Wireless Communications
From 5G and WiFi 6 to Low Power IoT

Lecture 6: 5G & WiFi 6

Haitham Hassanieh

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

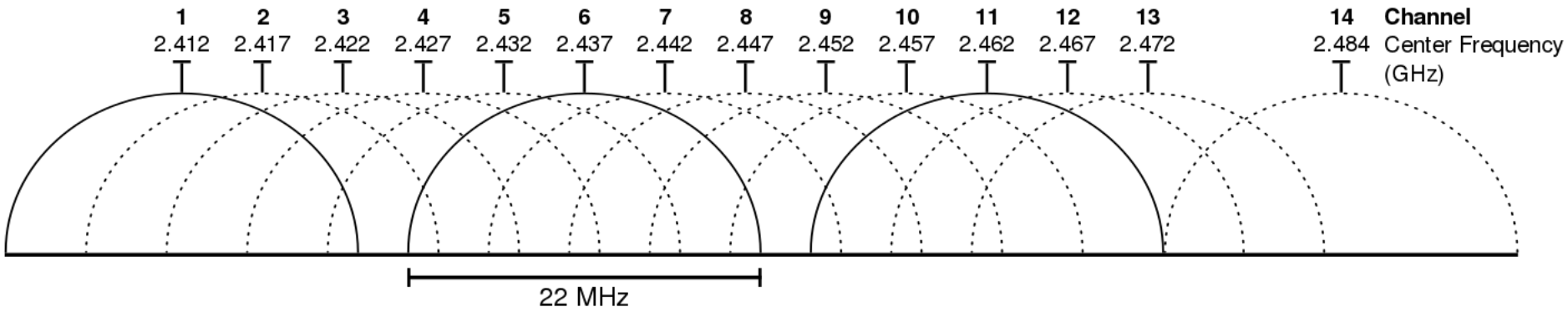
Previous Lecture:

- ✓ IoT Intro.
- ✓ Spread Spectrum
- ✓ Low Power Wide Area Networks
- ✓ Backscatter Communication
- ✓ Bluetooth

This Lecture:

- ❑ WiFi Overview
- ❑ MIMO & Multi-User MIMO
- ❑ OFDMA
- ❑ 5G Overview
- ❑ Millimeter Wave
- ❑ Massive MIMO

WiFi Standards from WiFi 1 to WiFi 6



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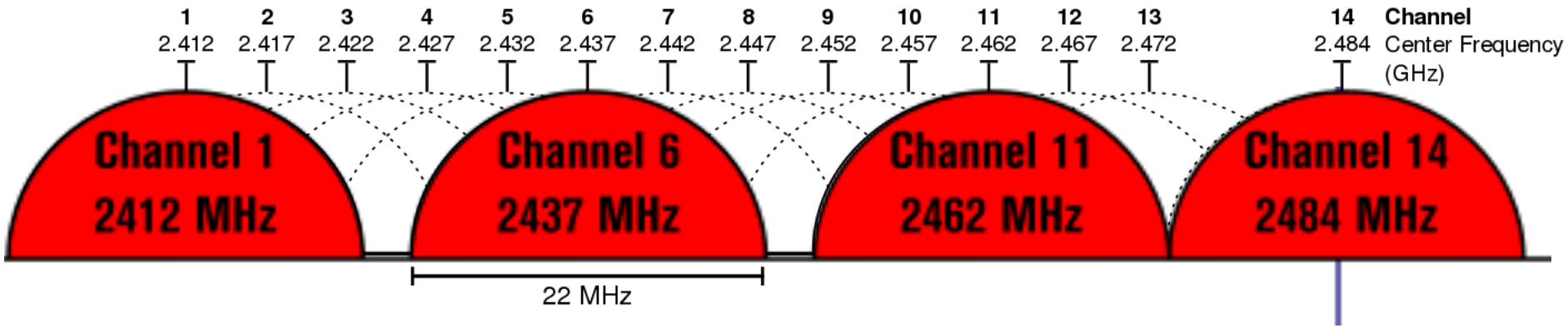

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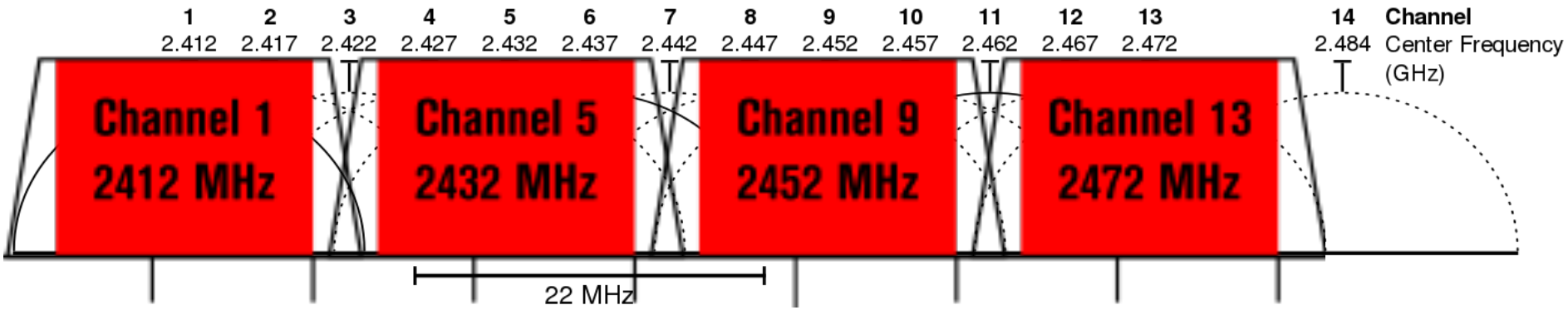

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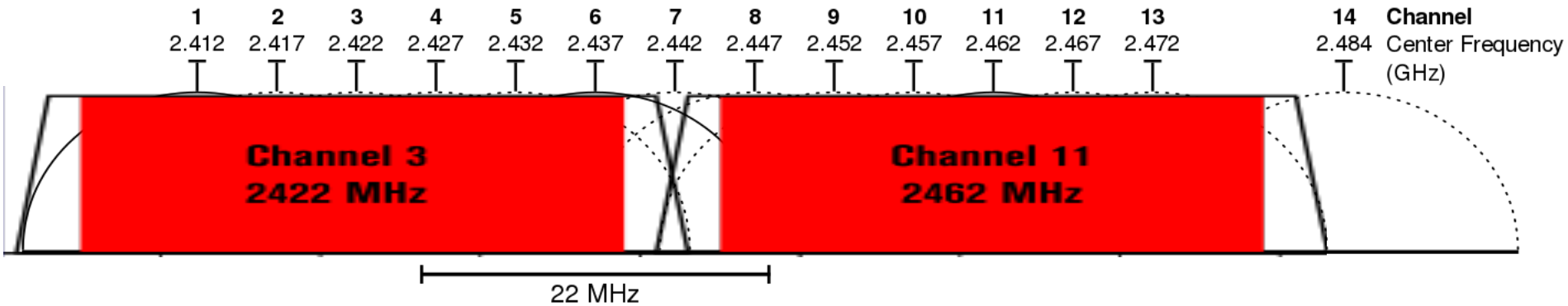

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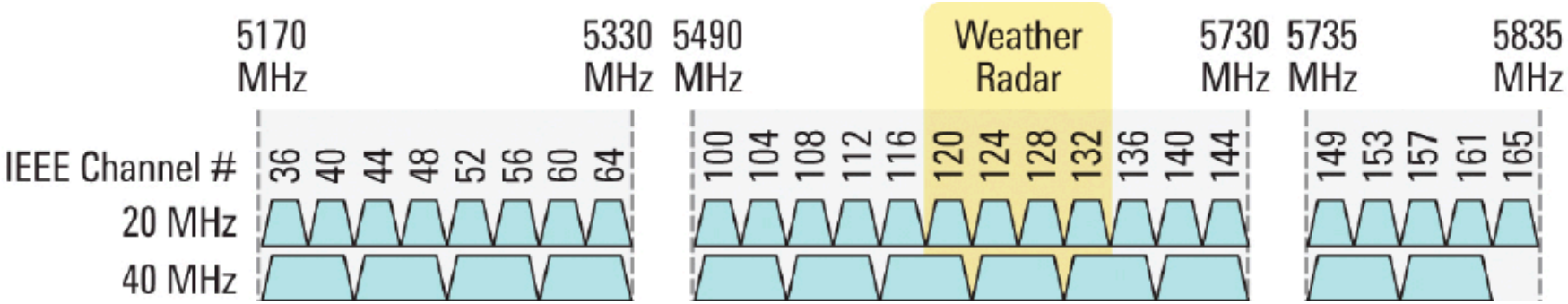

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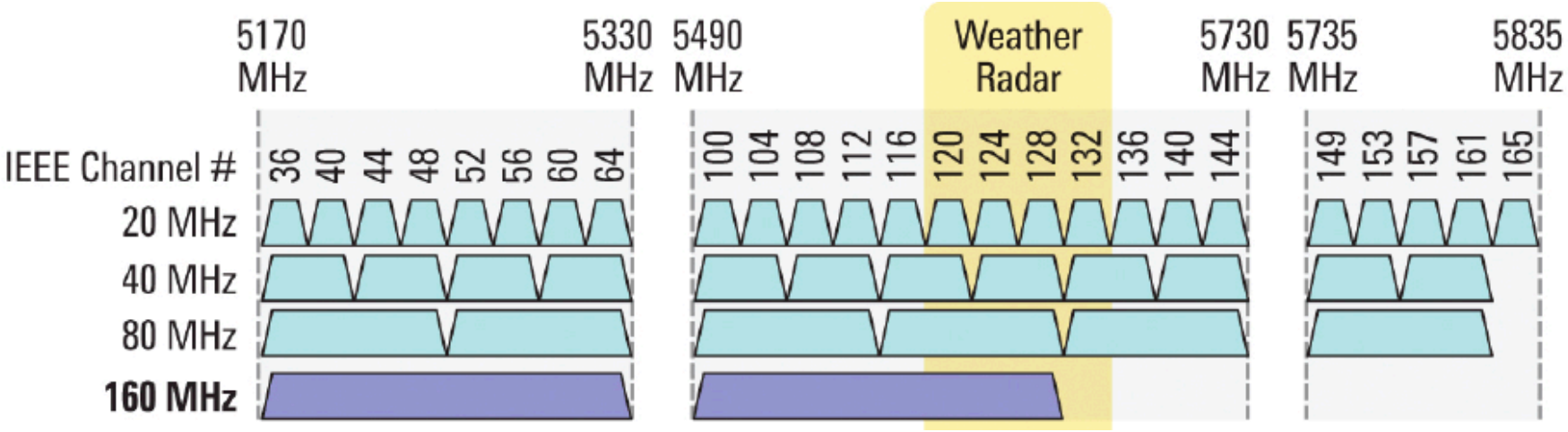

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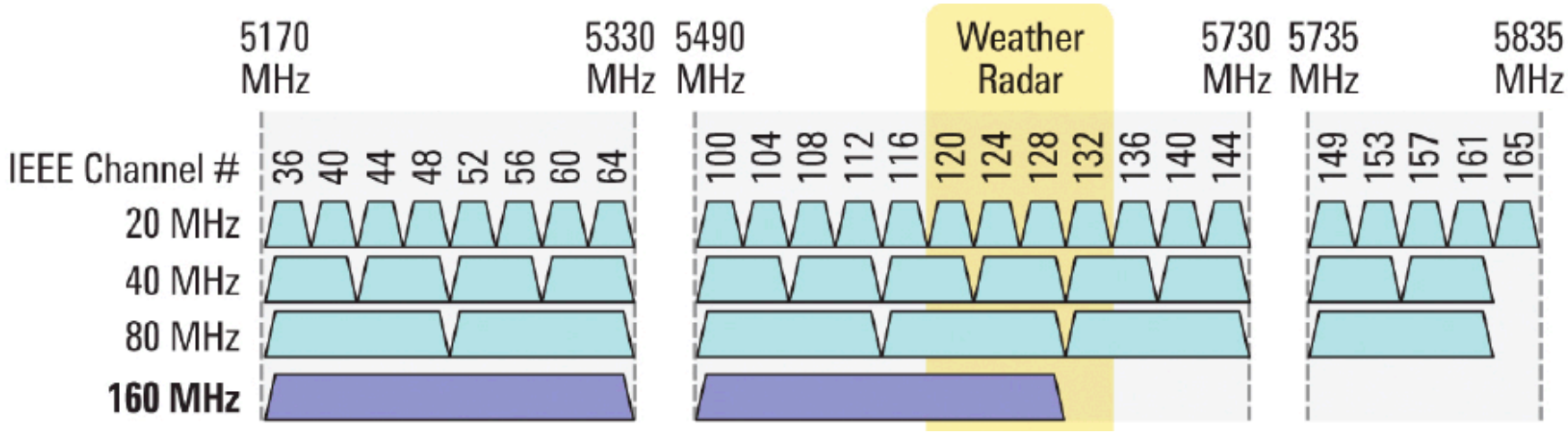

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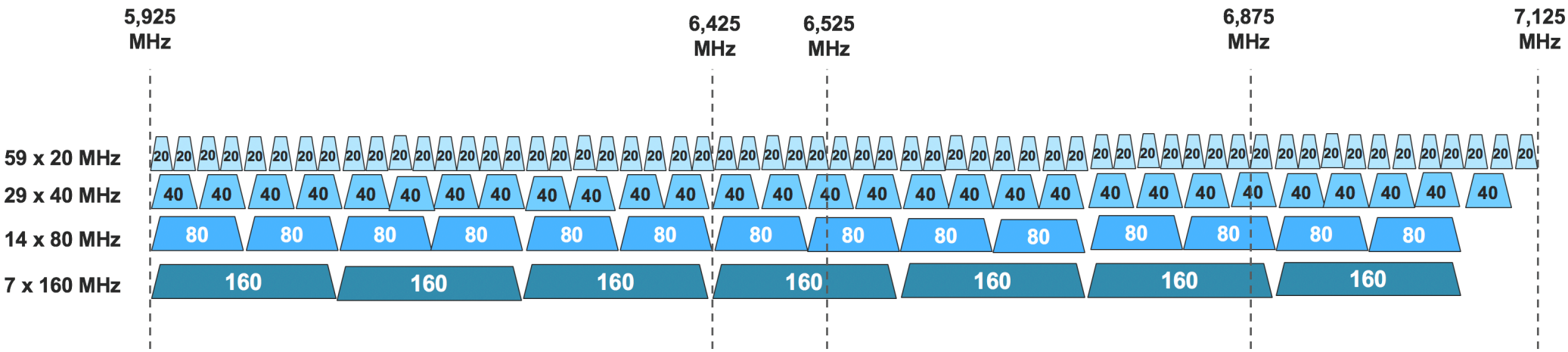

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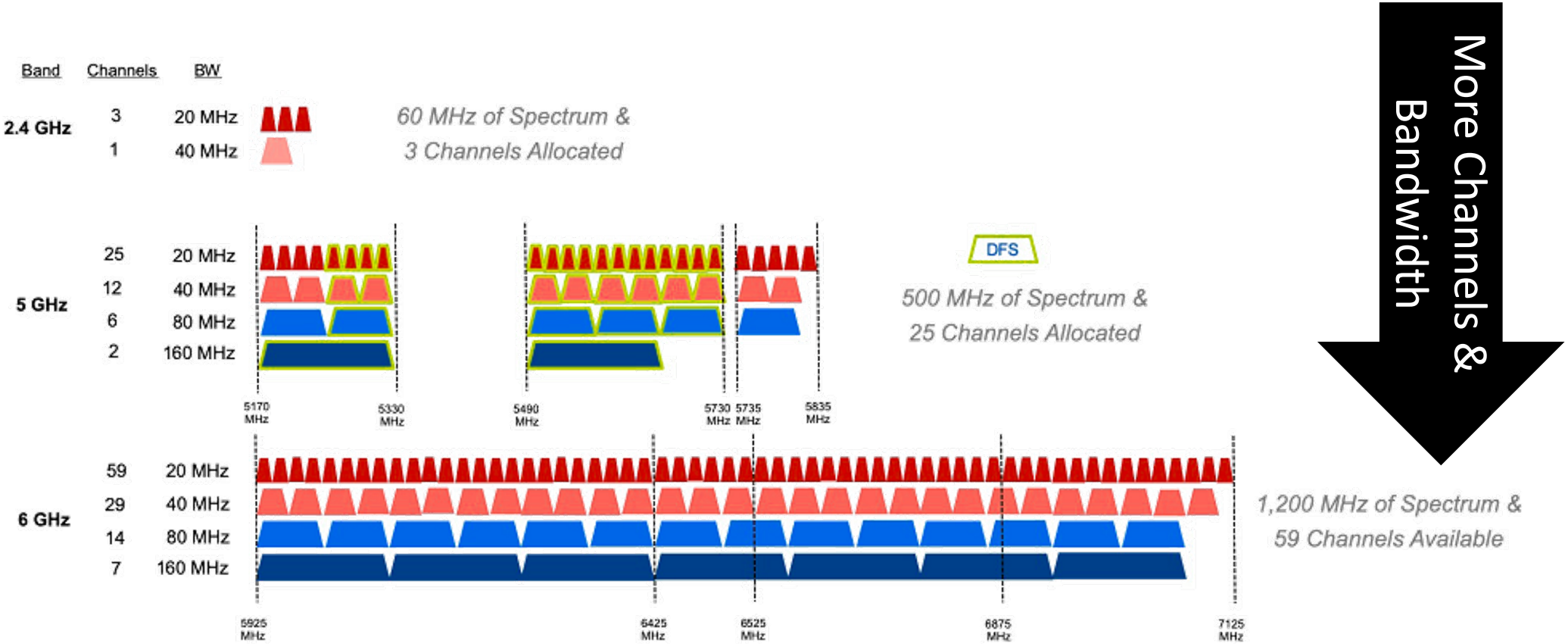
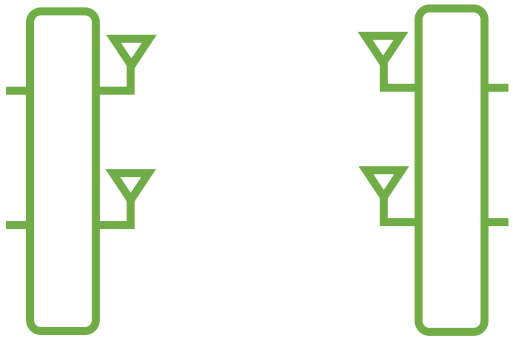


WiFi 1 — More MIMO Antennas — WiFi 5/6

MIMO: Multiple Input Multiple Output

So far: single input single output

MIMO: multiple input multiple output



Increase capacity of channel using multiple transmit and receive antennas.

MIMO: Multiple Input Multiple Output

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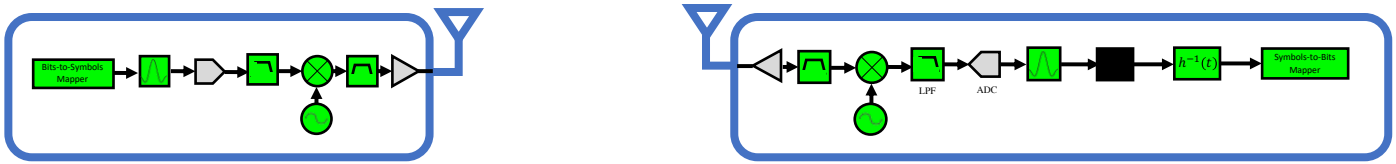
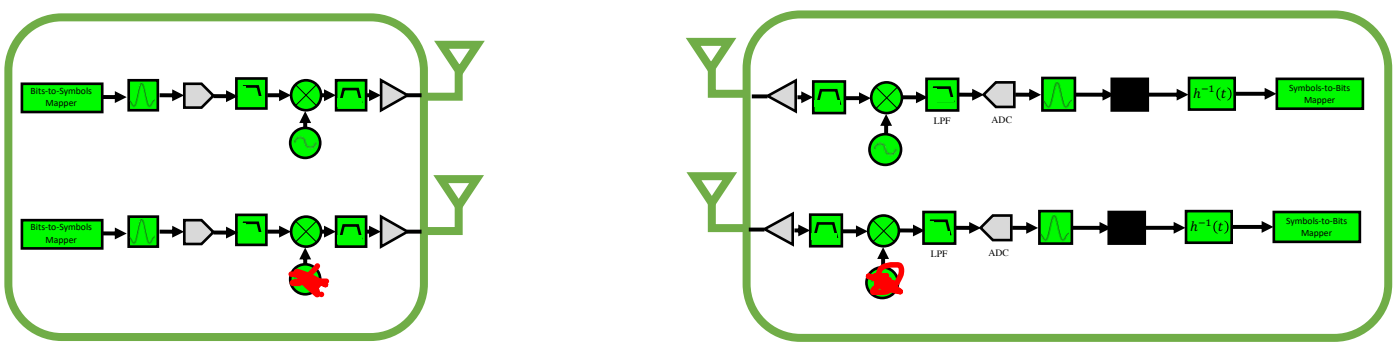
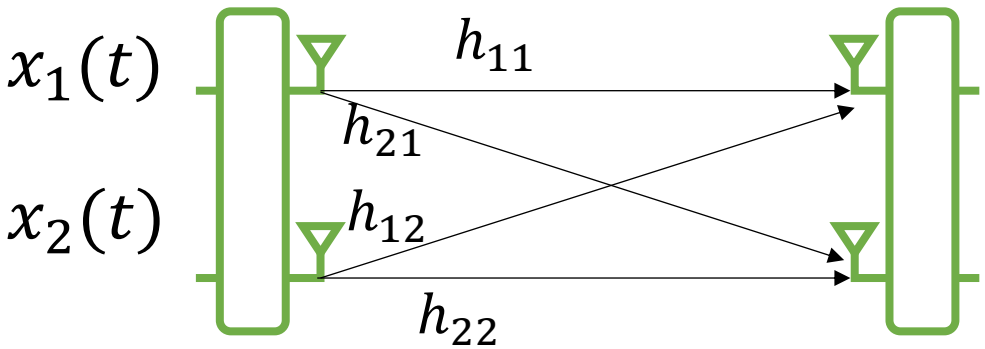


MIMO: multiple input multiple output



Increase capacity of channel using multiple transmit and receive antennas.

MIMO: Multiple TX-RX streams



$$y_1(t) = h_{11}x_1 + h_{12}x_2$$

$$y_2(t) = h_{21}x_1 + h_{22}x_2$$

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \quad \Rightarrow \quad \mathbf{y} = \mathbf{H}\mathbf{x}$$

How to recover x_1 and x_2?

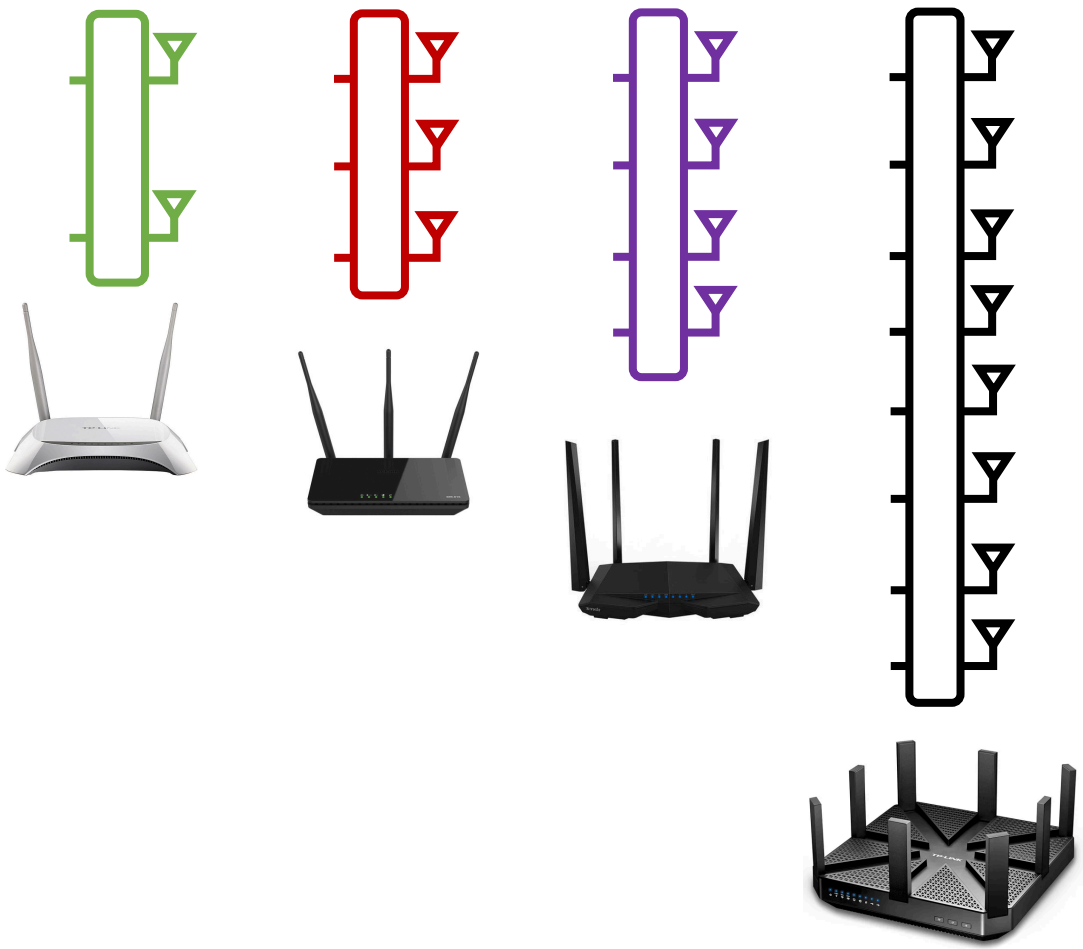
Estimate $\mathbf{H}$, compute $\mathbf{H}^{-1}$ and invert the channel!

$$\tilde{\mathbf{x}} = \mathbf{H}^{-1}\mathbf{y} = \mathbf{H}^{-1}\mathbf{H}\mathbf{x} = \mathbf{x}$$

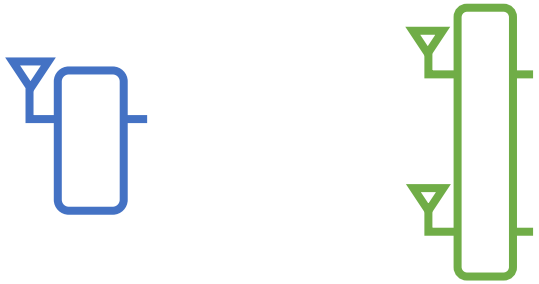
Transmit 2x at the same time!

MIMO: Multiple TX-RX streams

WiFi Access Points 2 to 8 MIMO

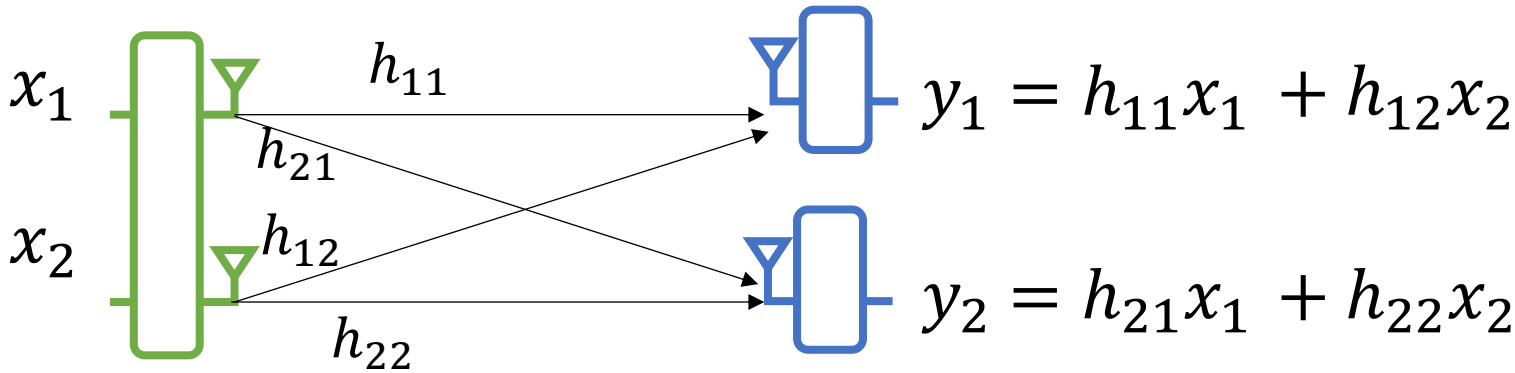


WiFi Devices 1 to 2 MIMO



- Power
- Form Factor & Antenna Separation
- Most mobile phones support 2 MIMO

Multi-User MIMO

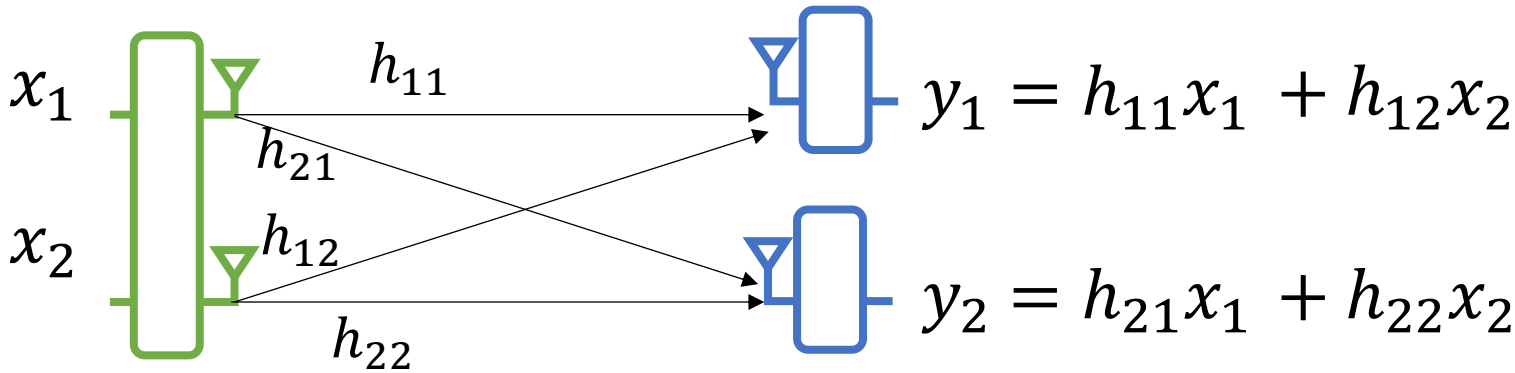


$$\mathbf{y} = \mathbf{H}\mathbf{x}$$

$$\tilde{\mathbf{x}} = \mathbf{H}^{-1}\mathbf{y} = \mathbf{H}^{-1}\mathbf{H}\mathbf{x} = \mathbf{x}$$

Does not work! Receivers do not have access to each other's signals.

MU-MIMO Beamforming



Send: $\tilde{\mathbf{x}} = \mathbf{H}^{-1}\mathbf{x}$

Receive: $\mathbf{y} = \mathbf{H}\tilde{\mathbf{x}} = \mathbf{H}\mathbf{H}^{-1}\mathbf{x} = \mathbf{x}$

Allows 1 AP to communicate with multiple users at the same time!

- Requires feedback from the receiver to know the channel at the transmitter.
- Introduces in 802.11ac but not widely used until 802.11ax

Channel Access in WiFi 1 – 5: CSMA

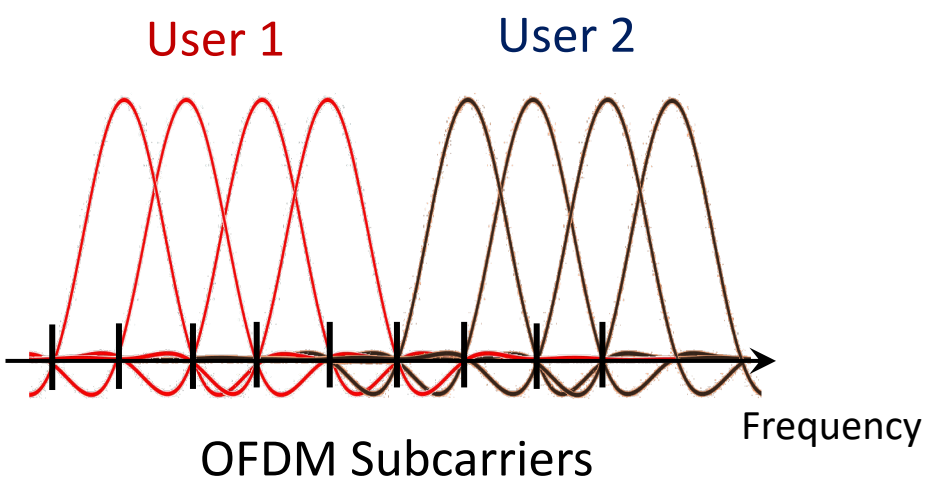
- CSMA: Carrier Sense Multiple Access
- Medium Access scheme in WiFi & Ethernet
- Simplified Version:
  1. Listen on the channel
  2. If no one is transmitting → back-off & wait for M slots
  3. If after M slots, still no one is transmitting, transmit.
  4. If collision, increase back-off time: $M = 2 \times M$
     If successful, decrease back-off window: $M = 2$

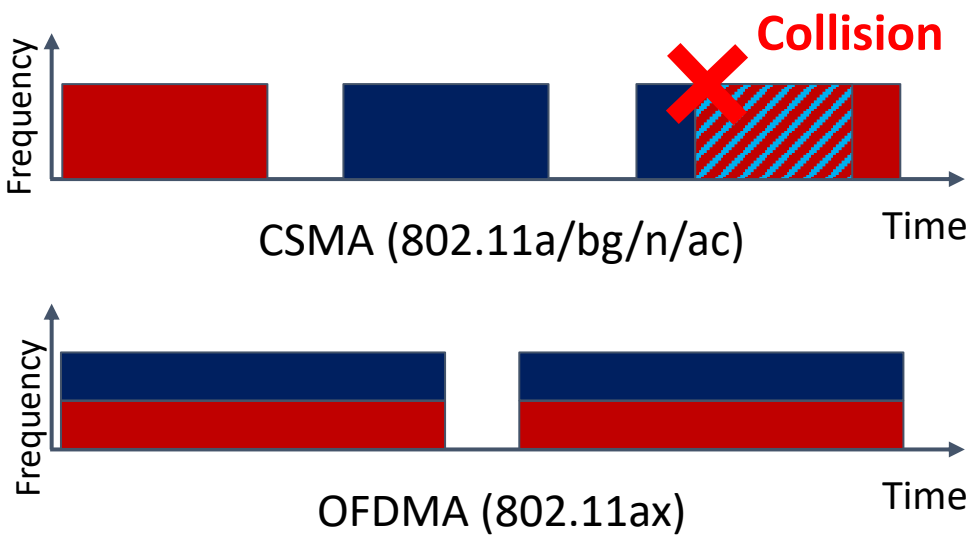
Suffers from significant number of collisions & problems known as hidden terminals & exposed terminals.

WiFi 6: OFDMA

- OFDMA: Orthogonal Frequency Division Multiple Access
- Assign different OFDM subcarriers to difference users.
- Since subcarriers are orthogonal → small guard bands (Efficient).

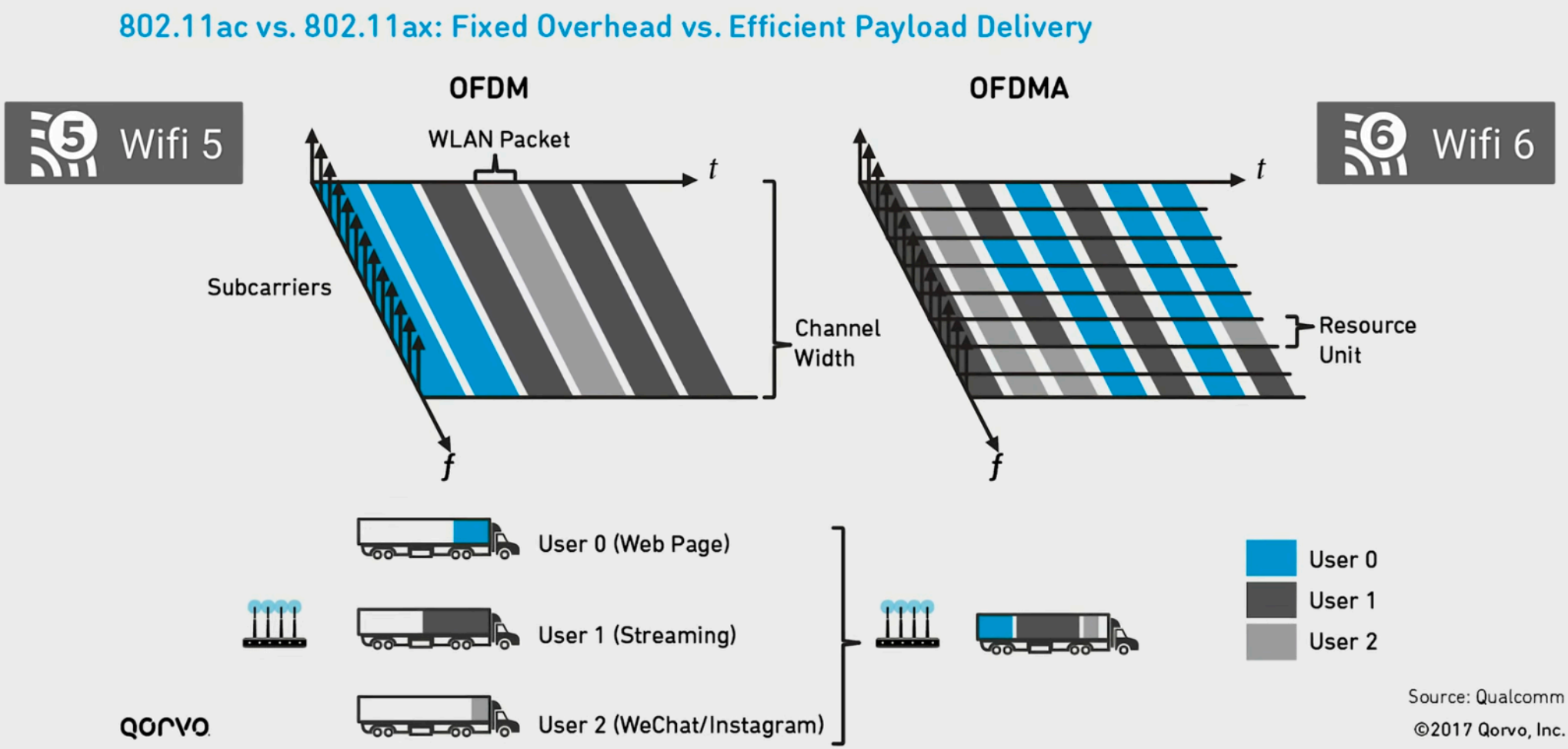
Transmit and Receive from multiple users at the same time.





Requires users to be synchronized on the uplink! Needs good hardware & synchronization algorithms.

WiFi 6: OFDMA


802.11ac vs. 802.11ax: Fixed Overhead vs. Efficient Payload Delivery
Wifi 5
OFDM
WLAN Packet
t
Subcarriers
Channel Width
f
OFDMA
Wifi 6
t
Resource Unit
f
User 0 (Web Page)
User 1 (Streaming)
User 2 (WeChat/Instagram)
User 0
User 1
User 2
Source: Qualcomm
qorvo
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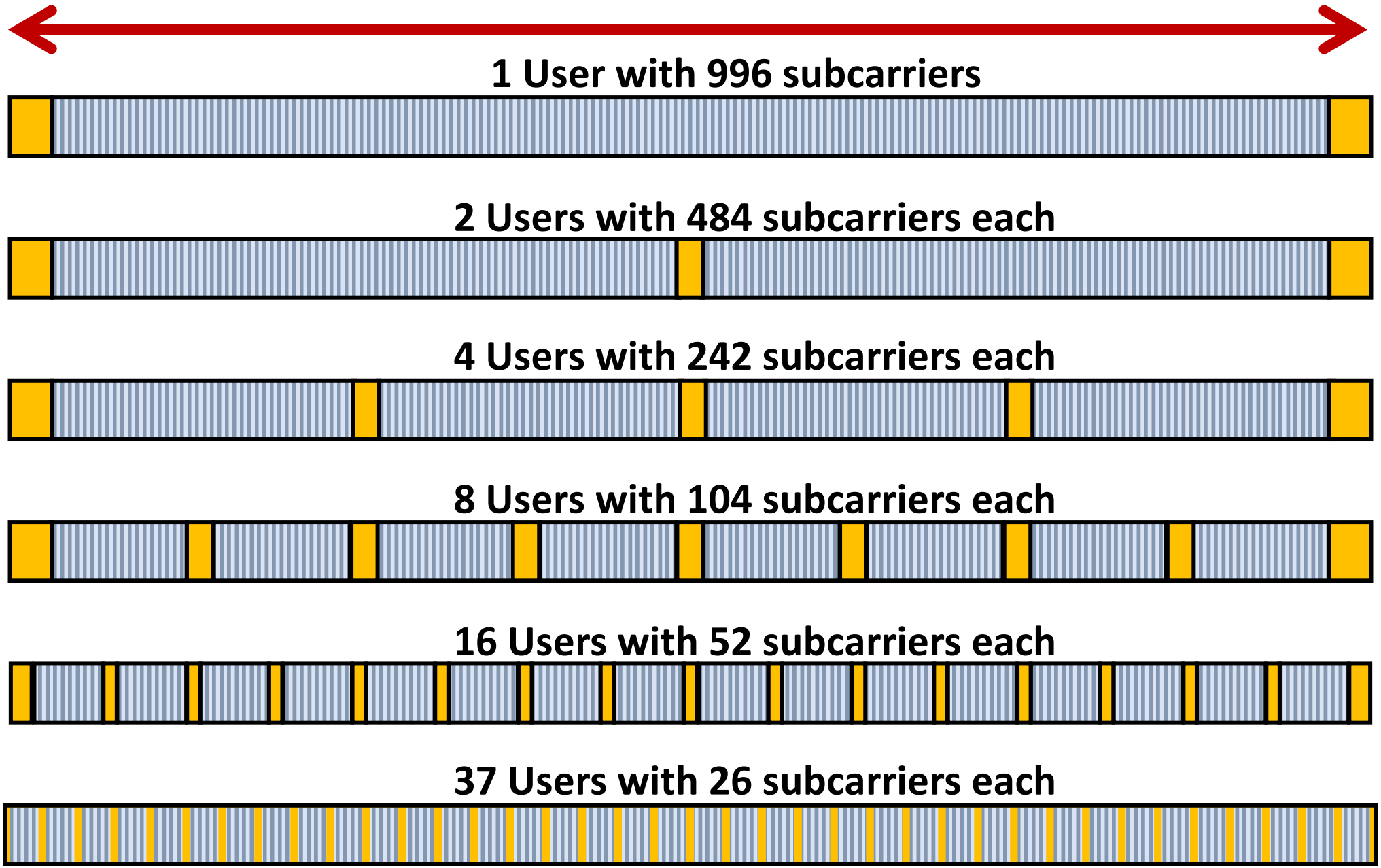
WiFi 6: OFDMA

OFDM Symbol with 1024 Subcarriers in 802.11ax



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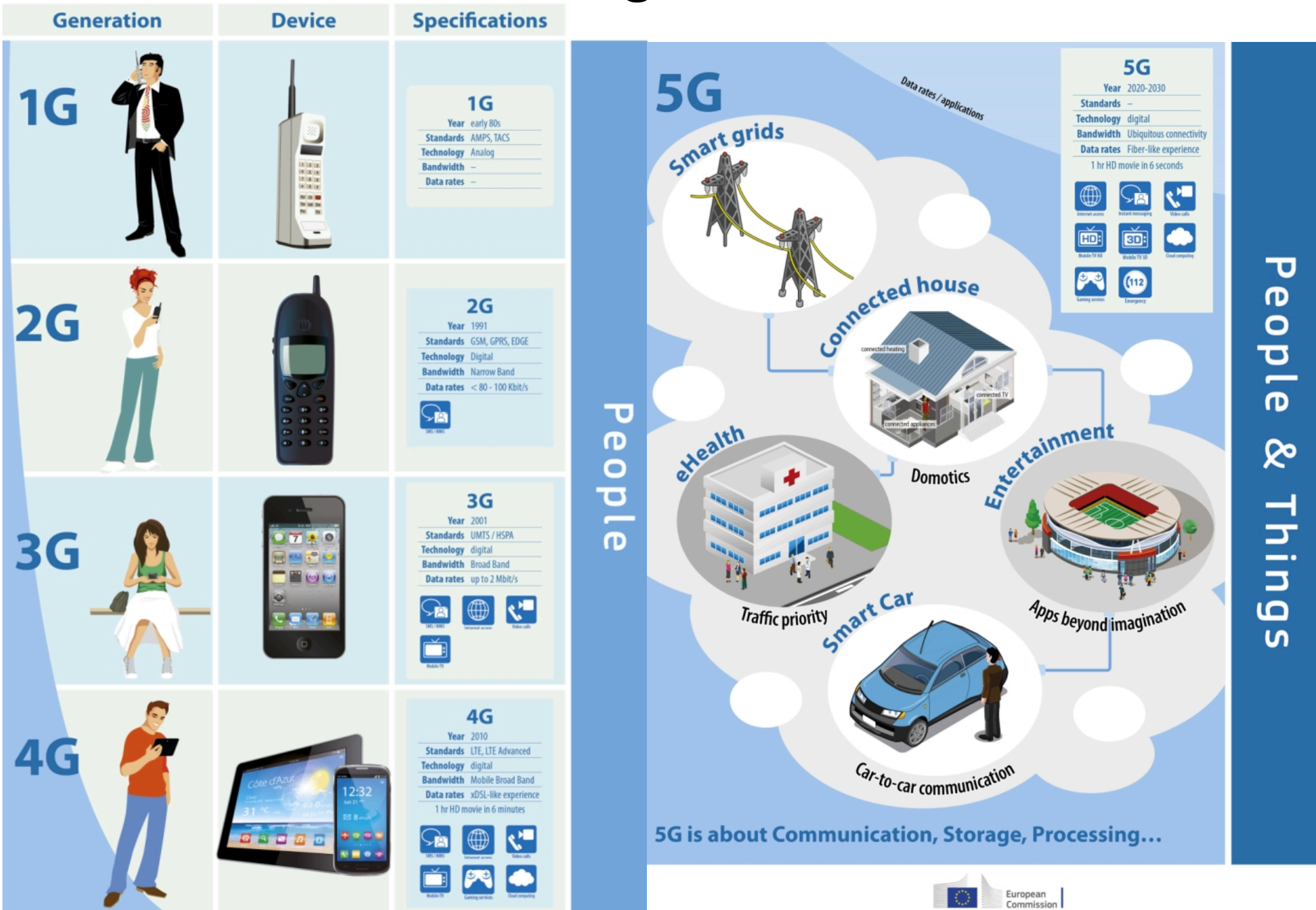
- ✓ OFDMA
- ❑ 5G Overview
- ❑ Millimeter Wave
- ❑ Massive MIMO

Mobile Technologies from 1G to 5G



5G: Unified Air Interface

Enhanced Mobile Broadband (eMBB)	Massive Machine Type Communications (mMTC)	Ultra-Reliable, Low-Latency Communications (URLLC)
▪ 100+ Mbps avg. throughput ▪ 10+ Gbps peak throughput	▪ 10^6/km^2 connection density ▪ Low cost/energy connectivity	▪ 99.999% service availability ▪ 1 – 10 ms latency
▪ Mobile video and gaming ▪ Cloud computing and storage ▪ High speed connectivity	▪ Billions of connected devices ▪ Sensor networks ▪ IoT / M2M / D2D	▪ Tactile Internet ▪ Natural disaster relief ▪ E-Medicine and Health care

5G: Underlying Technology

5G Radio Standard: NR (New Radio)

- Millimeter Wave
- Massive MIMO
- Small Cells (Extended from 4G)
- LDPC & Polar Codes
- Full Duplex
- F-OFDM

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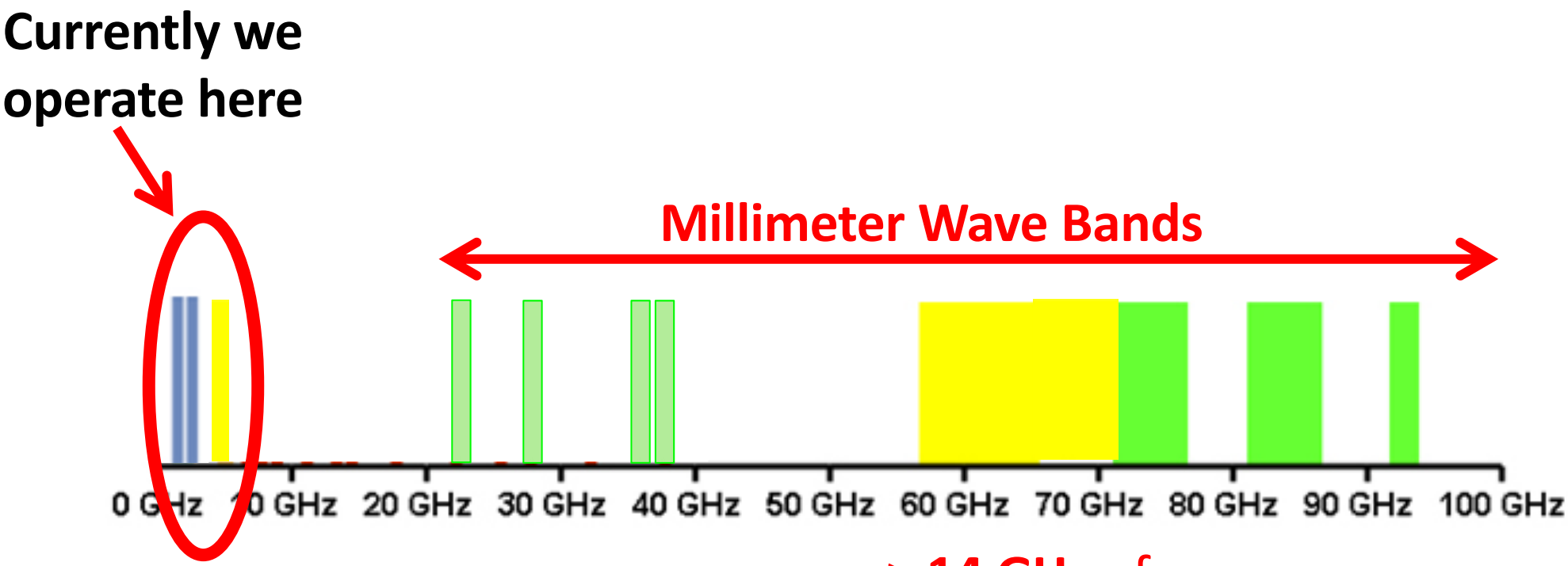
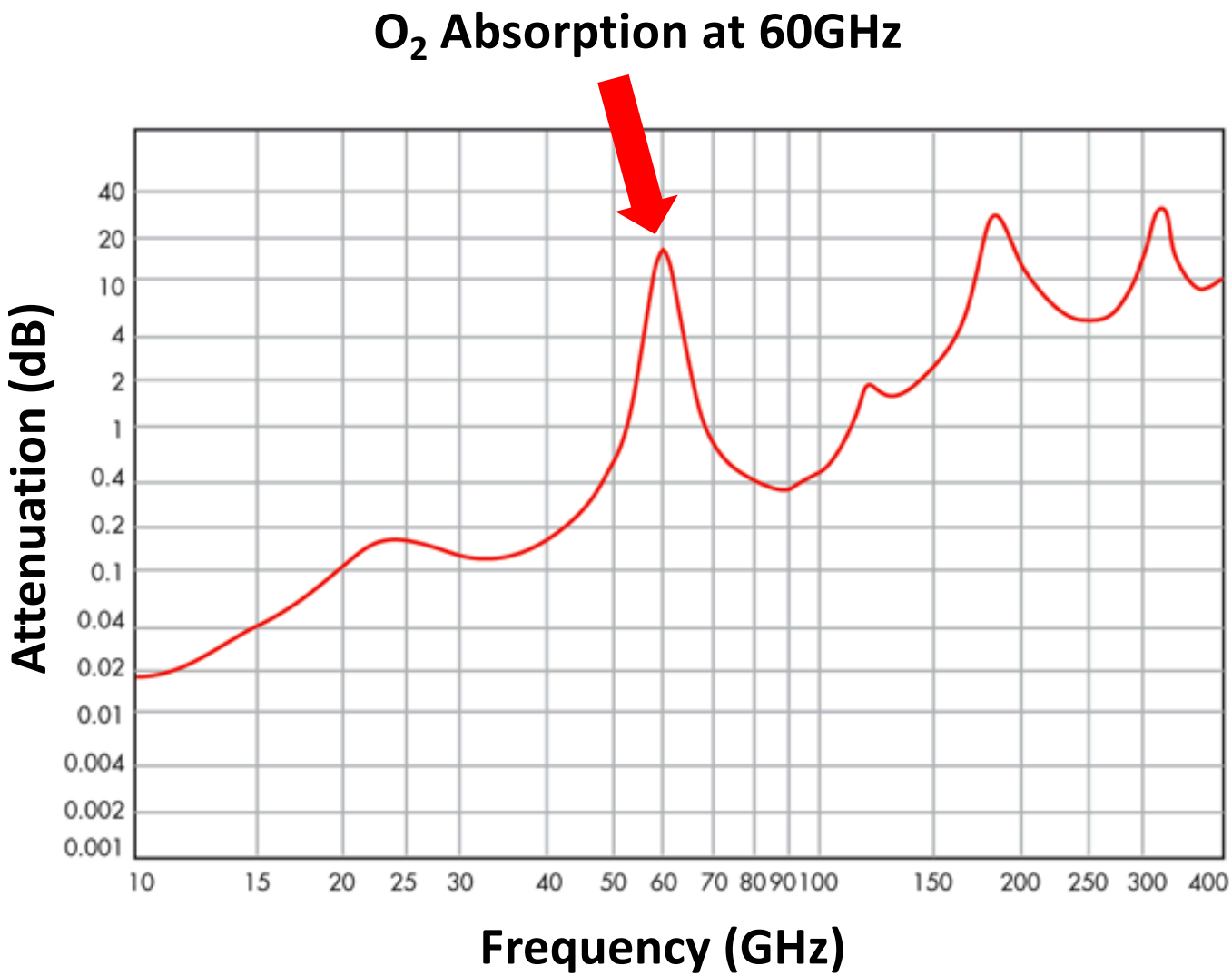
Millimeter Wave Technology

Huge bandwidth available at millimeter wave frequencies



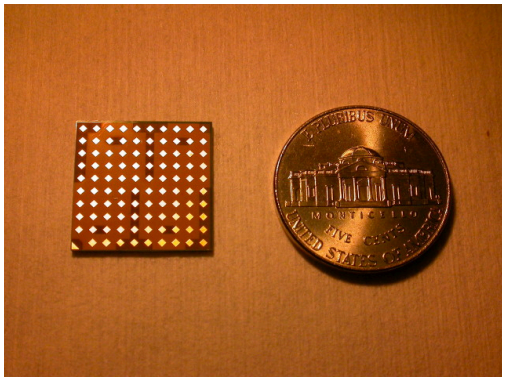
> 14 GHz of
Unlicensed Spectrum
For WiFi 802.11ad

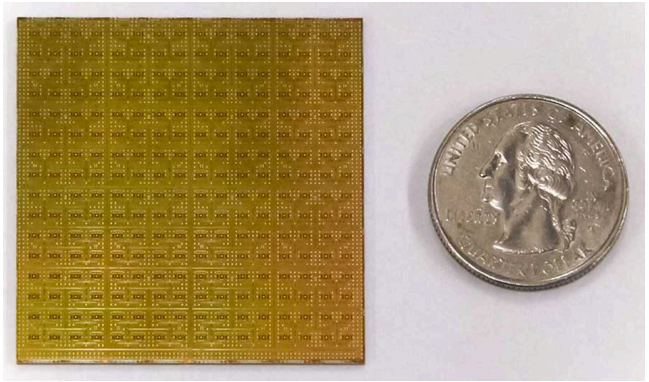
Millimeter Waves Suffer from Large Attenuation



Millimeter Waves Suffer from Large Attenuation

mmWave radios use phased antenna arrays to focus the power along one direction

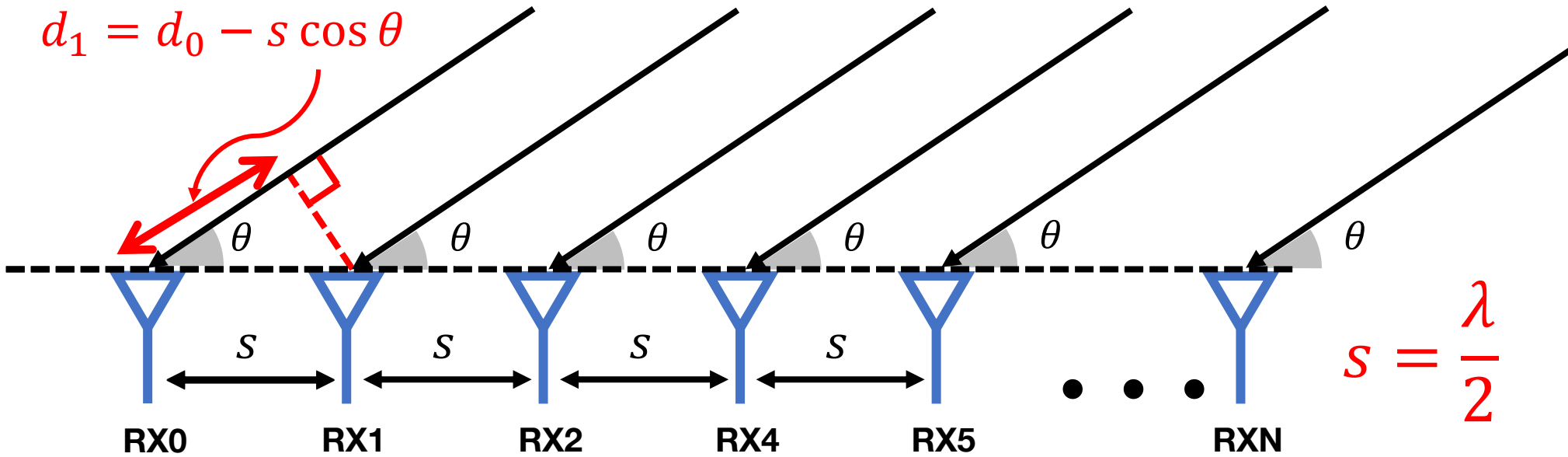




Small Wavelength enables thousands of antennas to be packed into small space

→ Extremely narrow beams

Antenna Arrays

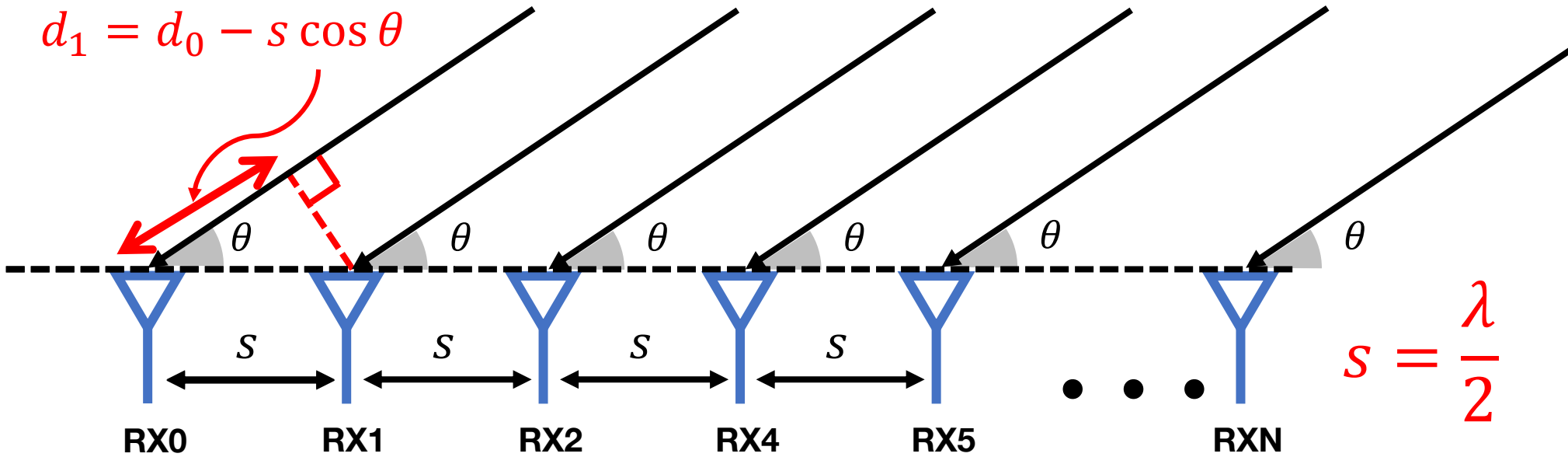


$$h_0 = \alpha e^{-j2\pi\frac{d_0}{\lambda}} = \alpha e^{-j\phi_0}$$

$$h_1 = \alpha e^{-j2\pi\frac{d_1}{\lambda}} = \alpha e^{-j2\pi\frac{d_0 - s\cos\theta}{\lambda}}$$

$$h_k = \alpha e^{-j2\pi\frac{d_k}{\lambda}} = \alpha e^{-j2\pi\frac{d_0 - ks\cos\theta}{\lambda}}$$

Antenna Arrays



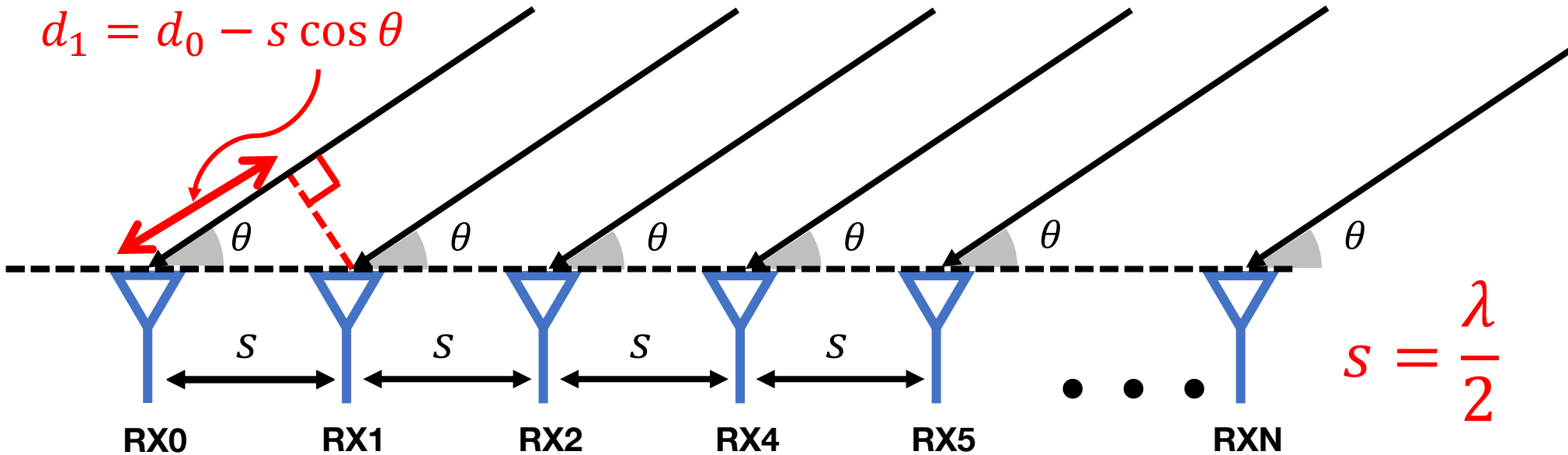
$$s = \frac{\lambda}{2}$$

$$h_0 = \alpha e^{-j2\pi\frac{d_0}{\lambda}} = \alpha e^{-j\phi_0}$$

$$h_1 = \alpha e^{-j2\pi\frac{d_1}{\lambda}} = \alpha e^{-j2\pi\frac{d_0 - s\cos\theta}{\lambda}} = \alpha e^{-j\phi_0 + j\pi\cos\theta}$$

$$h_k = \alpha e^{-j2\pi\frac{d_k}{\lambda}} = \alpha e^{-j2\pi\frac{d_0 - ks\cos\theta}{\lambda}} = \alpha e^{-j\phi_0 + j\pi k\cos\theta}$$

Antenna Arrays



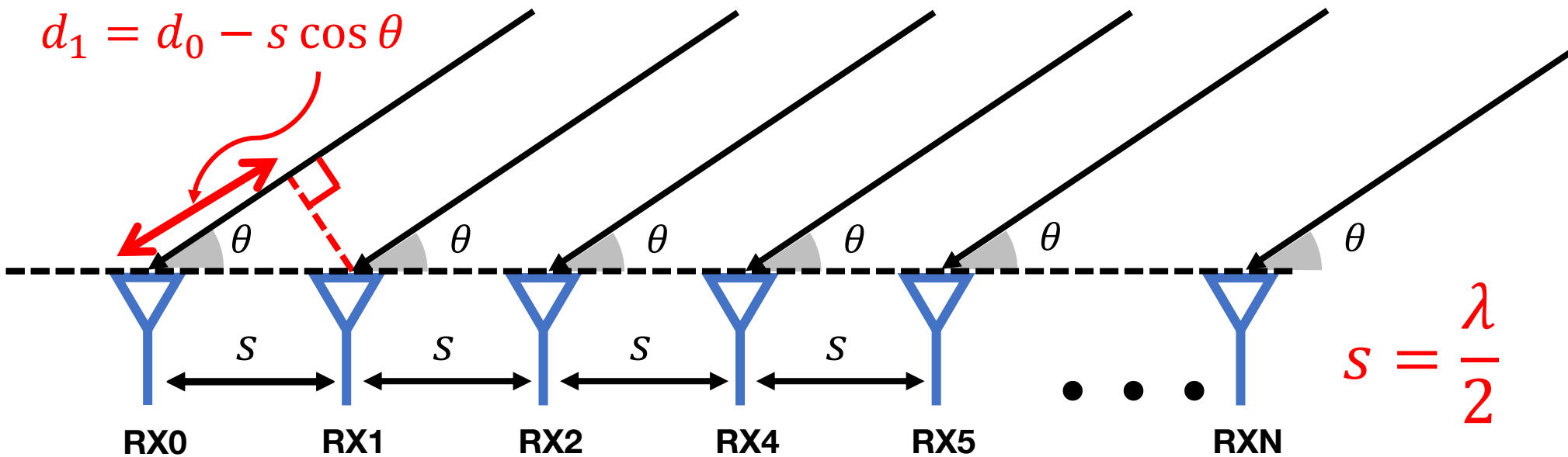
$$s = \frac{\lambda}{2}$$

$$y_k(t) = h_k x(t) \qquad h_k = \alpha e^{-j\phi_0 + j\pi k \cos\theta}$$

To receive from direction θ:

$$y_\theta(t) = \sum y_k(t) e^{-j\pi k \cos\theta}$$

Antenna Arrays



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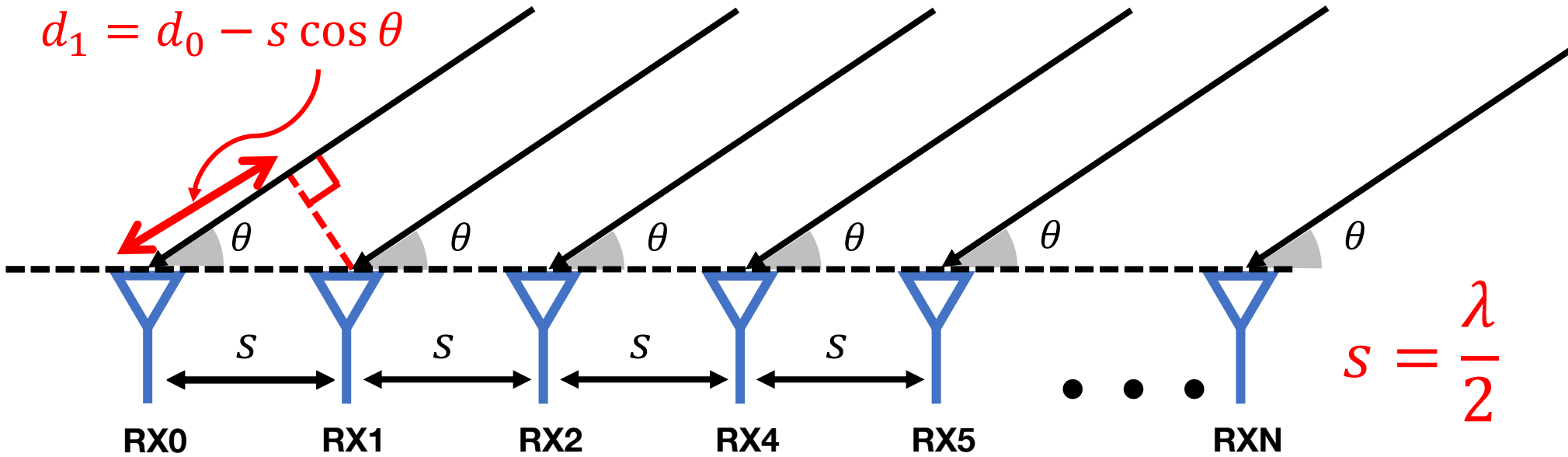
To receive from direction θ:

$$y_\theta(t) = \sum y_k(t) e^{-j\pi k \cos\theta} = \sum h_k x(t) e^{-j\pi k \cos\theta}$$

$$= \sum x(t) e^{-j\phi_0} = N x(t) e^{-j\phi_0}$$

Increased Transmit/Receiver power along θ by N times.

Antenna Arrays



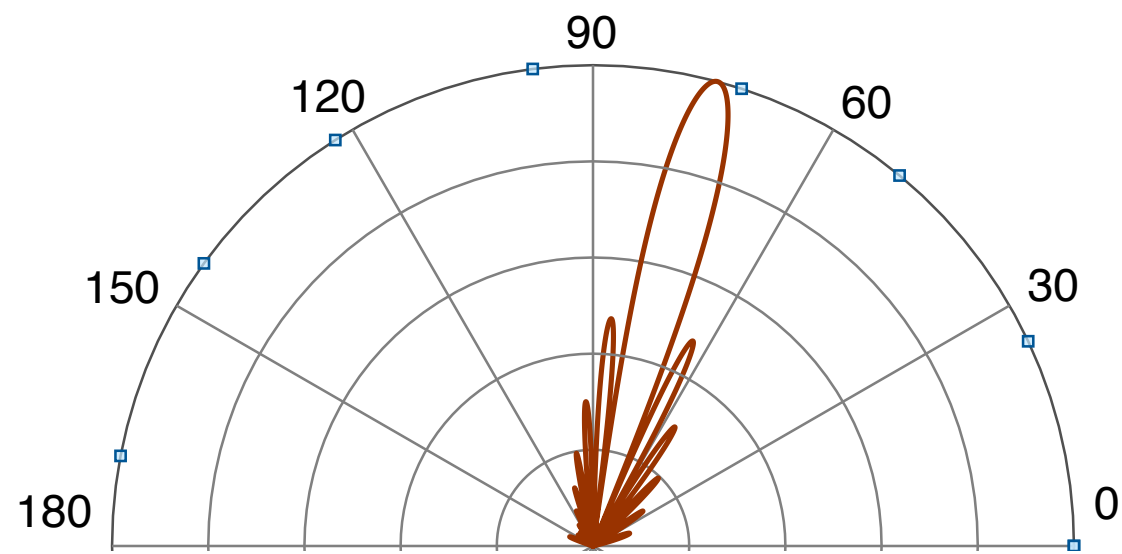
Increased Transmit/Receiver power along θ by N times.

To receive from direction θ:

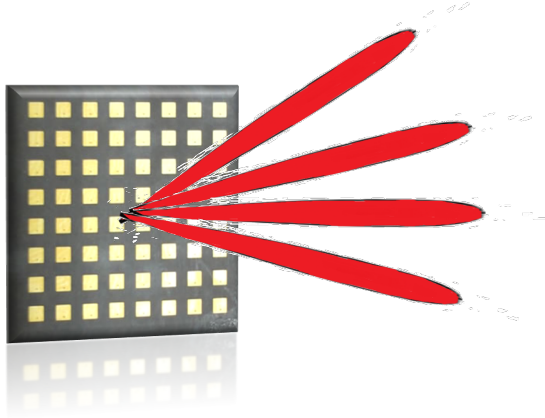
$$y_\theta(t) = \sum y_k(t) e^{-j\pi k \cos\theta}$$

To transmit along direction θ:

$$x_k(t) = x(t) e^{-j\pi k \cos\theta}$$

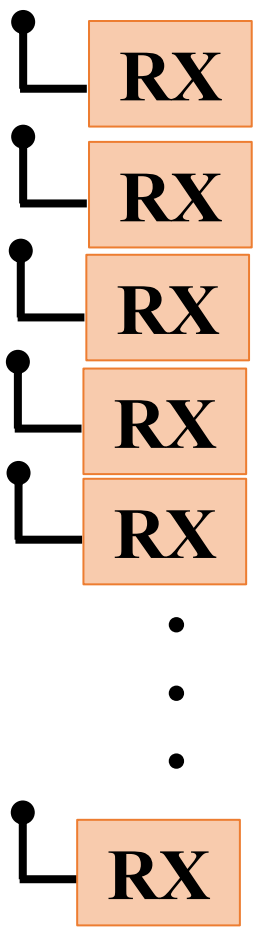


Millimeter Wave Phased Arrays



- Small Wavelength at mmWave enables massive antenna arrays to be packed into small space
  - → e.g. At 60 GHz, 1024 (32×32 ≈ 8cm×8cm)
  - →Huge antenna gains
  - →Very Narrow beams
  - →Electronic Steering

Beamforming using Antenna Arrays



To receive from direction θ:

$$y_\theta(t) = \sum y_k(t) e^{-j\pi k \cos\theta}$$

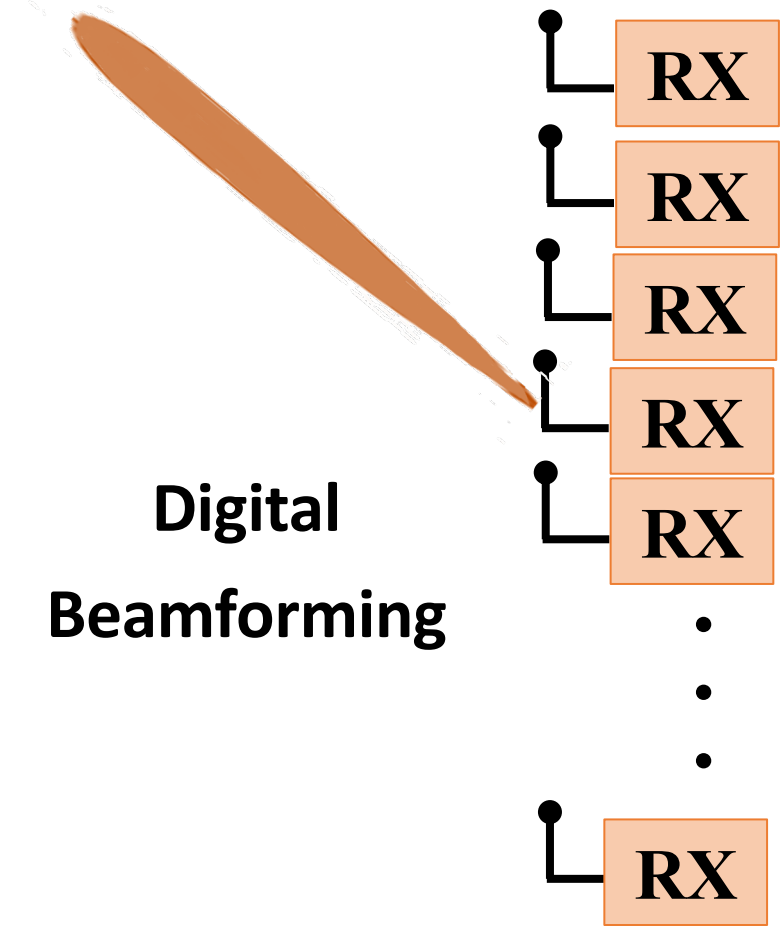
Cannot have a TX/RX chain per antenna!

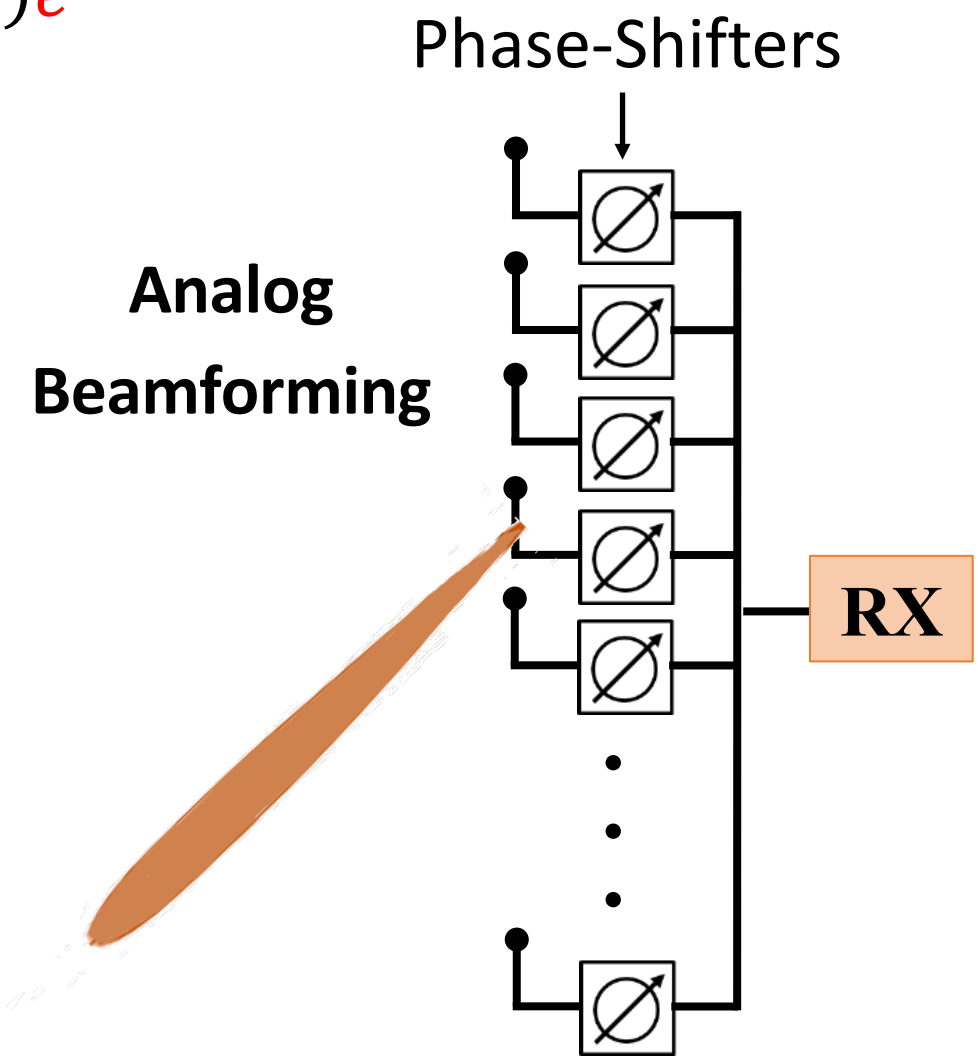
Cannot do digital beamforming

Beamforming using Antenna Arrays

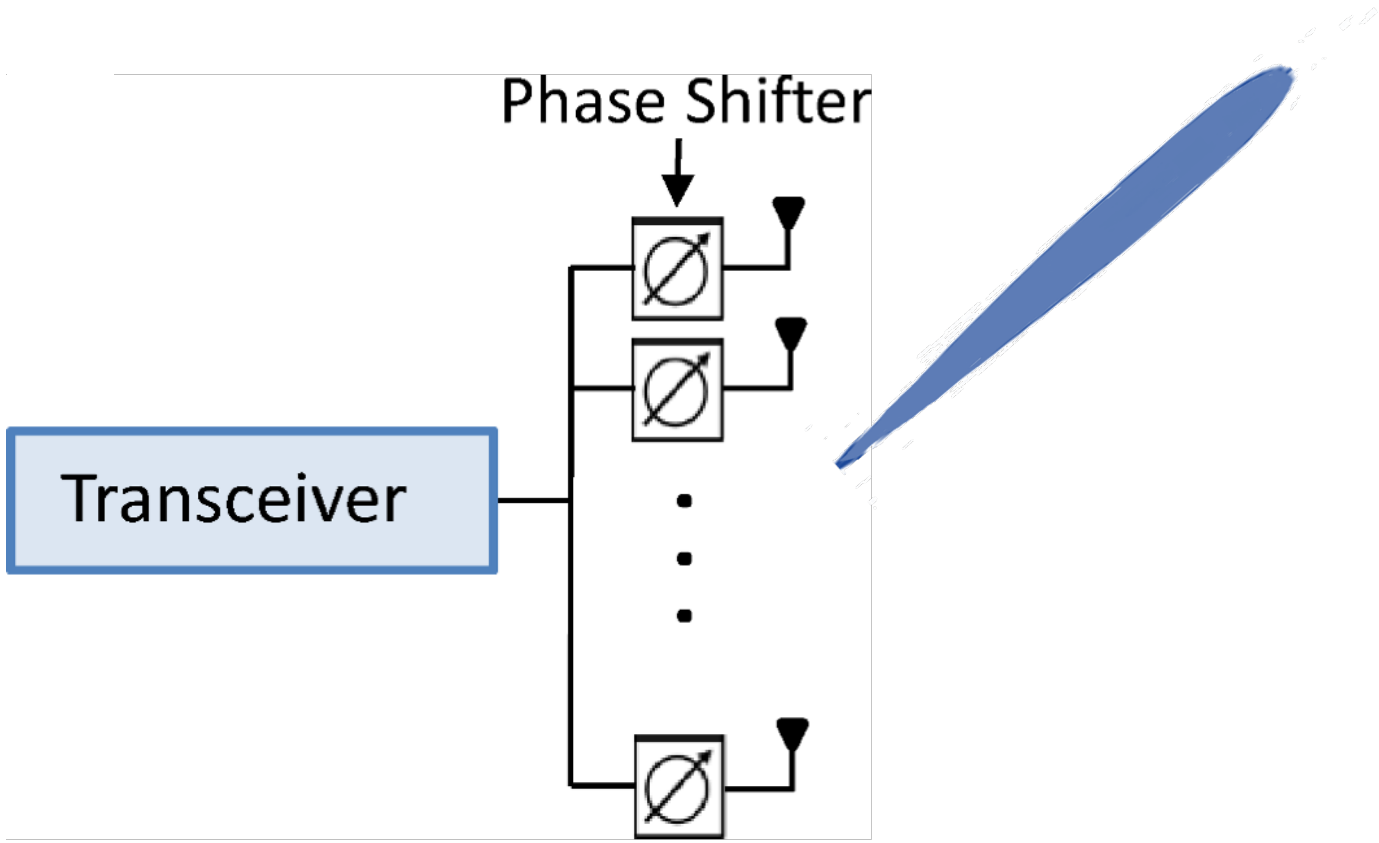
To receive from direction θ:

$$y_\theta(t) = \sum y_k(t) e^{-j\pi k \cos\theta}$$





Millimeter Wave Uses Phased Arrays



Early Measurement of Millimeter Wave 5G Deployments

https://fivegophers.umn.edu/www20/

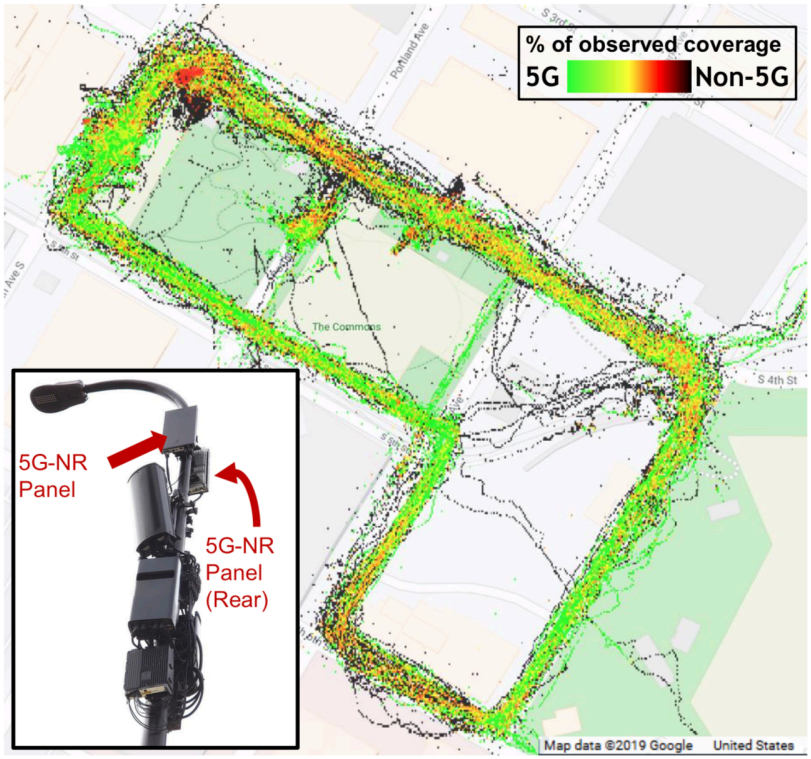


Figure 1: 5G coverage recorded at Minneapolis's Commons Park. A color gradient from green to black indicates the percentage of observed 5G coverage (high to low respectively). We sampled 6.8 million data points to inform this visualization. Also indicated is a 5G mmWave base station.

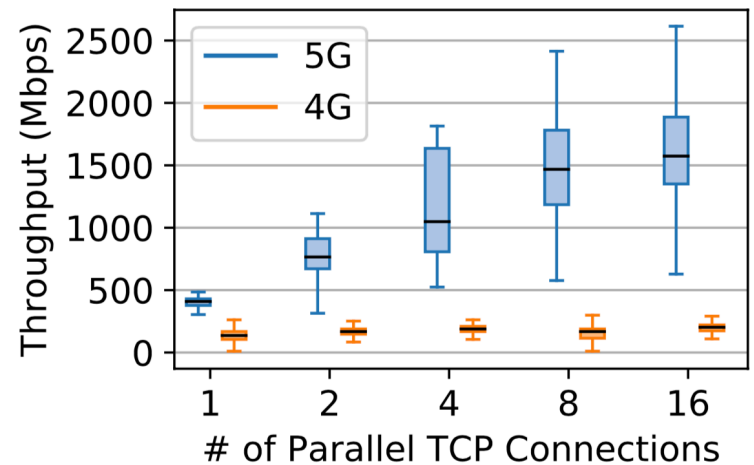


Figure 5: TCP performance under LoS: throughput.

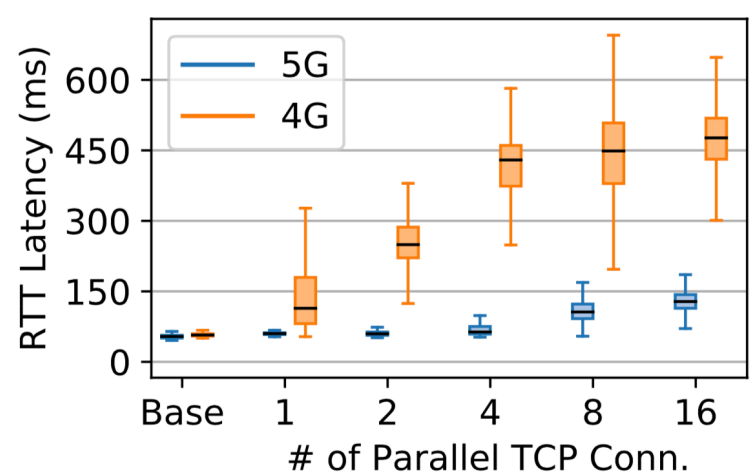


Figure 6: TCP performance under LoS: RTT.

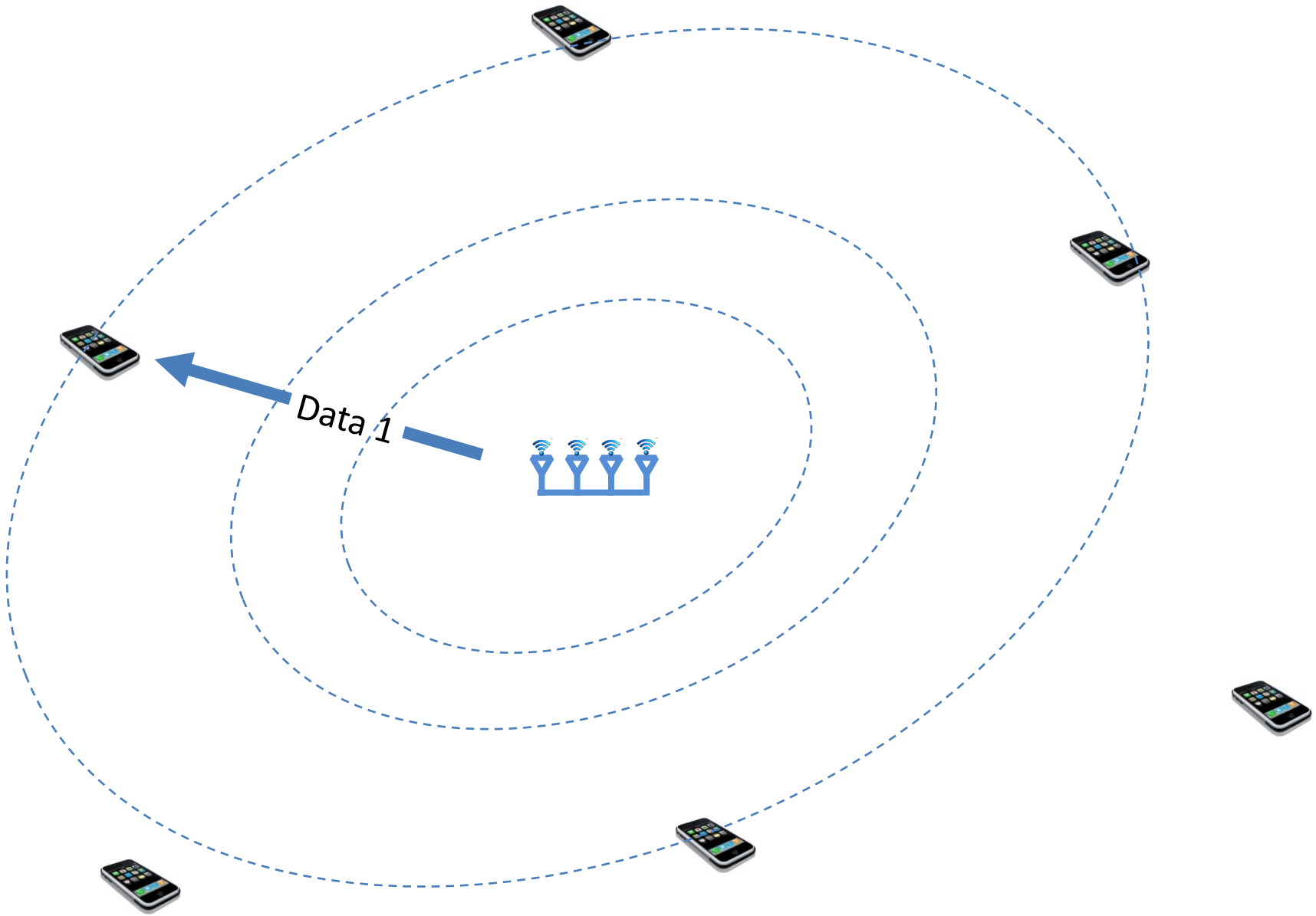
Previous Lecture:

- ✓ IoT Intro.
- ✓ Spread Spectrum
- ✓ Low Power Wide Area Networks
- ✓ Backscatter Communication
- ✓ Bluetooth

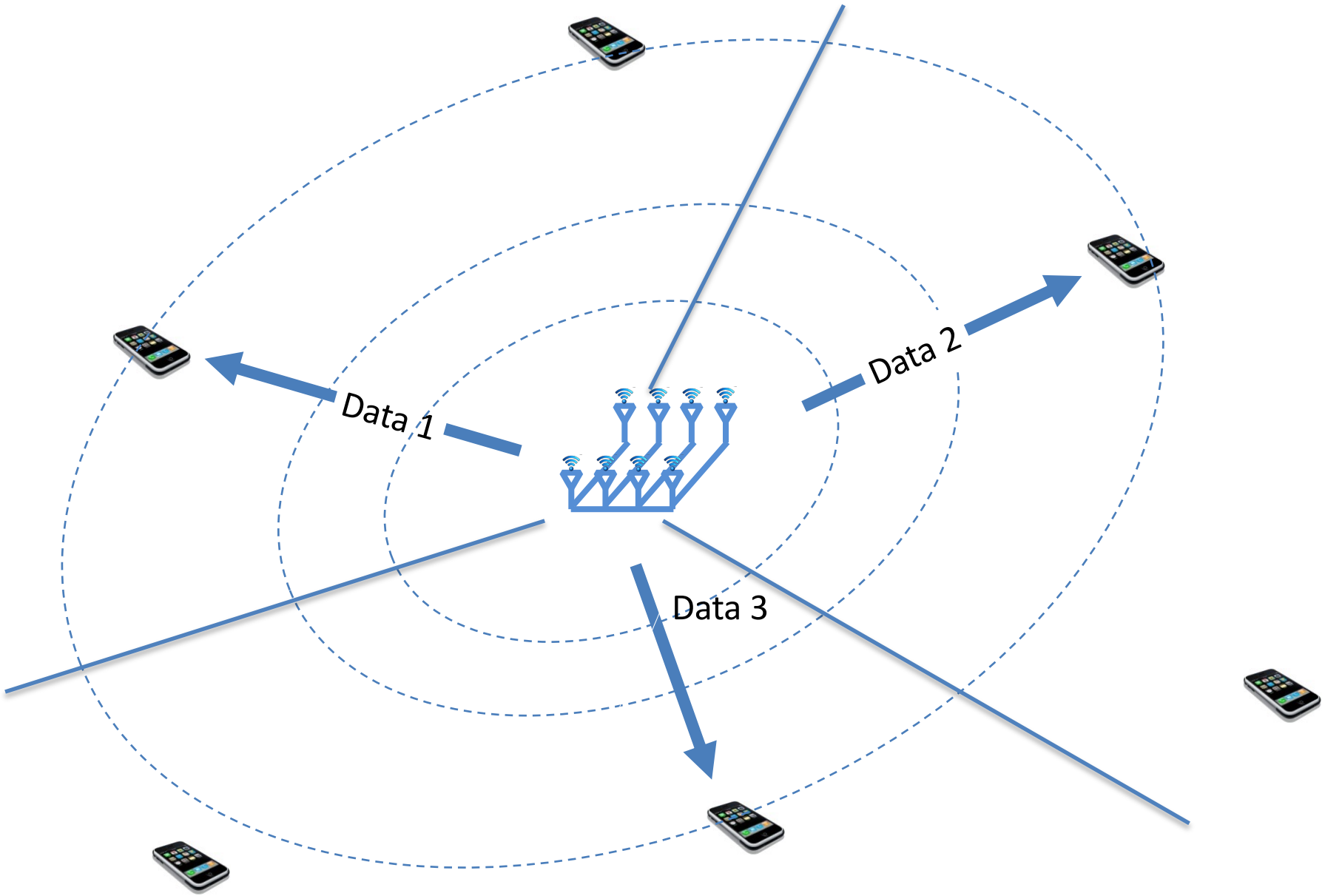
This Lecture:

- ✓ WiFi Overview
- ✓ MIMO & Multi-User MIMO
- ✓ OFDMA
- ✓ 5G Overview
- ✓ Millimeter Wave
- ❑ Massive MIMO

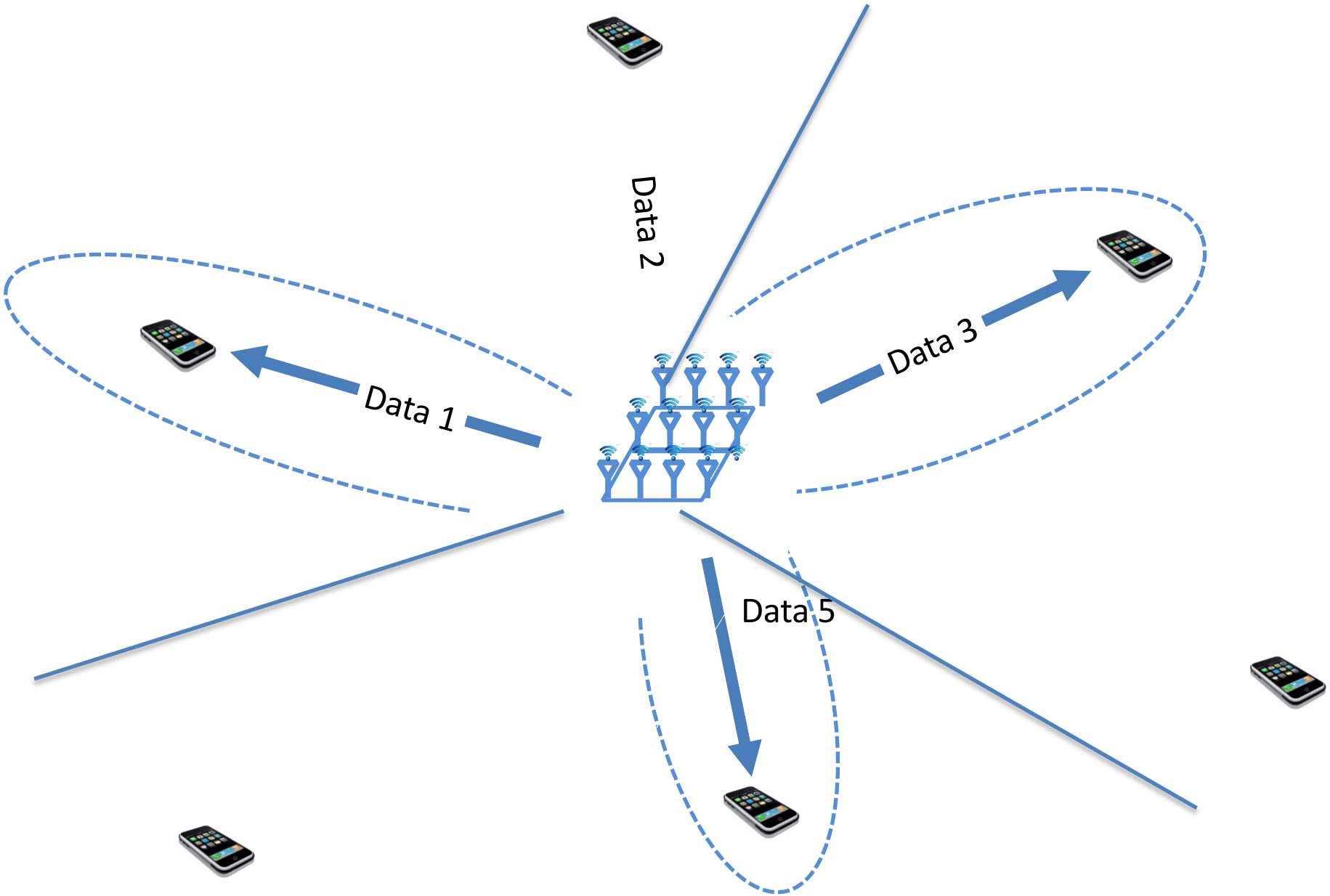
Multi-User MIMO at < 6 GHz



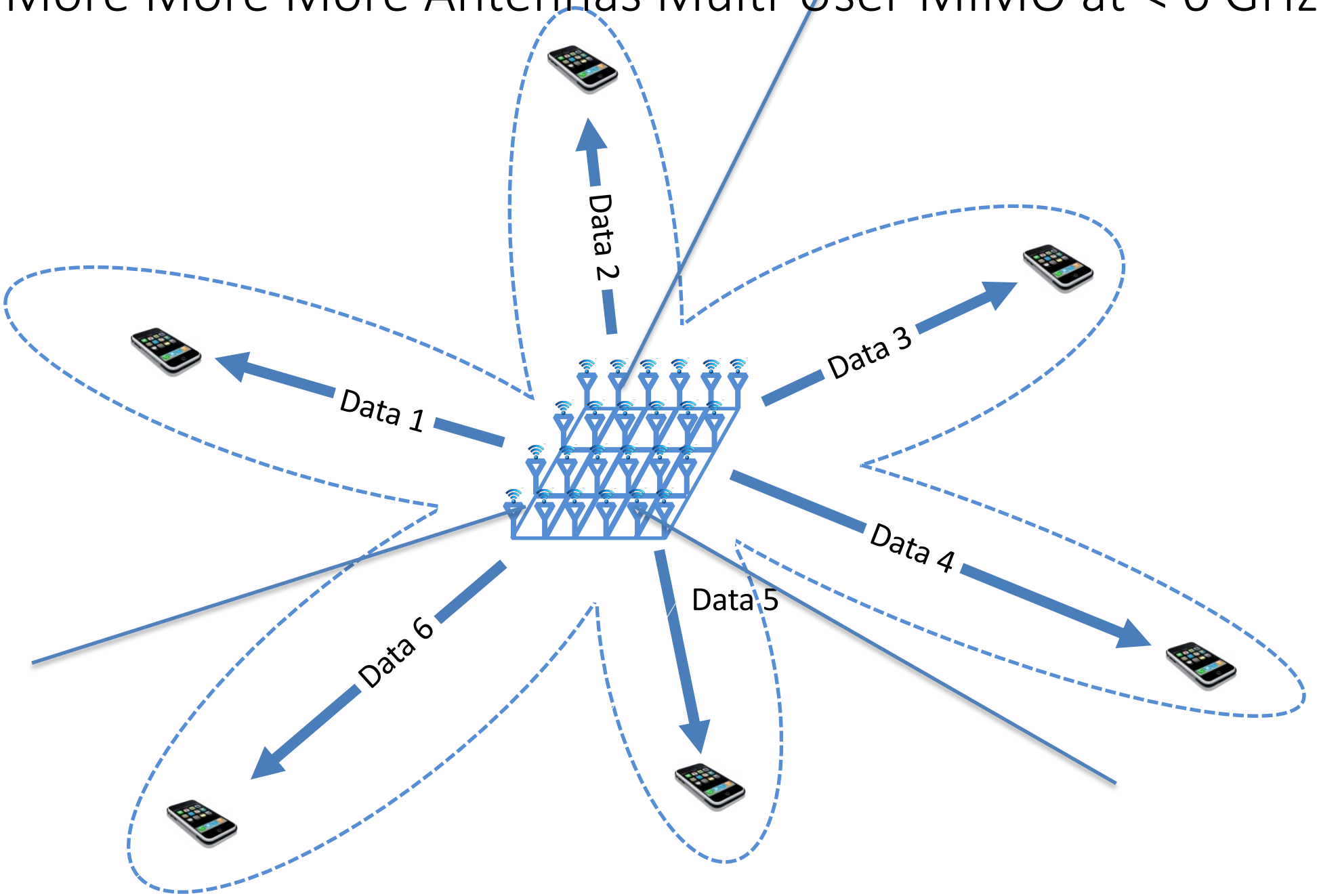
More Antennas Multi-User MIMO at < 6 GHz



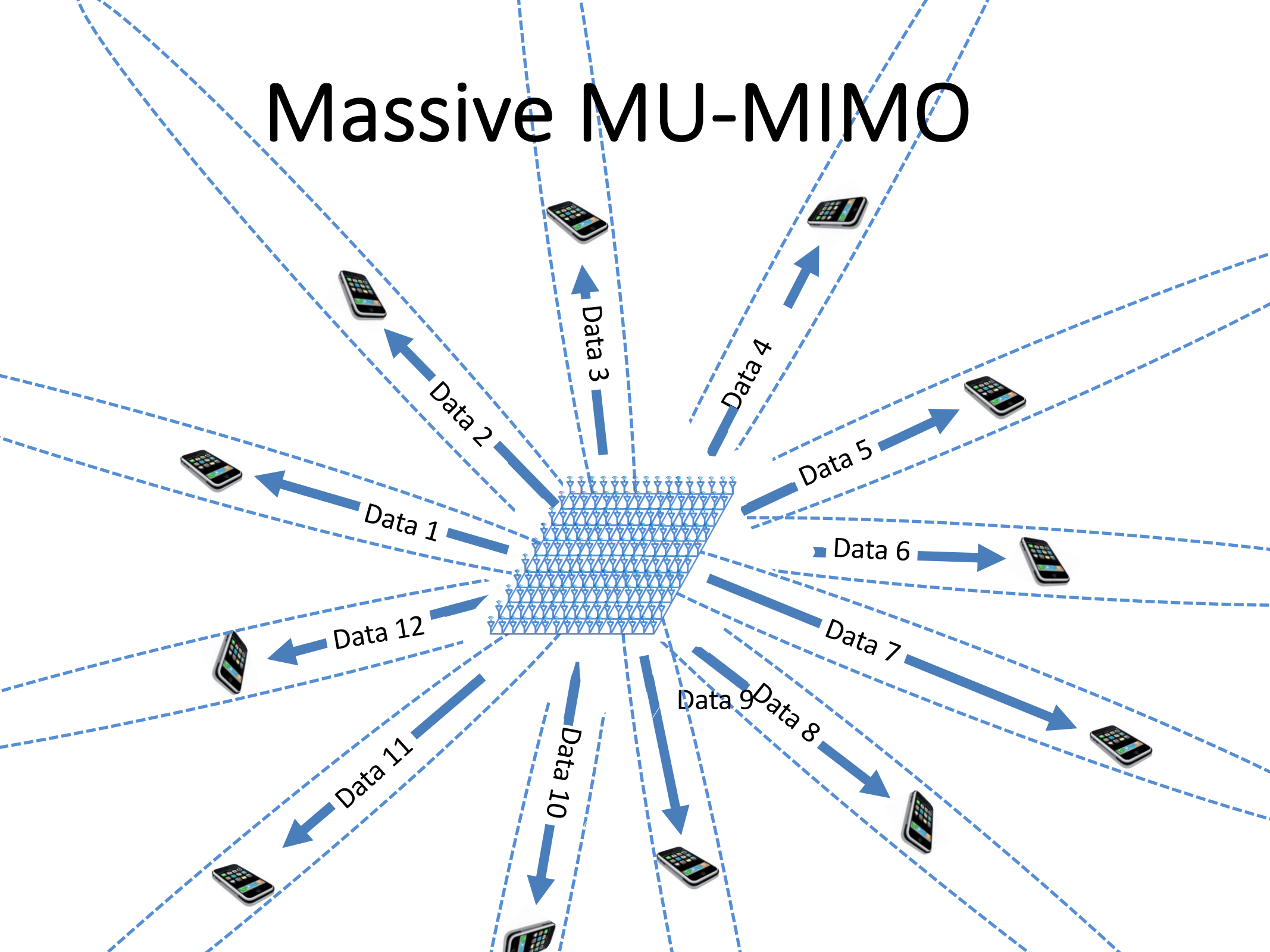
More More Antennas Multi-User MIMO at < 6 GHz



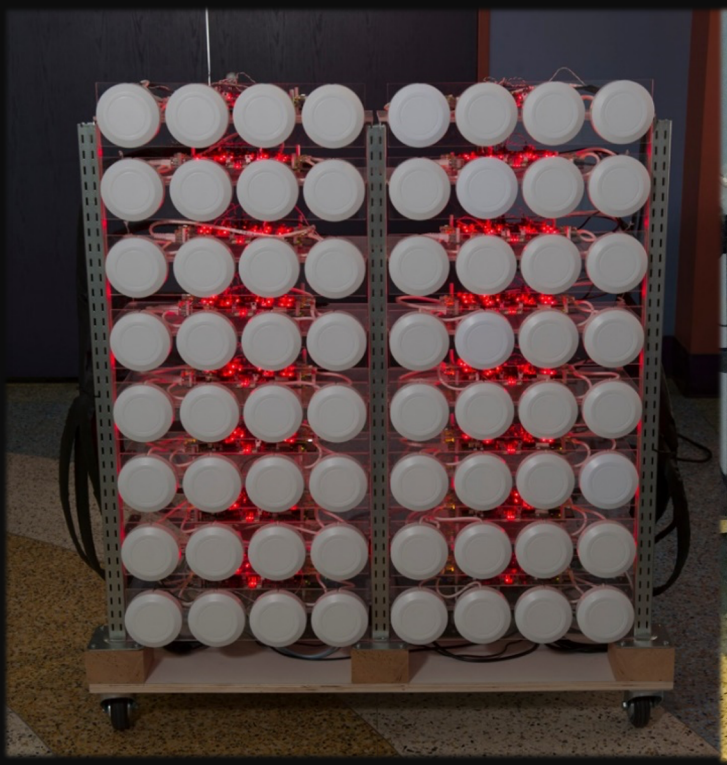
More More More Antennas Multi-User MIMO at < 6 GHz

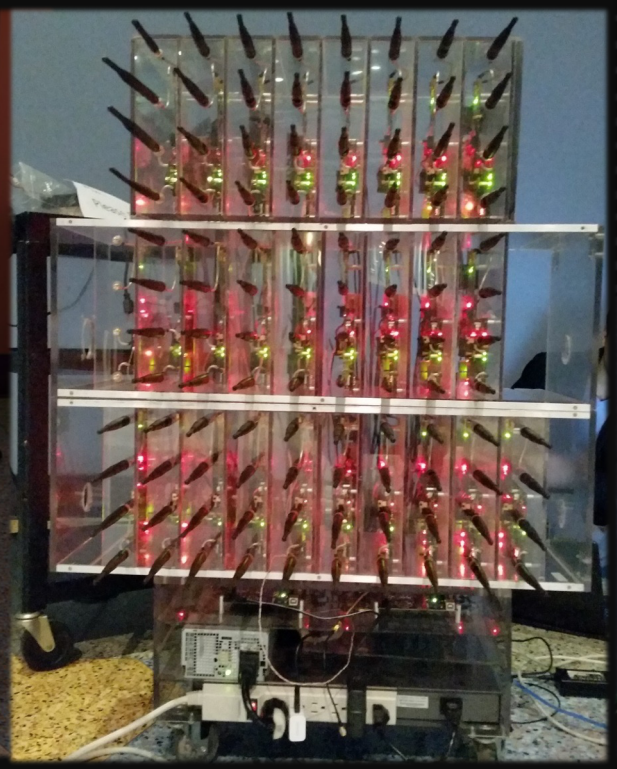


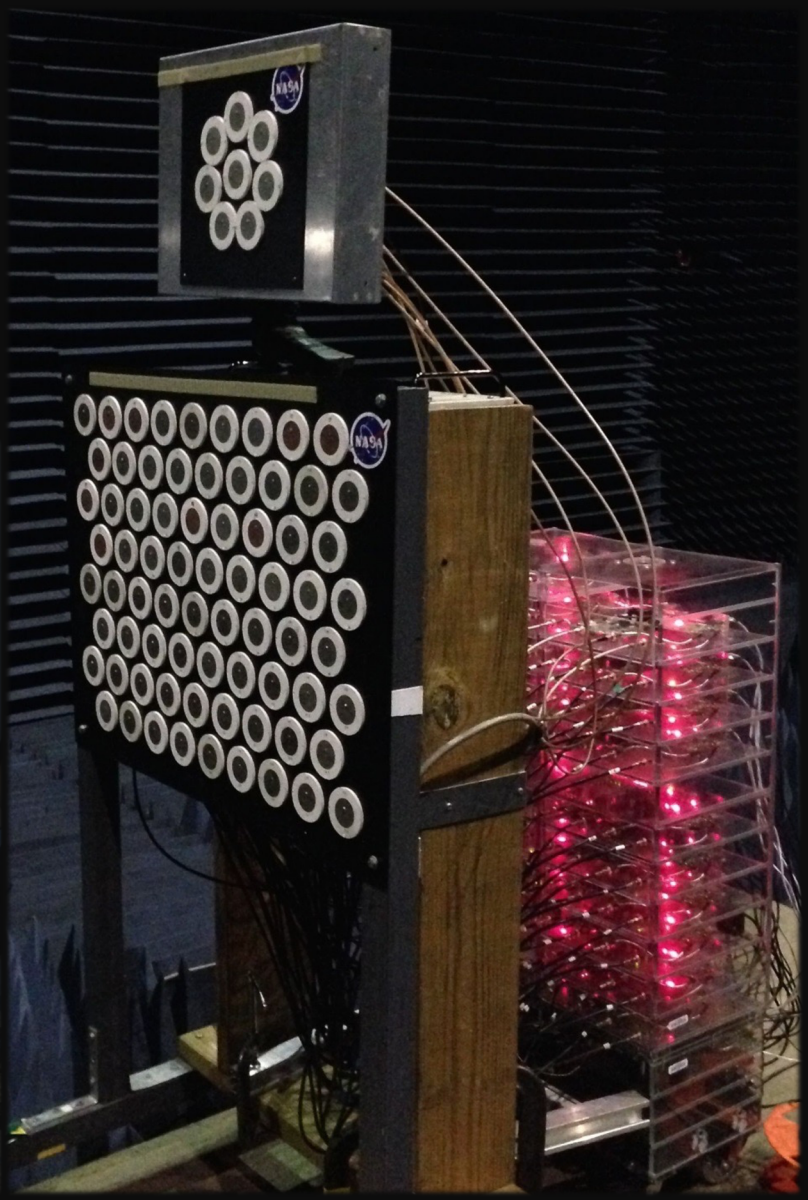
Massive MU-MIMO



Argos: World's first Massive MIMO Testbed (2011)







Differences between Massive MIMO & Millimeter Wave

A. mmWave operates > 24GHz vs. Massive MIMO < 6 GHz

B. mmWave supports higher bandwidth → higher data rates

C. Massive MIMO has 1 TX/RX per antenna whereas mmWave has 1 TX/RX for all antennas

D. Massive MIMO can transmit/receive to multiple users at the same time where mmWave (no MIMO) can transmit/receiver from only 1 user at a time.

Opinion of this Class

A. I really enjoyed this class and learned a lot.

B. I only enjoyed the last part but not the first part.

C. I learned new stuff but did not enjoy the class.

D. This class is not at all what I expected. I did not like it.

In this Class

1. Components of Wireless Transmitter & Receiver
2. Modulation
3. Wireless Channel
4. OFDM
5. IoT
6. WiFi
7. 5G Cellular Networks