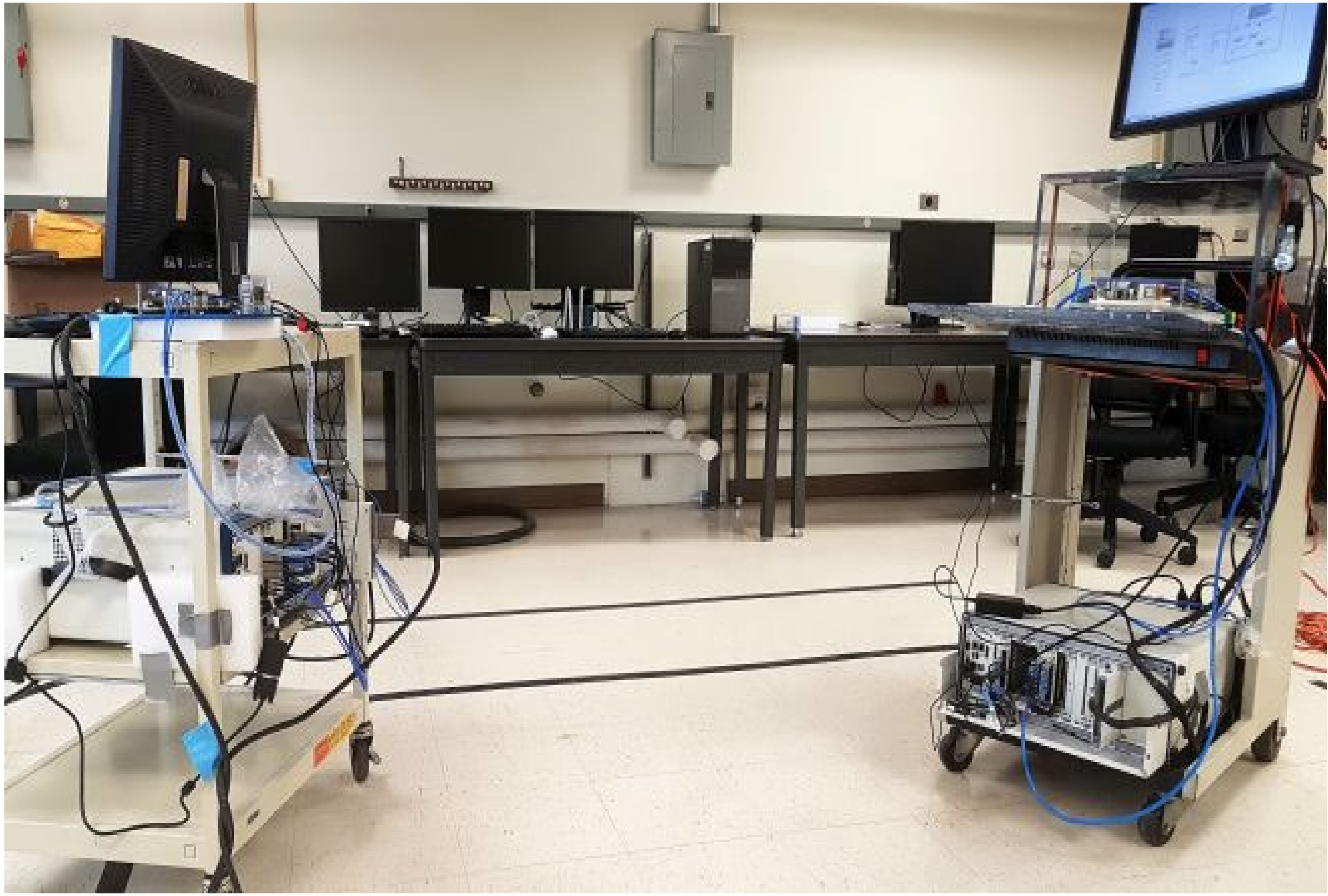


Comparison of Maximum #Measurements to align

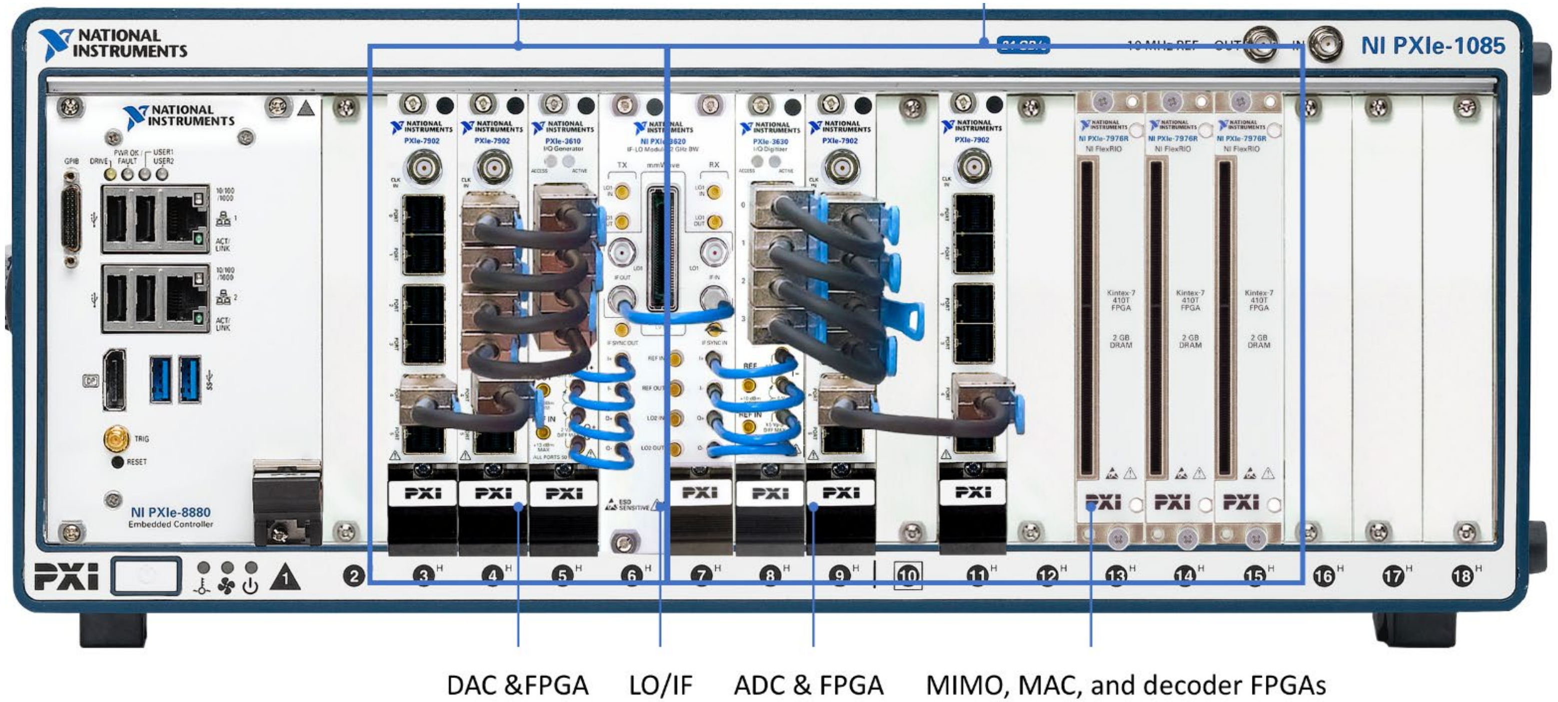
State of the art	Maximum number of measurements
BeamSurfer	8
Beam-forecast	40
HBA	63
Swift Link	70
FALP	70
Agile Link	110
Exhaustive Search	1024

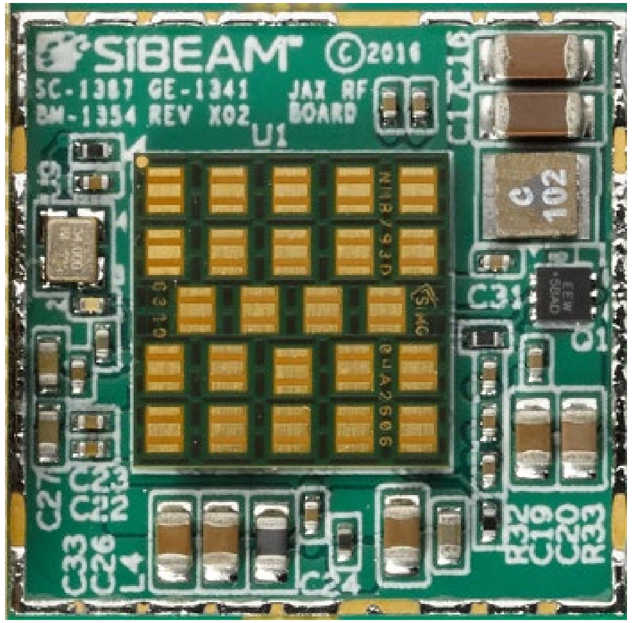
Testbed

- **Operation:** 60 GHz
- **Bandwidth:** 2 GHz
- **Waveform:** OFDM
- **Slot Duration:** 100us
- **#Azimuth Beams:** 25
- **Beam width:** 15^0
- **Field of view:** 120^0



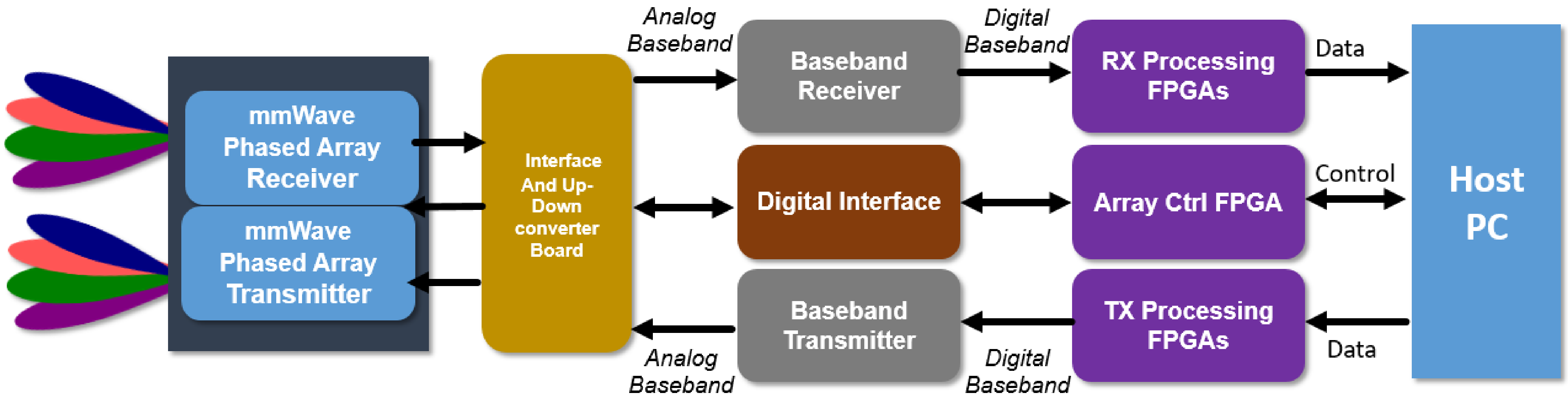
Transceiver





https://www.ni.com/pdf/product-flyers/mmwave-transceiver-system.pdf

Transceiver Block Diagram



Summary

- We have presented a protocol that is minimalistic yet addresses difficult challenges at mmWave bands
- Quick mobility adaptation
- Blockage ready for **indoor** environments
- Minimalistic Protocol
- Low complexity
- Implemented in Tested
- Can be implemented in 5G NR

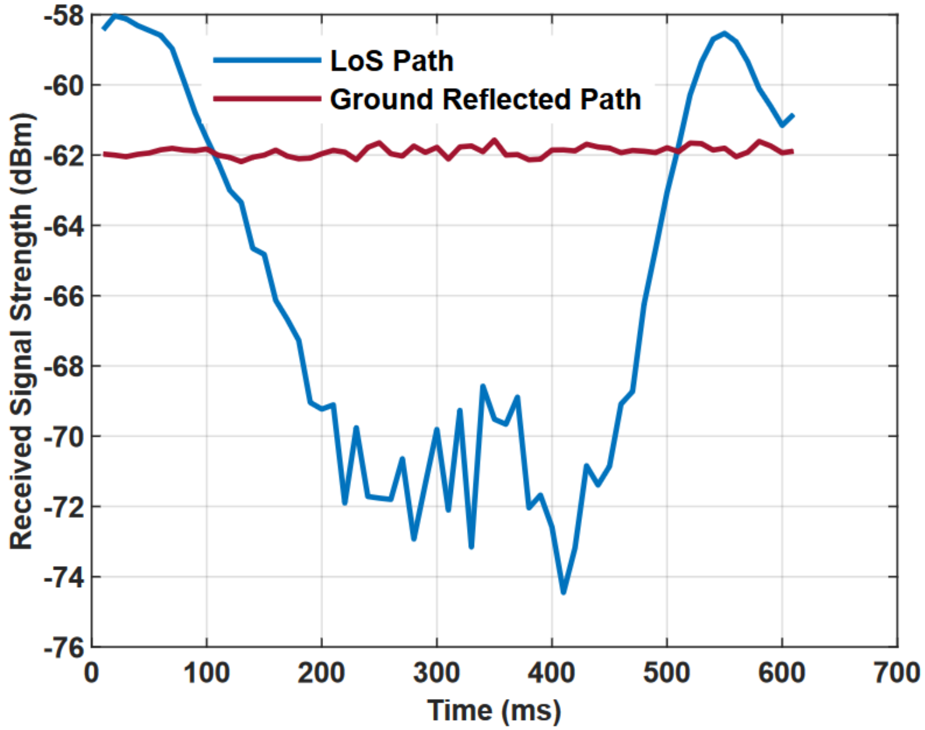
Outdoors

- Blockage, still a problem outdoors

- Suggested Solutions:
  - Handoff or Coordinated multipoint transmission
- Both require high base station density
  - 200 $Base\ Station/KM^2$ is a must to handover during blockage for 5G
  - Expensive proposition

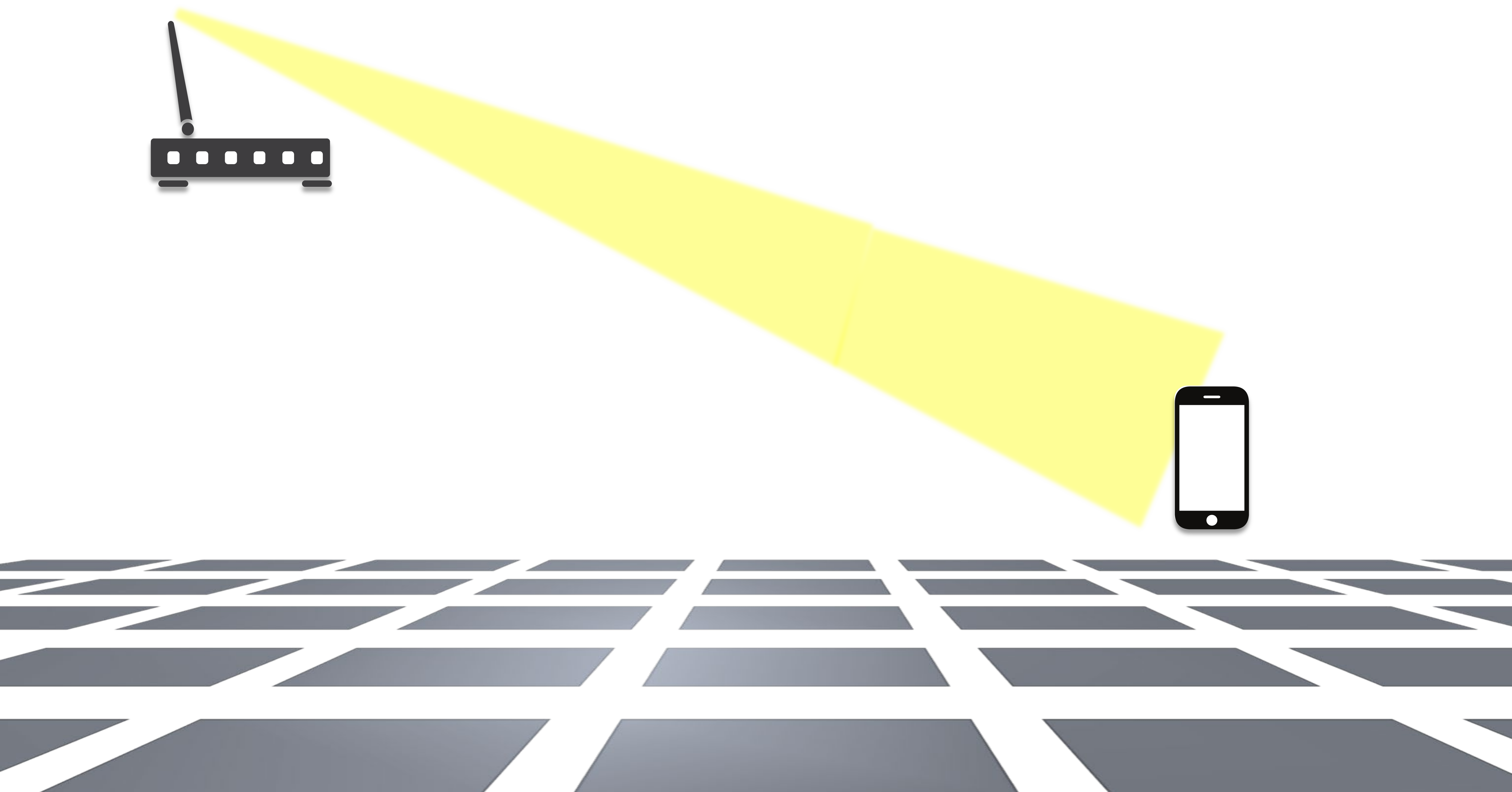
- Our experimental confirmation: **Ground reflections** are strong in mmWave bands

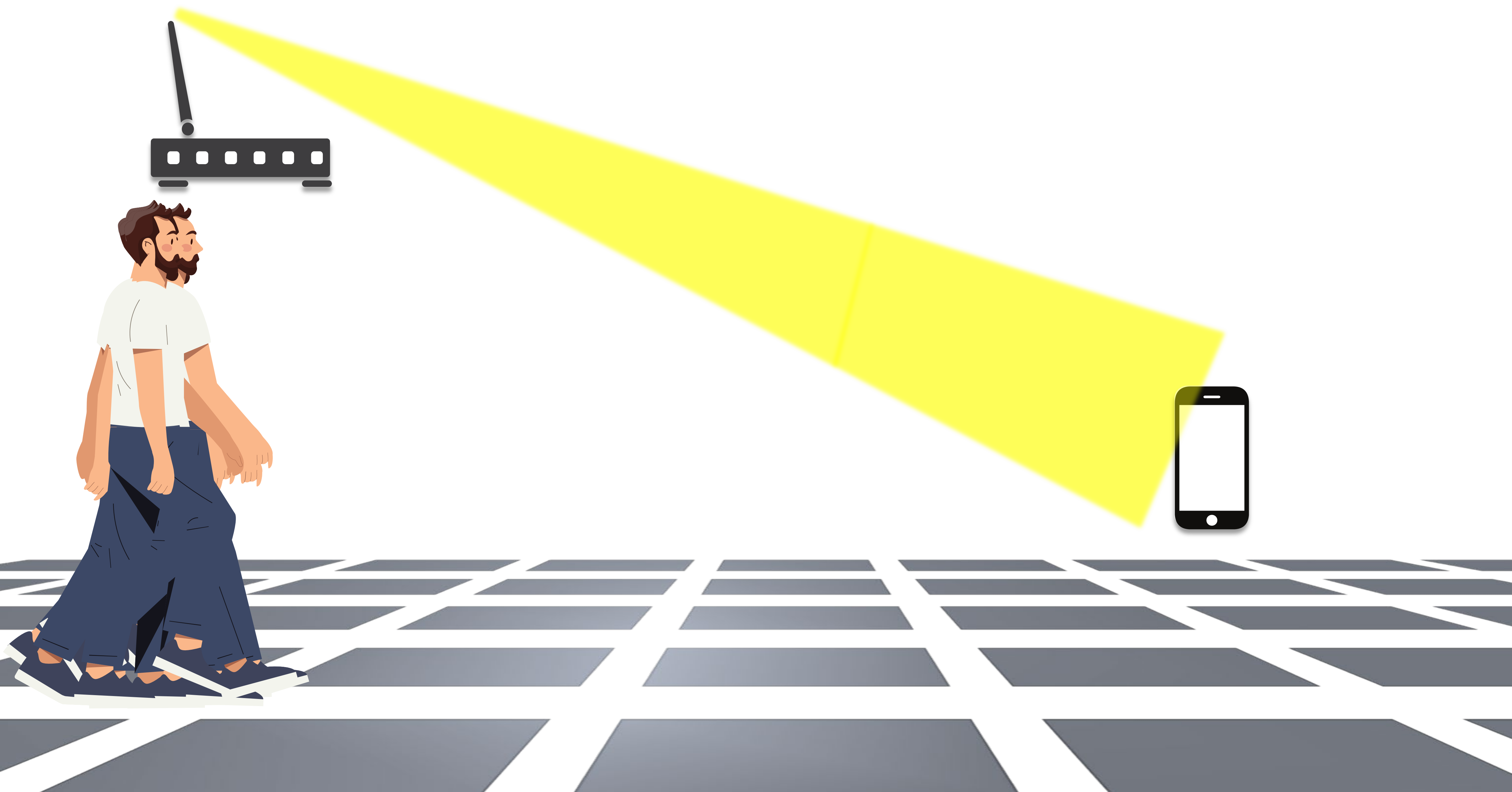
Experiments show RSS is 4-6 dB within LoS

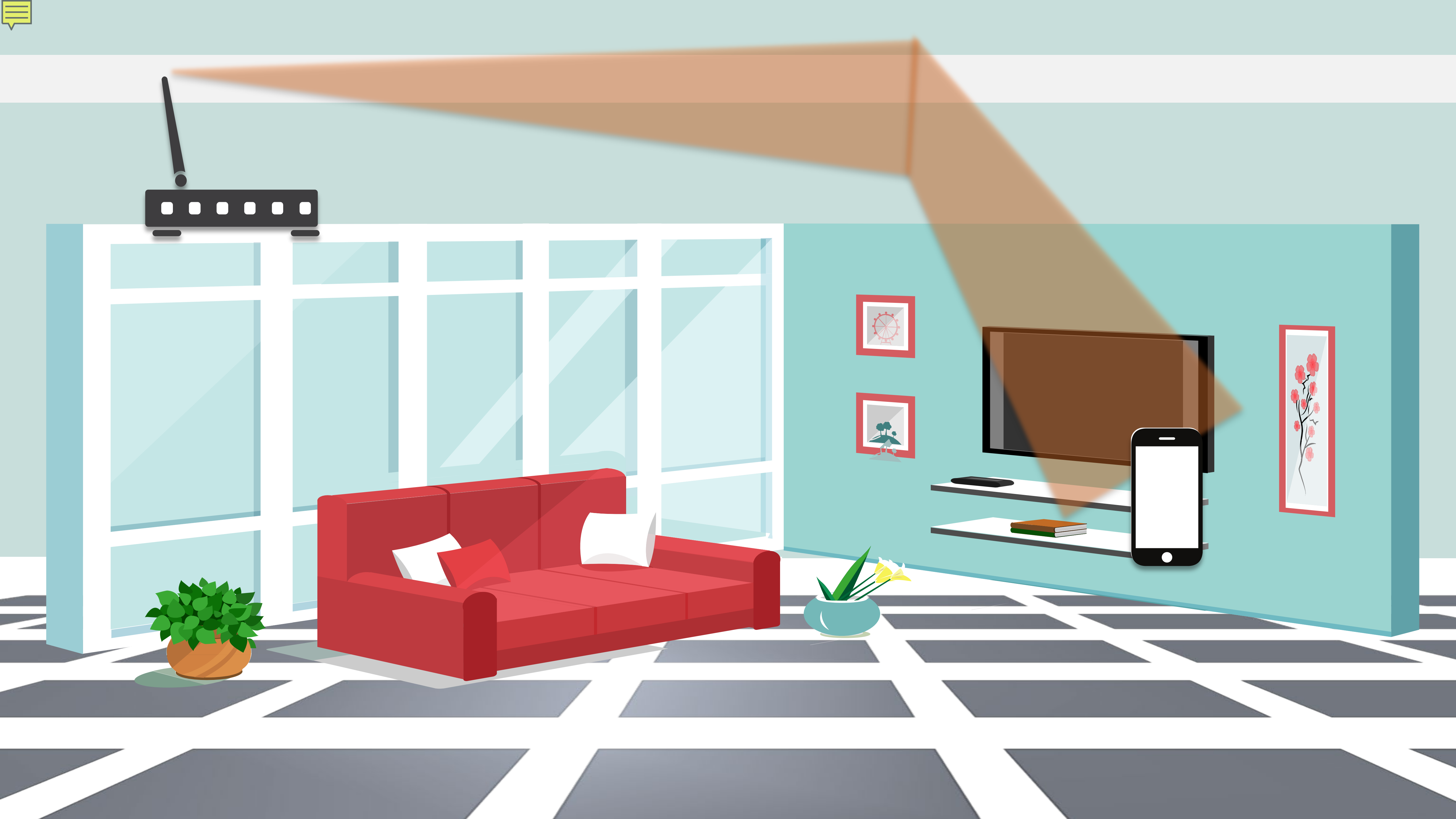


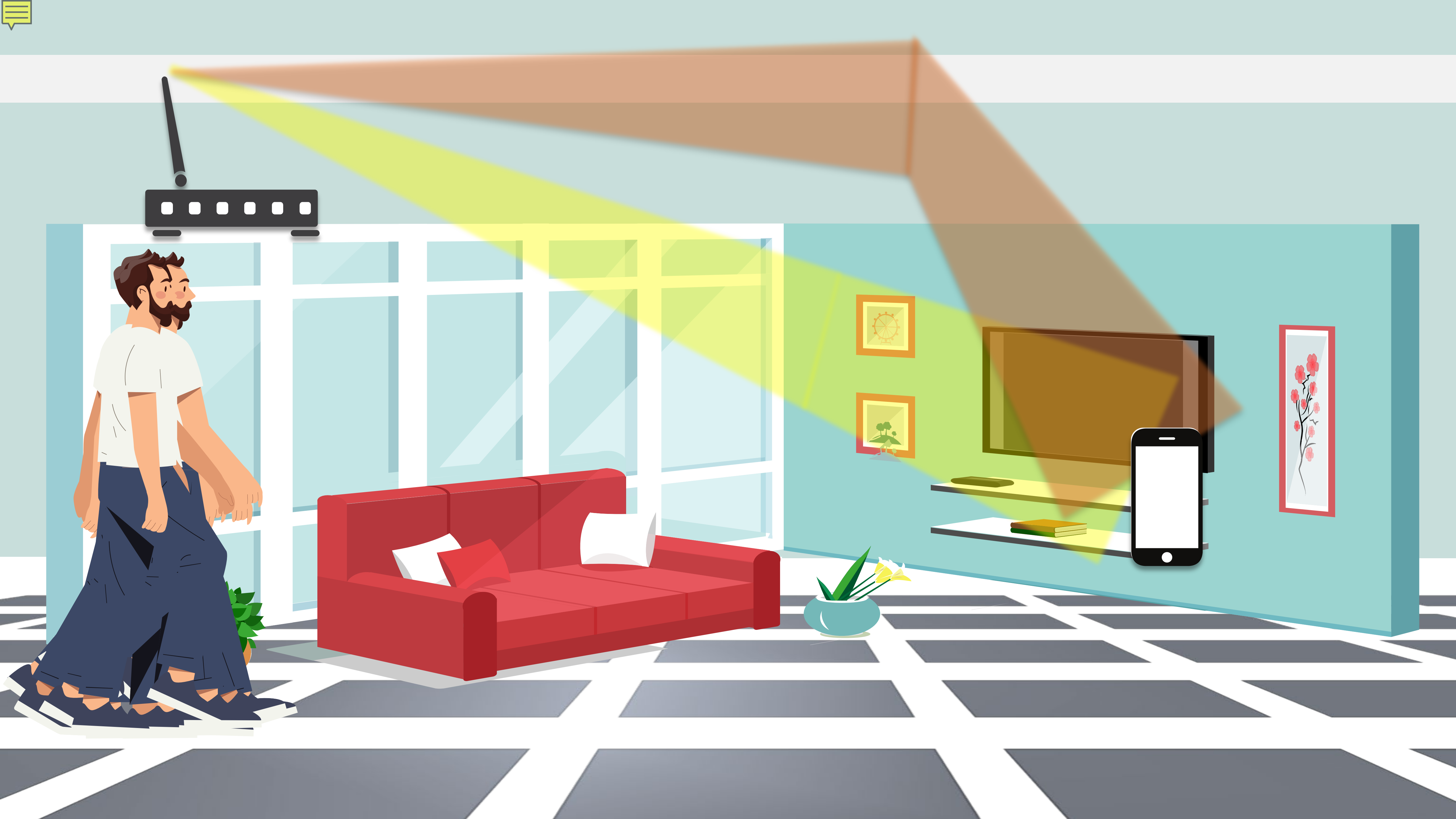
Ish Kumar Jain, Rajeev Kumar, and Shivendra S. Panwar. 2019. The Impact of Mobile Blockers on Millimeter Wave Cellular Systems. IEEE Journal on Selected Areas in Communications

Terra: Blockage Resilience in Outdoor mm-Wave Networks









RSS Chart (dBm)
Plot 0
-51.00
-54.00
-56.00
-58.00
-60.00
-62.00
-64.00
-66.00
-68.00
-70.00
RSS (dbm)
RSS Chart (dBm)
Plot 0
-51.00
-54.00
-56.00
-58.00
-60.00
-62.00
-64.00
-66.00
-68.00
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RSS (dbm)
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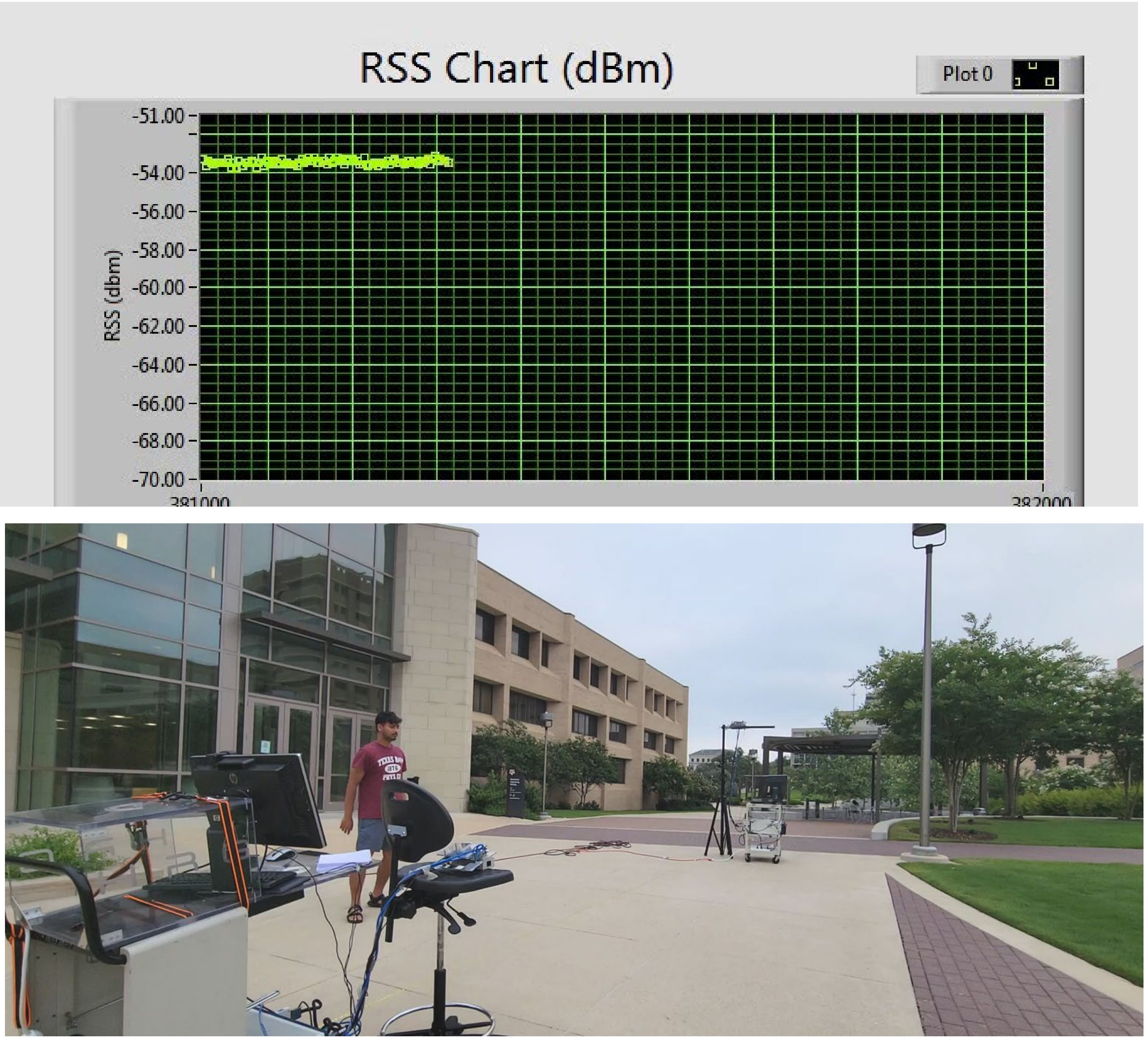
Plot 0
-51.00
-54.00
-56.00
-58.00
-60.00
-62.00
-64.00
-66.00
-68.00
-70.00
RSS (dbm)

Without Terra



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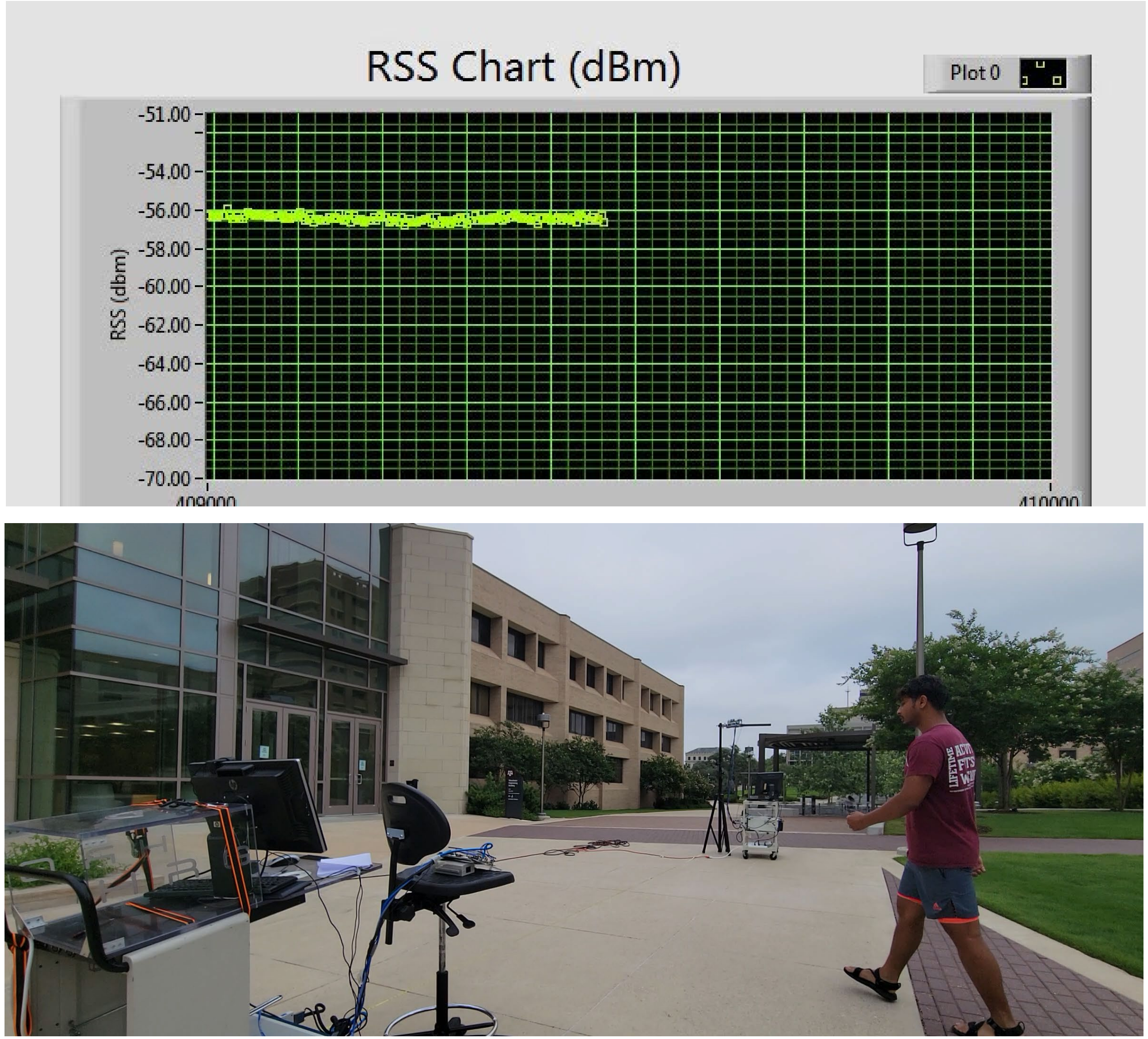
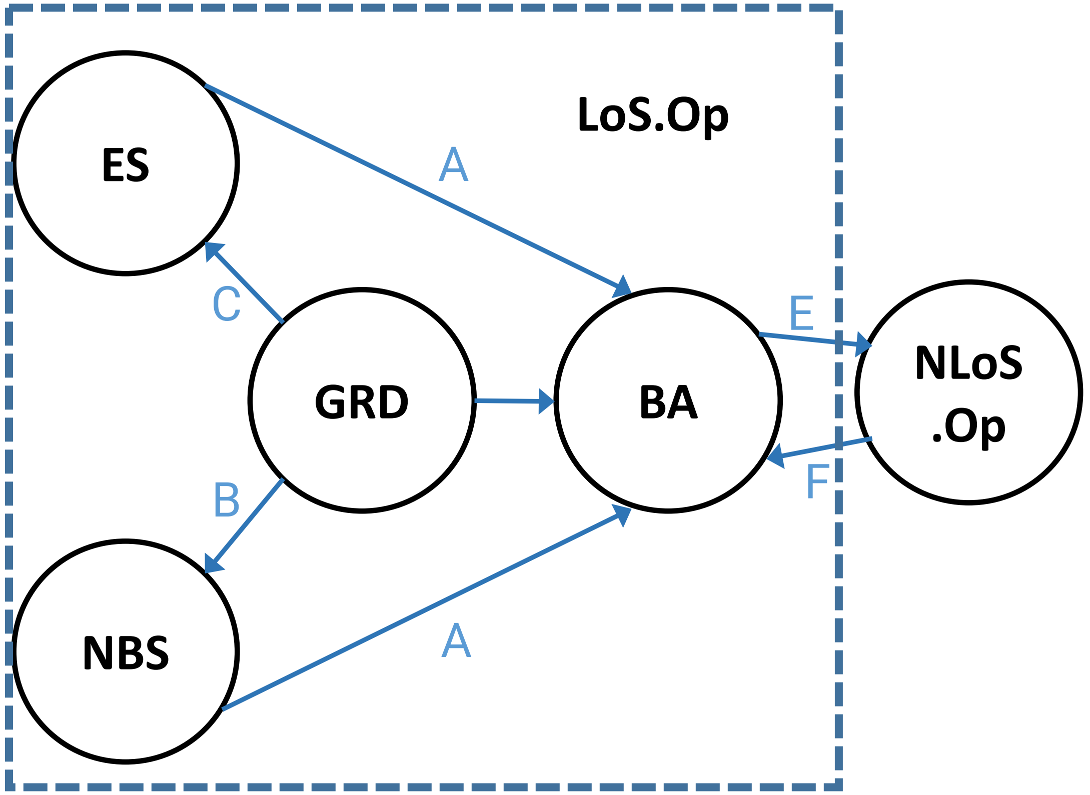
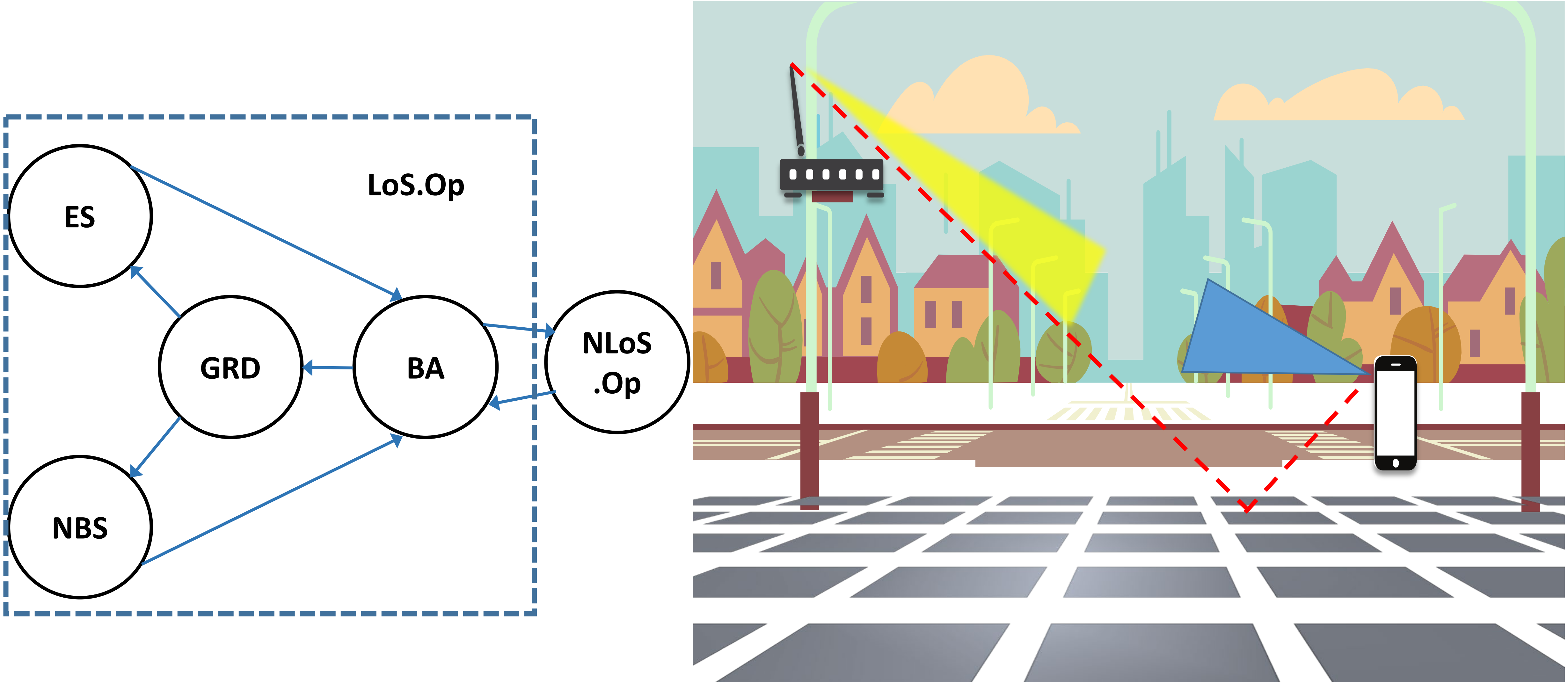


Terra

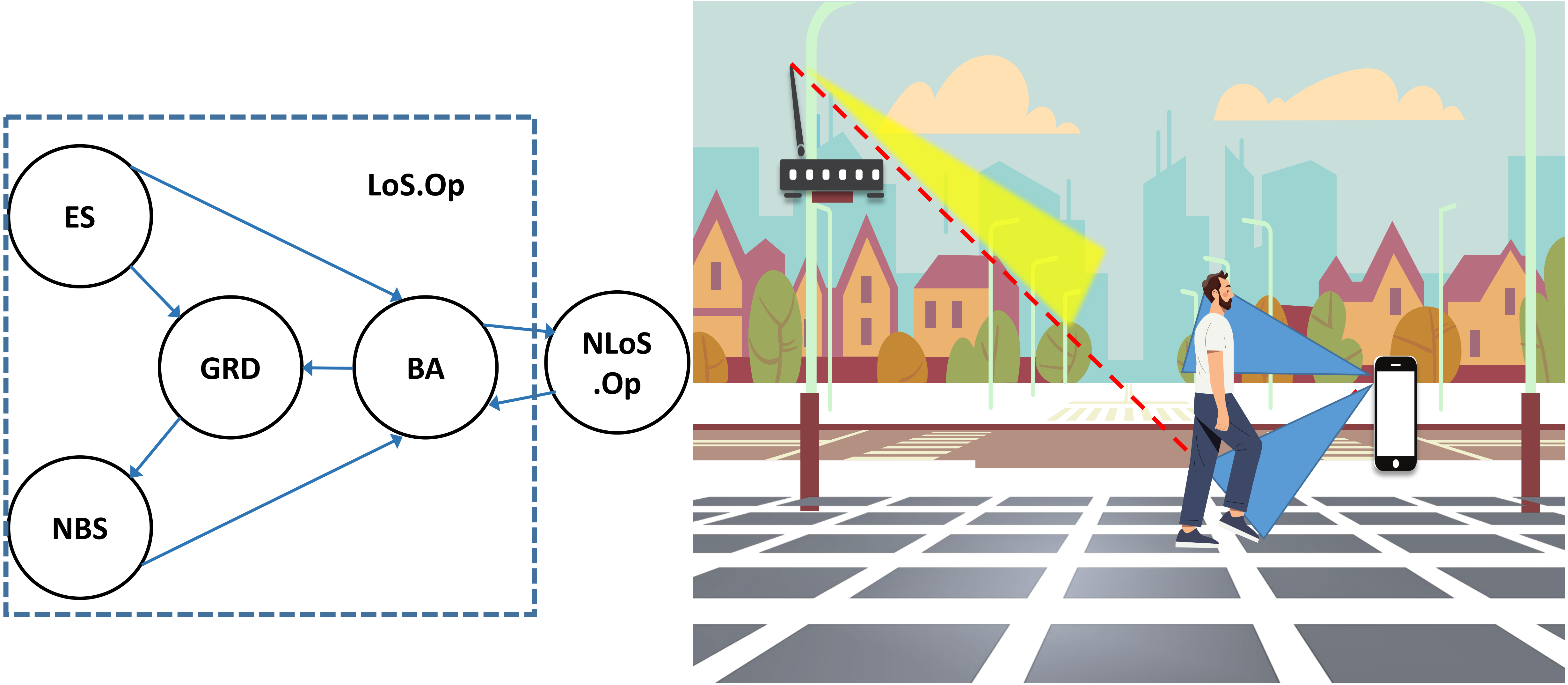


LoS.Op: Line of Sight Operation
NLoS.Op: Non Line of Sight Operation
BA: Beam Adaptation
GRD: Ground Reflection Discovery
NBS: Neighbor Beam Search
ES: Exhaustive Search

A: Beam Alignment to counter mobility
B: Ground Reflection Discovery
C: No pose information
D: Pose information
E: Blockage event
F: Normal Operation



LoS.Op
ES
GRD
BA
NBS
NLoS
.Op



LoS.Op
ES
GRD
BA
NBS
NLoS
.Op

Thank you-