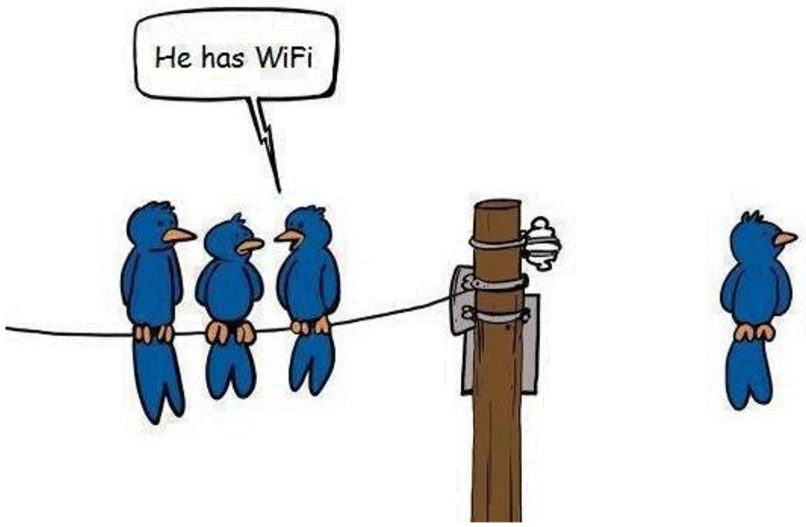
COM-405: Mobile Networks

Lecture 7.1: Cellular Networks I

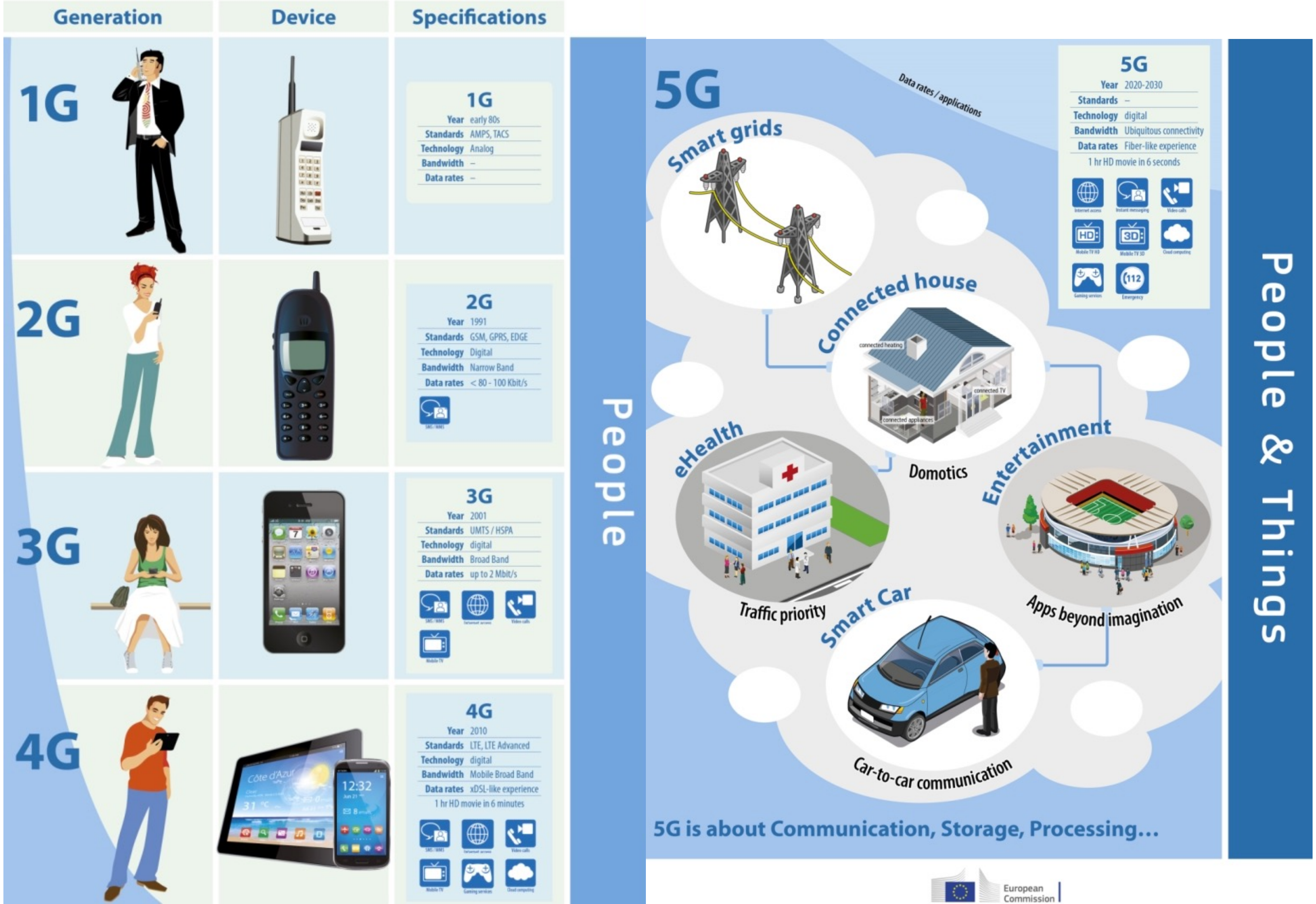
Haitham Hassanieh



EPFL

Laboratory of SEnsing
& Networking Systems

Mobile Technologies from 1G to 5G



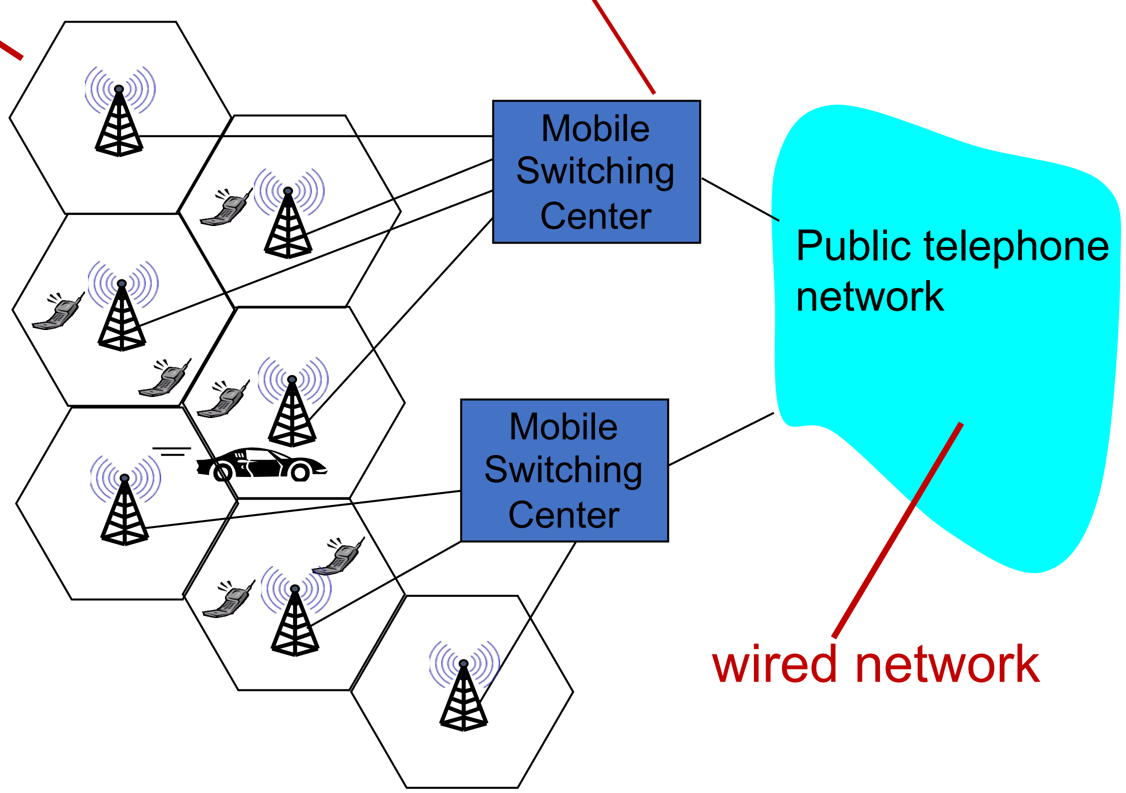
Components of cellular network architecture

MSC

- connects cells to wired tel. net.
- manages call setup
- handles mobility

cell

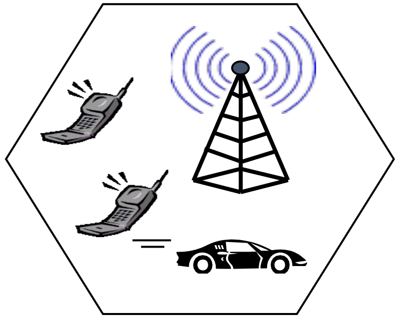
- covers geographical region
- *base station* (BS) analogous to 802.11 AP
- *mobile users* attach to network through BS
- *air-interface:* physical and link layer protocol between mobile and BS

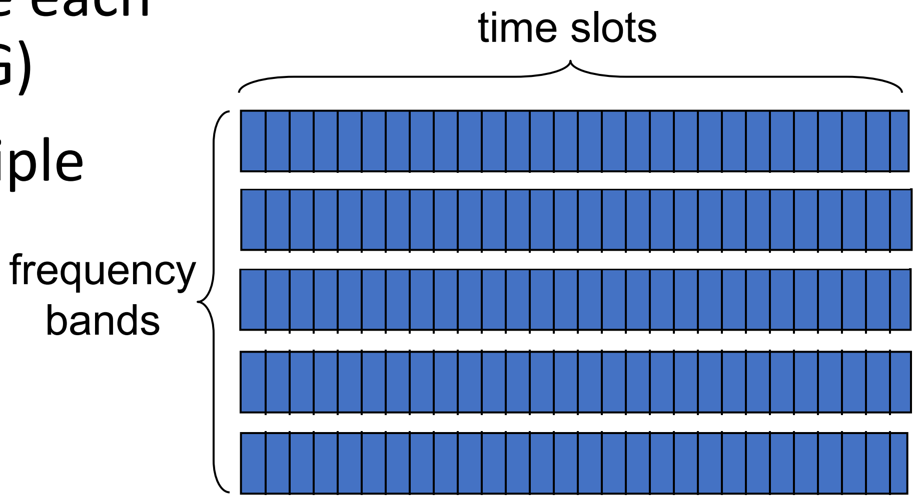


Cellular networks: the first hop

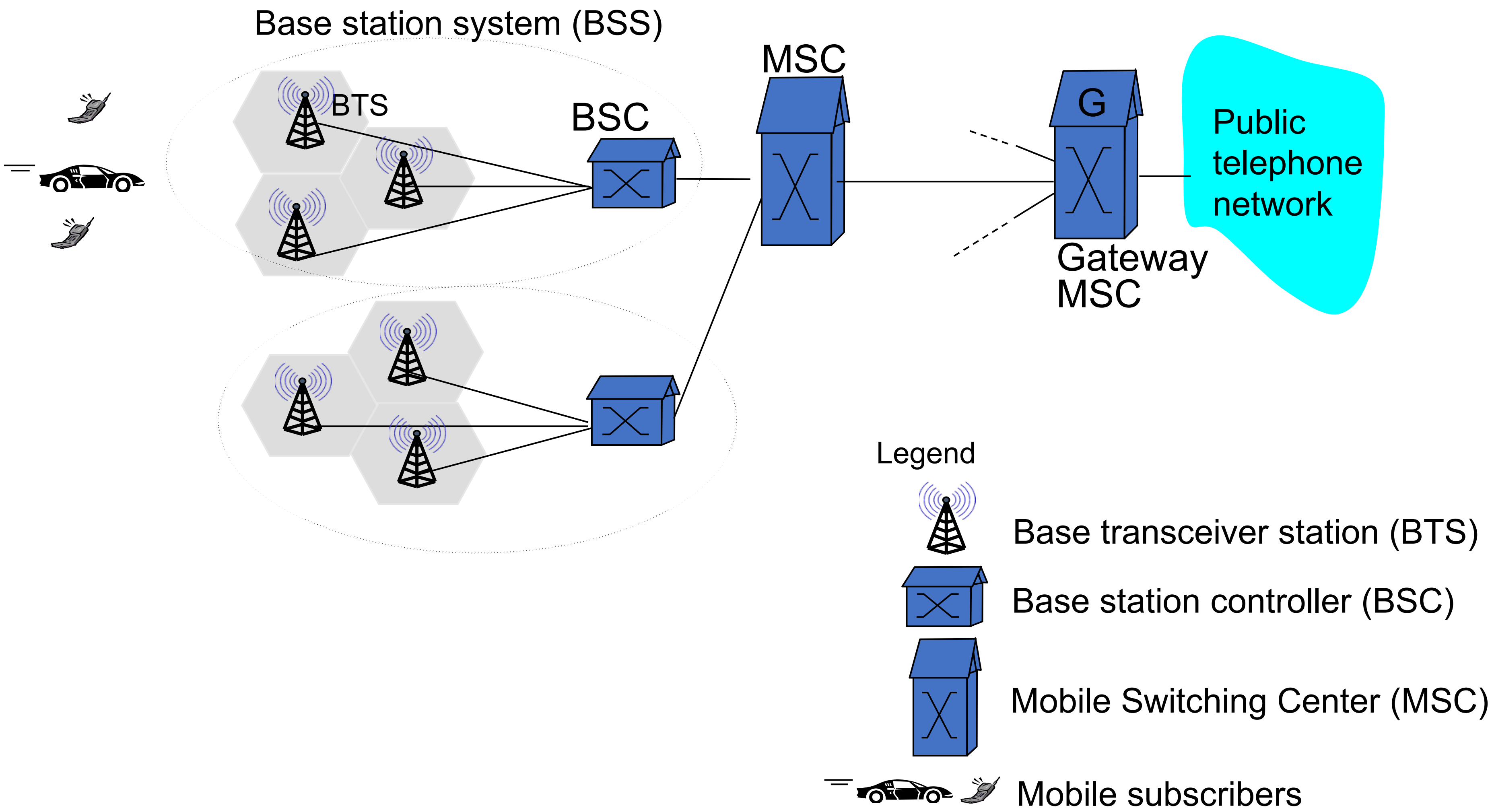
Two techniques for sharing mobile-to-BS radio spectrum

- combined OFDMA/TDMA: divide spectrum (subcarriers) in frequency channels, divide each channel into time slots (4G)
- CDMA: code division multiple access. (3G)

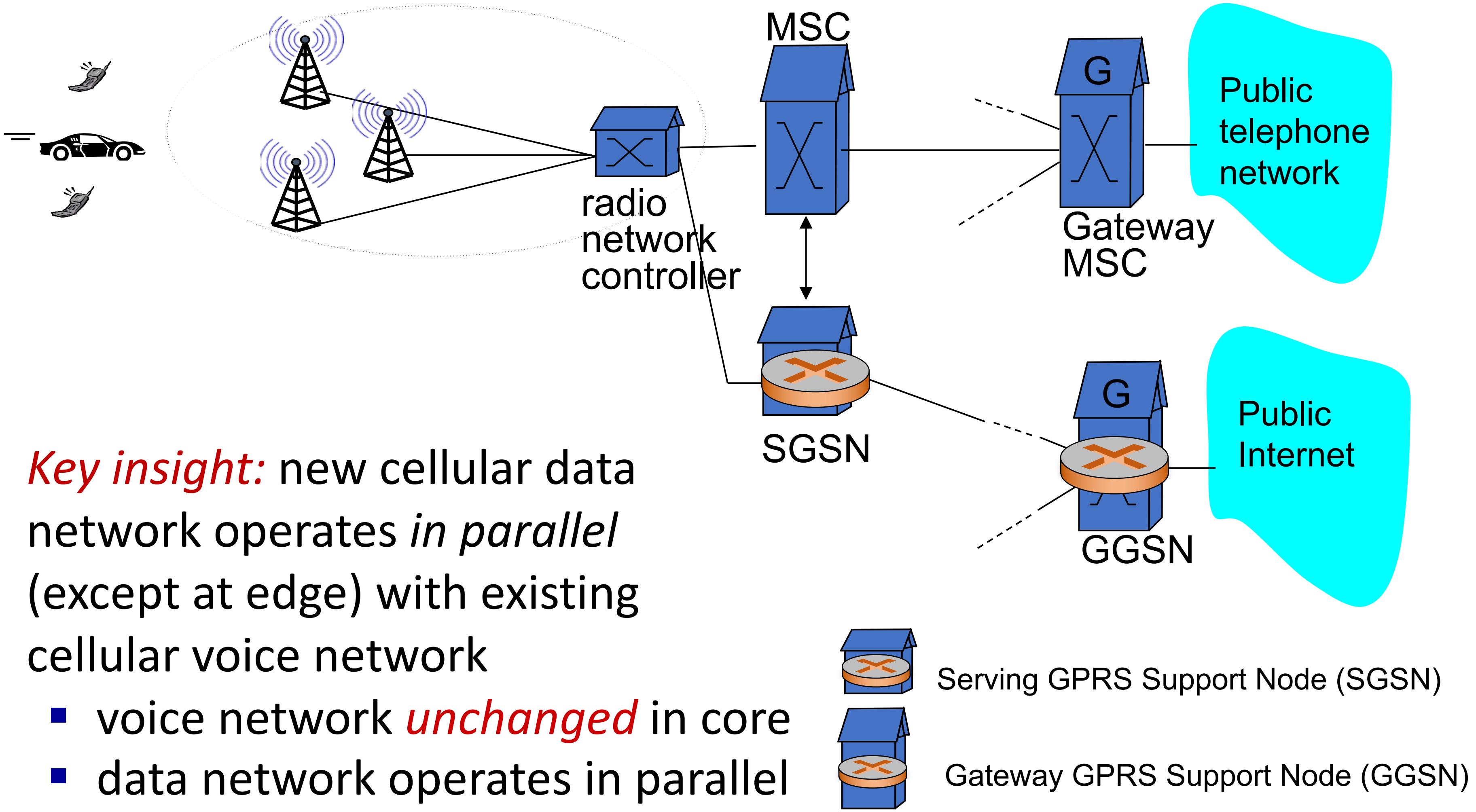




2G (voice) network architecture



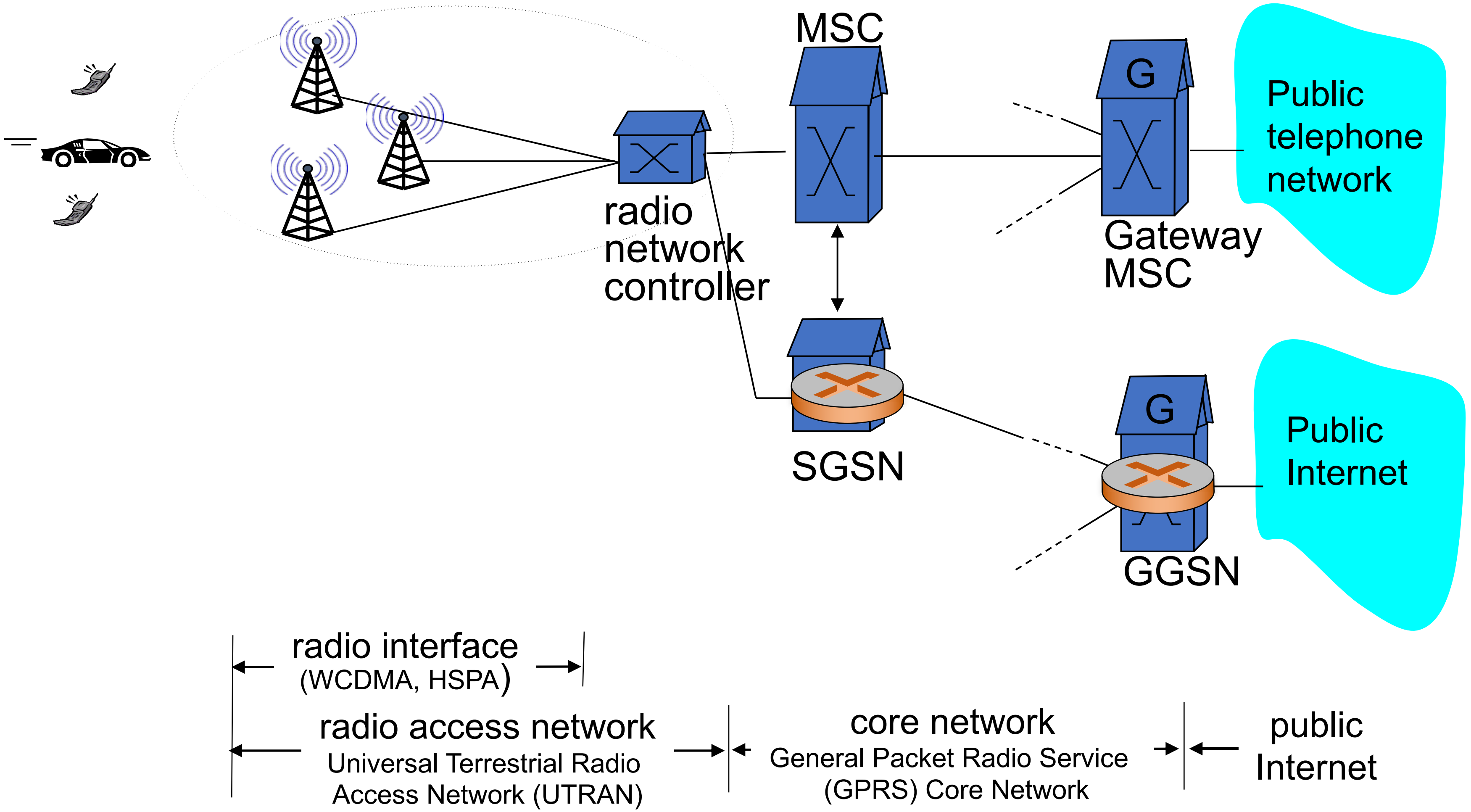
3G (voice+data) network architecture



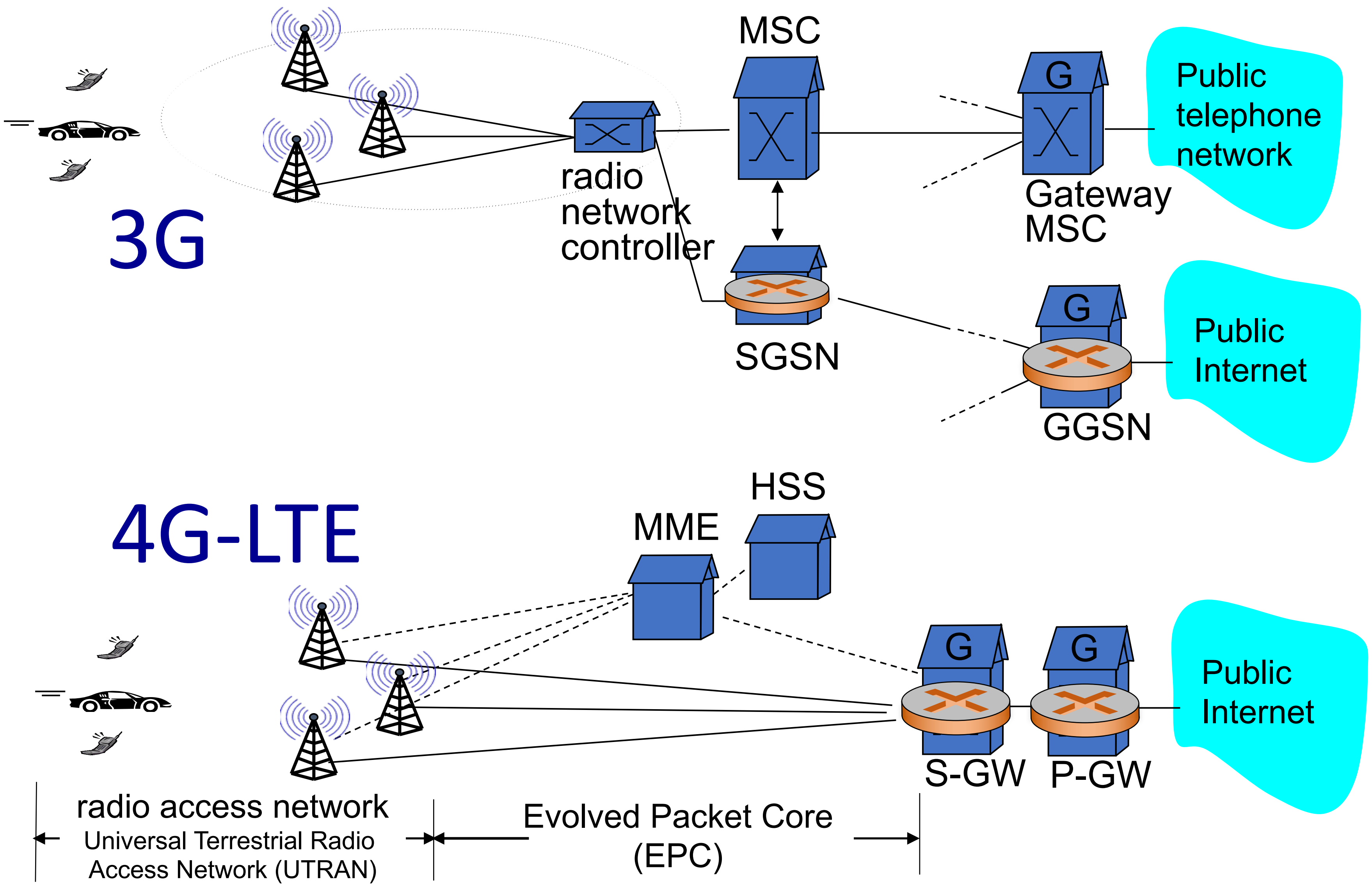
Key insight: new cellular data network operates *in parallel* (except at edge) with existing cellular voice network

- voice network *unchanged* in core
- data network operates in parallel

3G (voice+data) network architecture

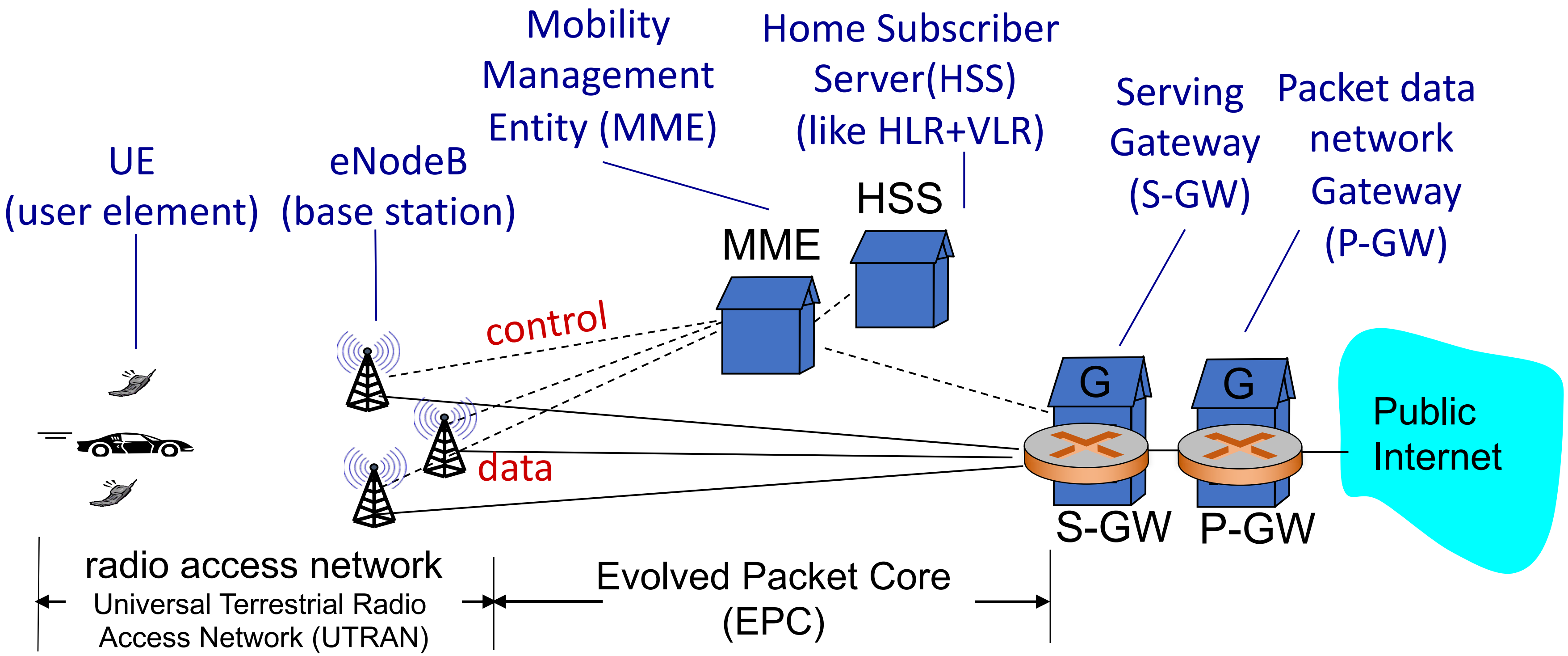


3G versus 4G LTE network architecture



4G: differences from 3G

- all IP core: IP packets tunneled (through core IP network) from base station to gateway
- no separation between voice and data – all traffic carried over IP core to gateway



Mobile fueled the last 30 years—interconnecting people

1G
1980s
Analog voice
AMPS, NMT, TACS

2G
1990s
Digital voice
D-AMPS, GSM, IS-95 (CDMA)

3G
2000s
Mobile broadband
WCDMA/HSPA+, CDMA2000/EV-DO

4G
2010s
Mobile Internet
LTE, LTE Advanced

A unifying connectivity fabric

Always-available, secure cloud access

Enhanced mobile broadband

Mission-critical services

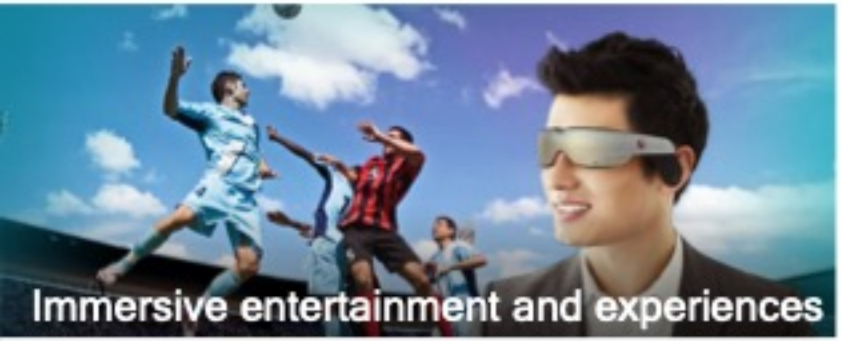
Massive Internet of Things

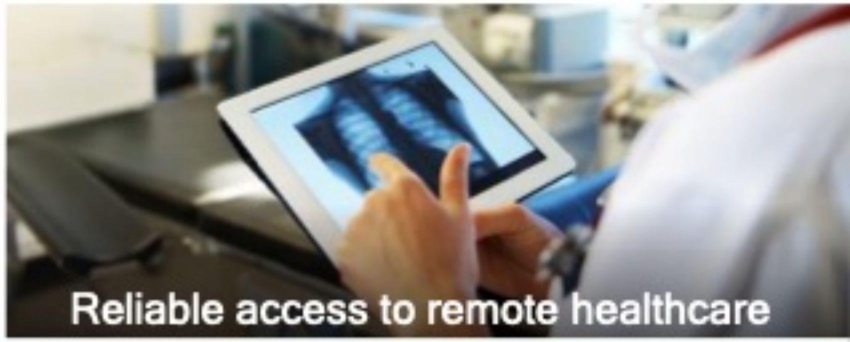
Unifying connectivity platform for future innovation

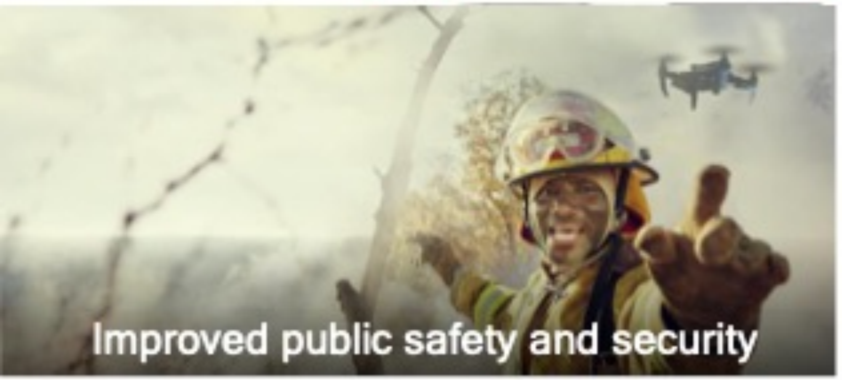
Convergence of spectrum types/bands, diverse services, and deployments, with new technologies to enable a robust, future-proof 5G platform

5G will redefine a wide range of industries

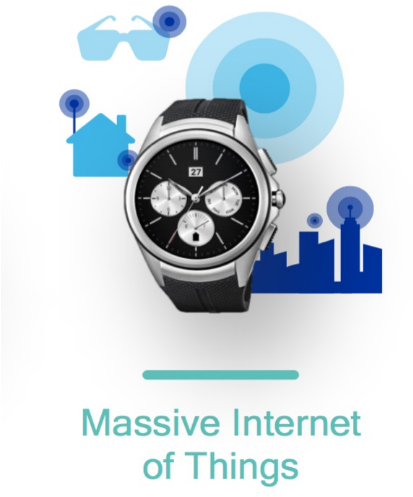
A platform for new connected services - existing, emerging and unforeseen

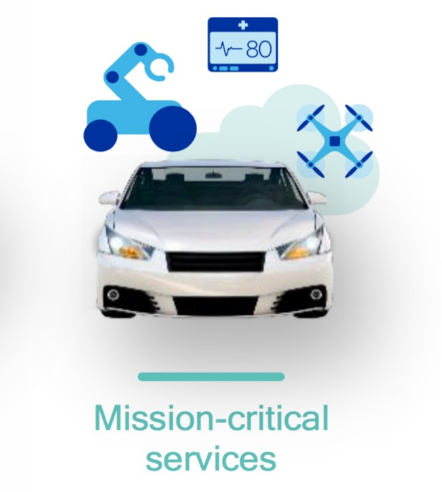






5G: Unified Air Interface





Enhanced Mobile Broadband (eMBB)

- 100+ Mbps avg. throughput
- 10+ Gbps peak throughput

- Mobile video and gaming
- Cloud computing and storage
- High speed connectivity

Massive Machine Type Communications (mMTC)

- $10^6/km^2$ connection density
- Low cost/energy connectivity

- Billions of connected devices
- Sensor networks
- IoT / M2M / D2D

Ultra-Reliable, Low-Latency Communications (URLLC)

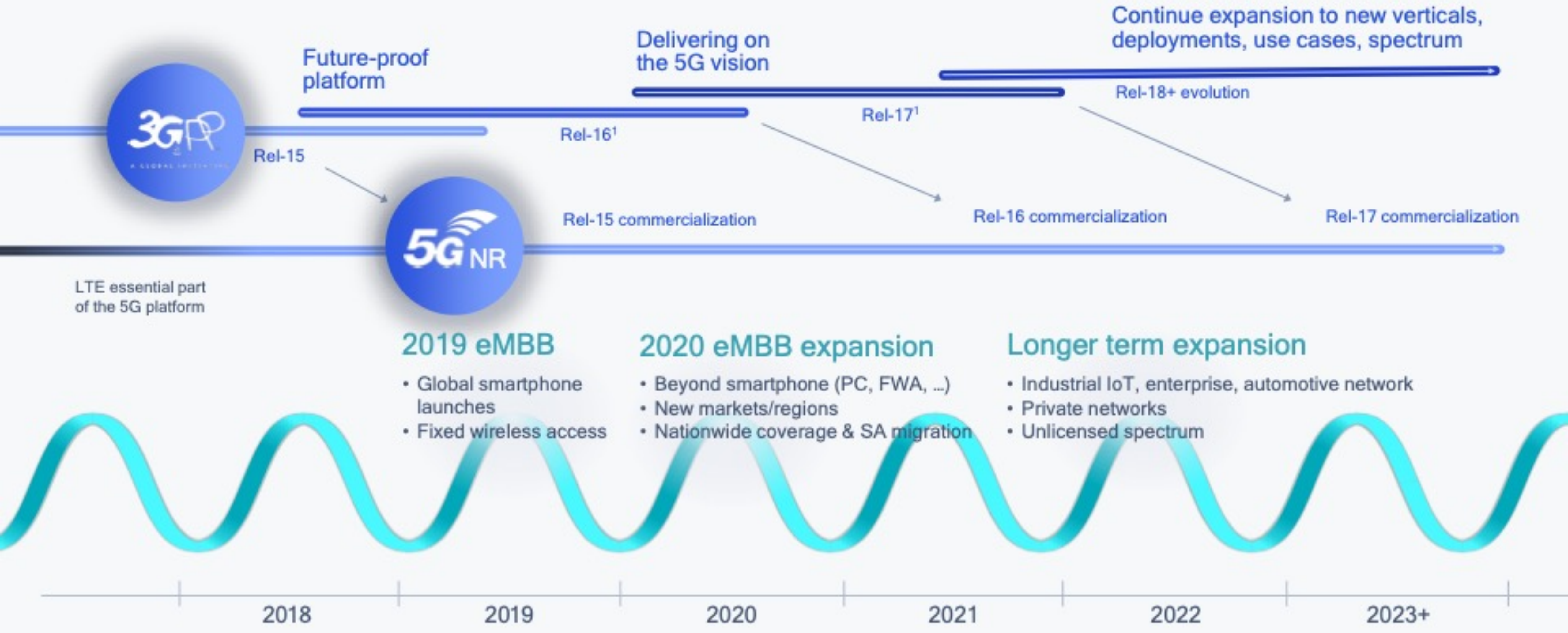
- 99.999% service availability
- 1 – 10 ms latency

- Tactile Internet
- Natural disaster relief
- E-Medicine and Health care

5G Radio Standard: NR (New Radio)

- Spectrum
  - Millimeter Wave (Very High Frequency Communication).
  - Dynamic Spectrum Sharing.
- Physical Layer
  - Massive MIMO (MIMO Beamforming with 100s of antennas)
  - LDPC & Polar Codes, F-OFDM, …
- Architecture
  - Small Cells (Extended from 4G)
  - Virtualization (NFV, SDNs)
  - Cloud RAN (Radio Access Network)

Driving the 5G expansion



1. 3GPP start date indicates approval of study package (study item->work item->specifications), previous release continues beyond start of next release with functional freezes and ASN.1

Getting the most out of every bit of diverse spectrum

5G NR

Low bands below 1 GHz: longer range for e.g. mobile broadband and massive IoT
e.g. 600 MHz, 700 MHz, 850/900 MHz

Mid bands 1 GHz to 6 GHz: wider bandwidths for e.g. eMBB and mission-critical
e.g. 3.4-3.8 GHz, 3.8-4.2 GHz, 4.4-4.9 GHz

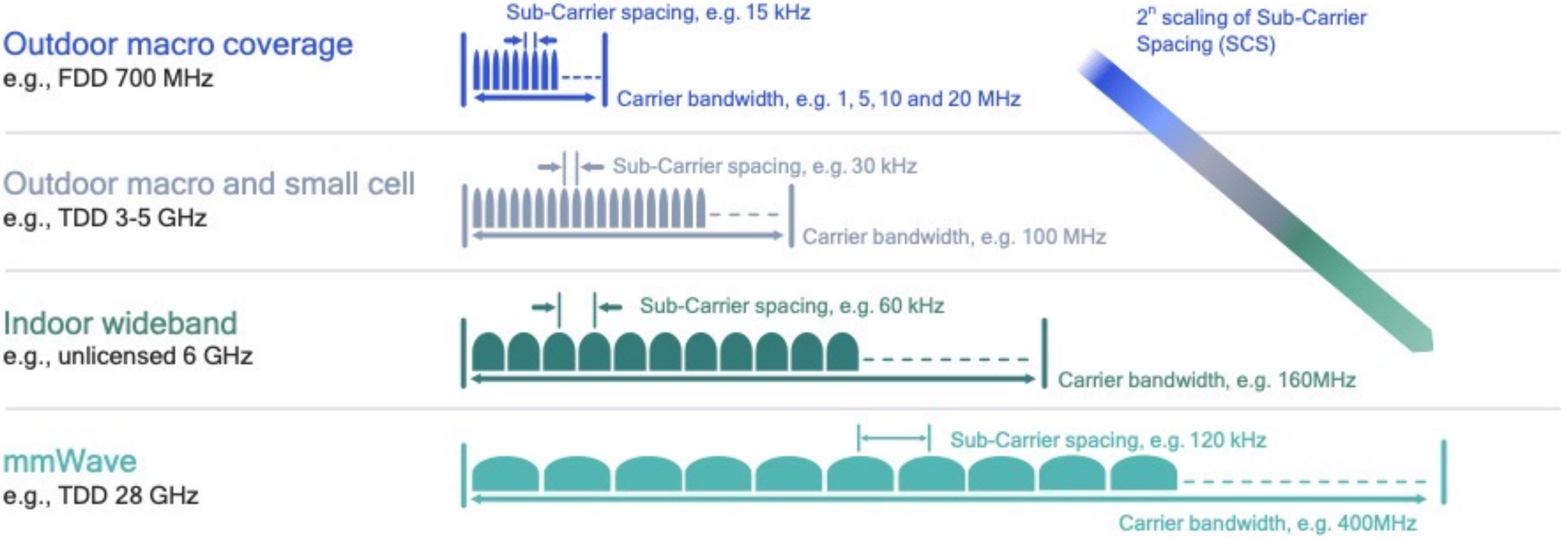
High bands above 24 GHz (mmWave): extreme bandwidths
e.g. 24.25-27.5 GHz, 27.5-29.5, 37-40, 64-71 GHz

Licensed Spectrum
Exclusive use

Shared Spectrum
New shared spectrum paradigms

Unlicensed Spectrum
Shared use

Scalable 5G NR OFDM numerology—examples

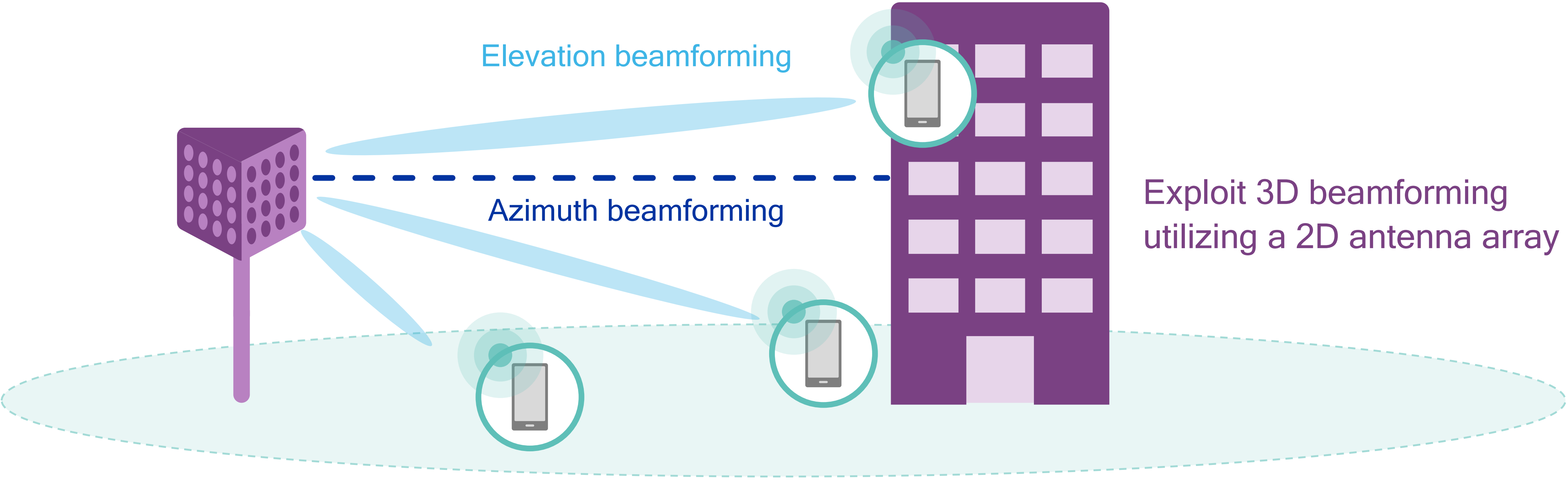


Efficiently address 5G diverse spectrum, deployments and services

Scaling reduces FFT processing complexity for wider bandwidths with reusable hardware

Many more antennas to increase coverage and capacity

Evolving towards Massive MIMO



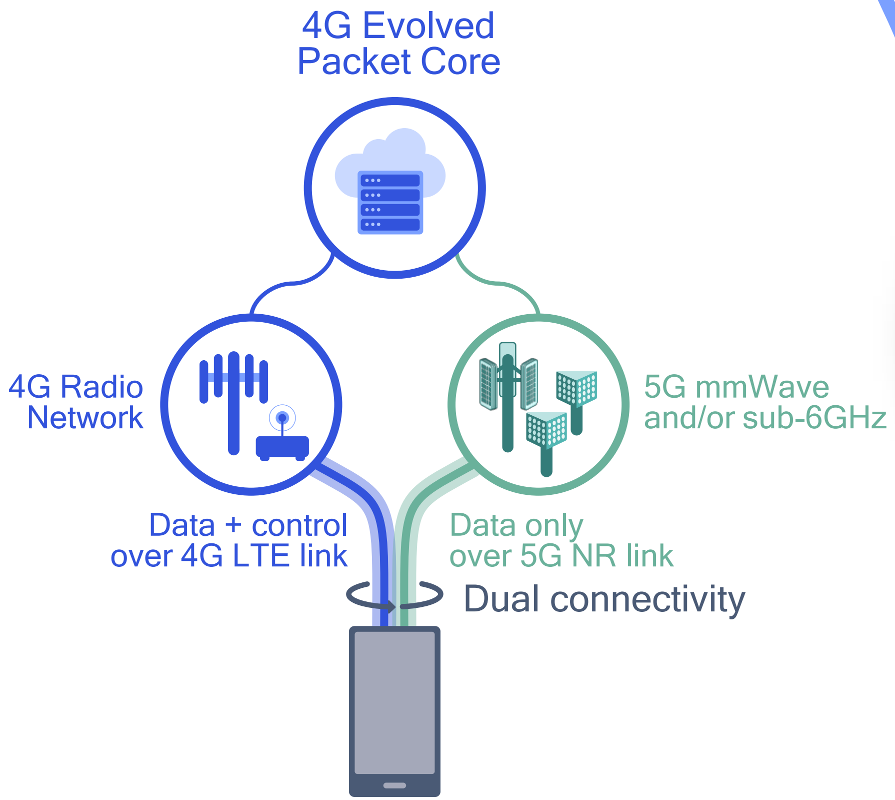
Exploit 3D beamforming utilizing a 2D antenna array

LTE Today
Fixed codebook for up to 8-antenna elements with azimuth beamforming only

LTE Rel. 13 (FD-MIMO)
2D codebook support for 8-, 12- and 16-antenna elements with Reference Signal enhancements for beamforming

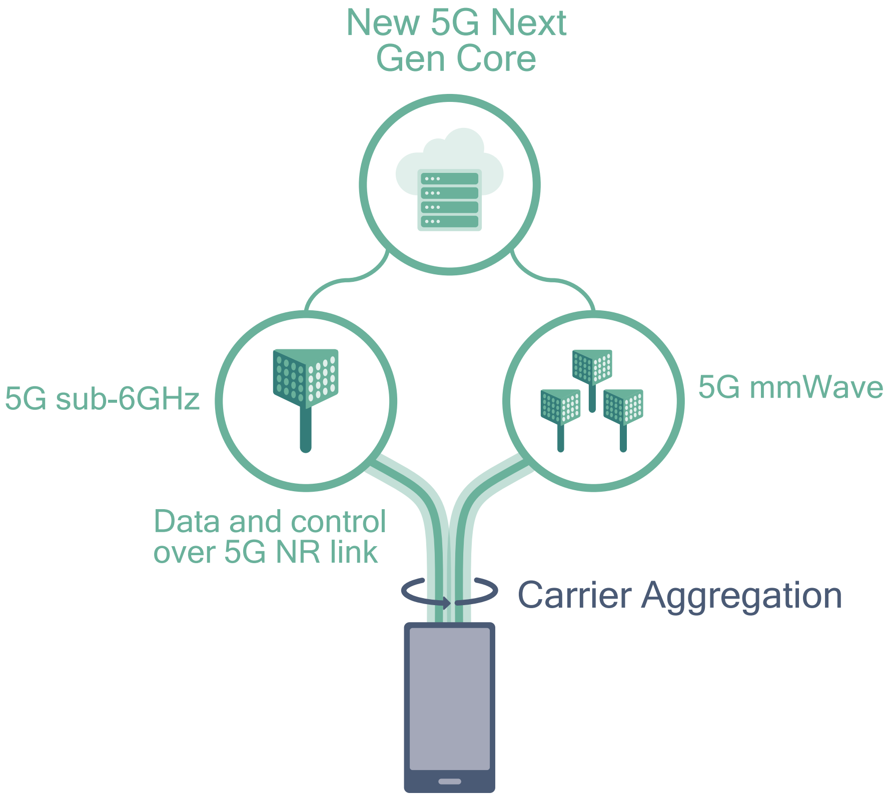
5G NR Rel. 15 (Massive MIMO)
Support even larger # of antenna elements (up to 256) with new features, e.g. hybrid beamforming, distributed MIMO

Non-Standalone (NSA) stepping stone to new core



Fast-to-launch | VoLTE & CS voice

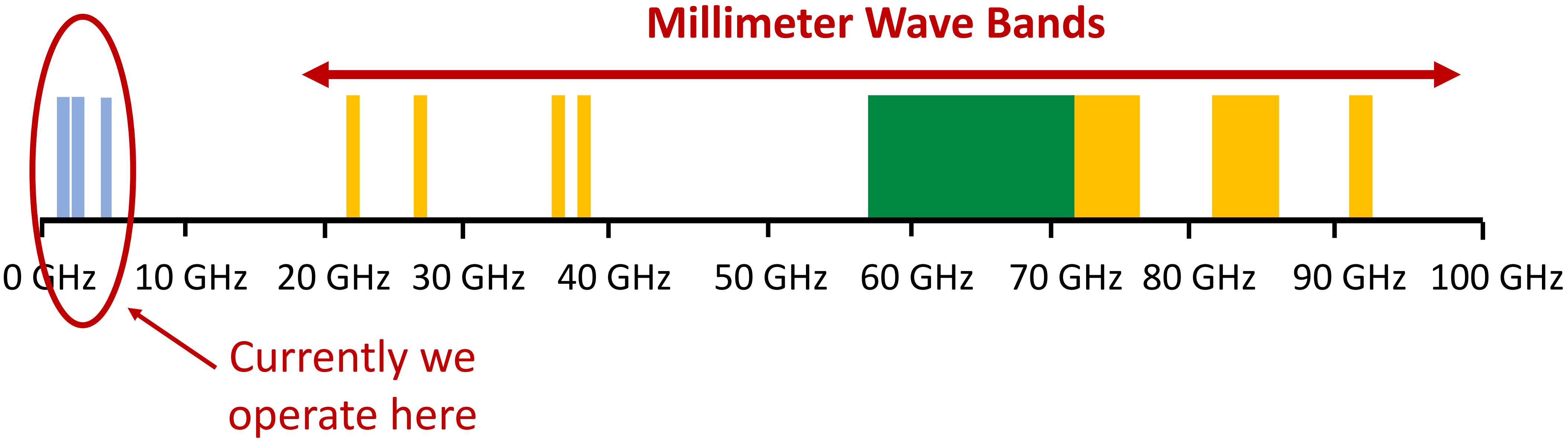
Standalone (SA) for new core benefits



NFV and SDN | VoNR & fallback to VoLTE

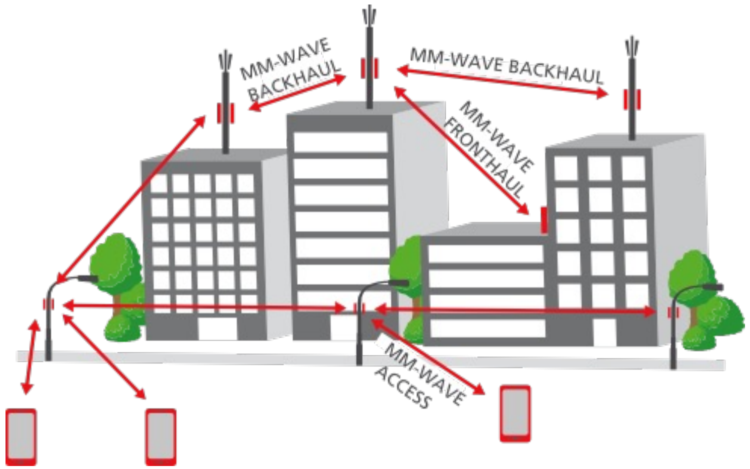
Millimeter Wave Technology

Huge bandwidth available at millimeter wave frequencies



Millimeter Wave can support data rates of multi-Gbps

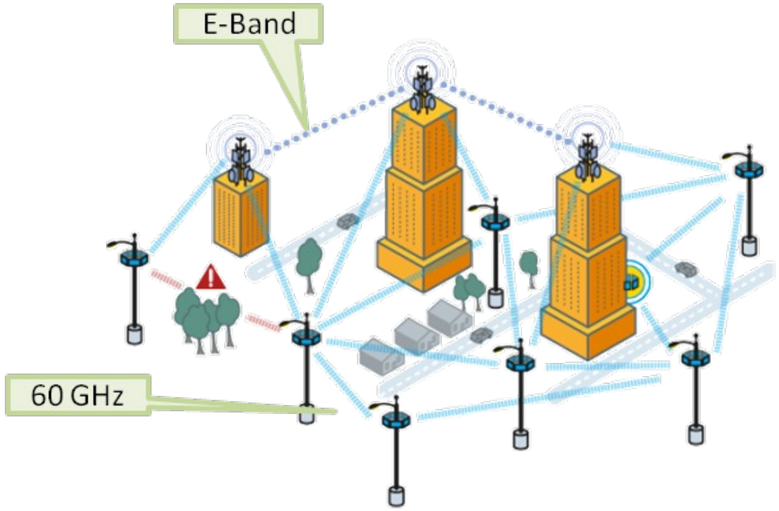
Millimeter Wave Wireless Applications



5G Wireless Backhaul & Access

Virtual Reality

Connected Vehicles



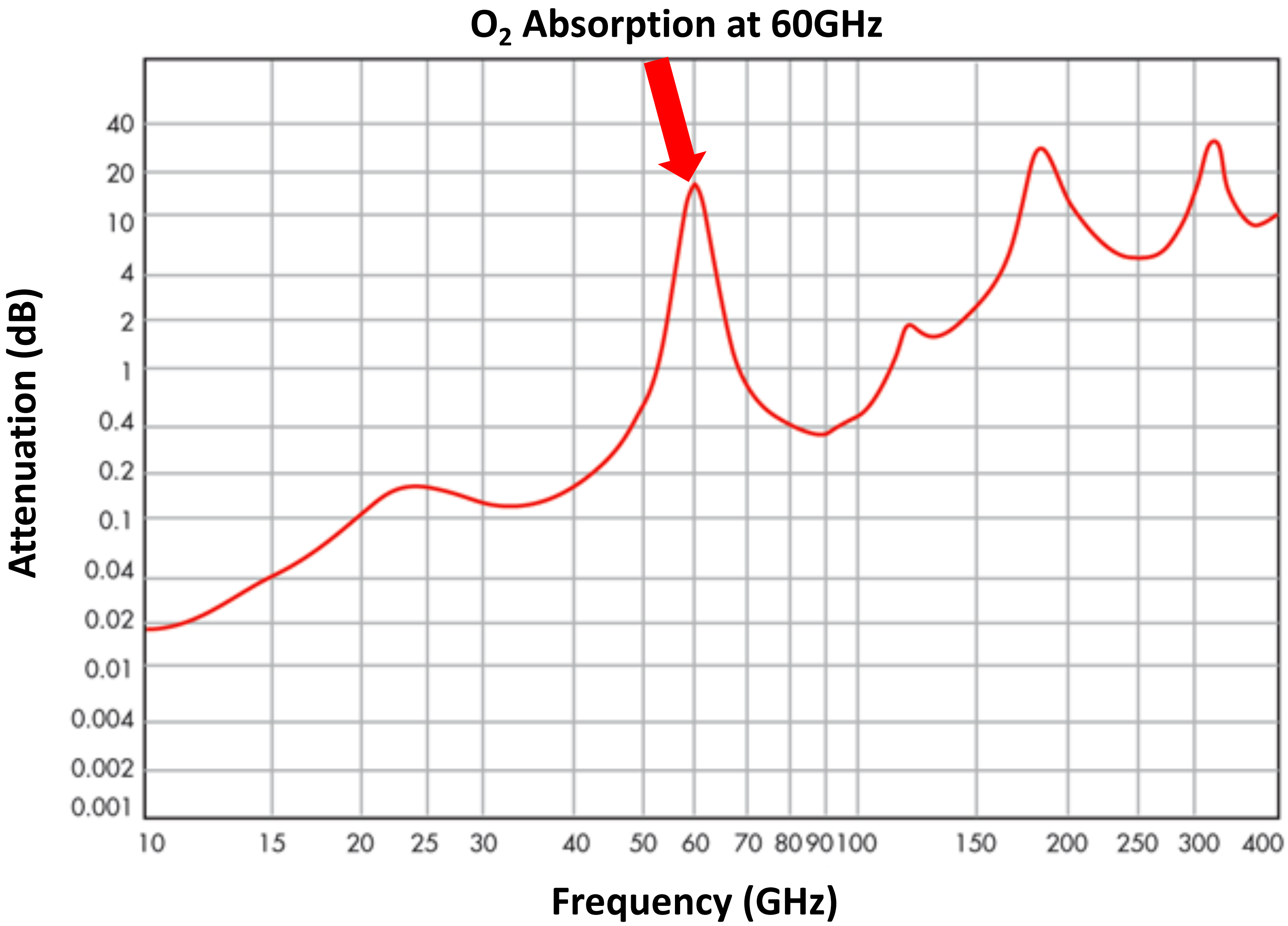
60 GHz WiGi Mesh Networks

Robotic Networks

Wireless Data Centers

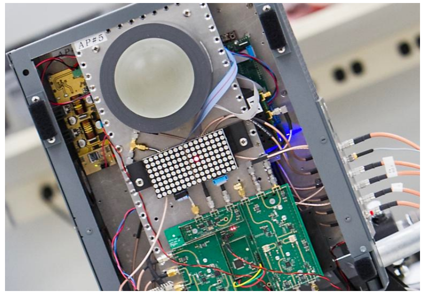
Significantly limits mobility & experience

Millimeter Waves Suffer from Large Attenuation

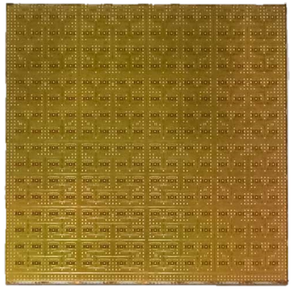


Millimeter Waves Suffer from Attenuation

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

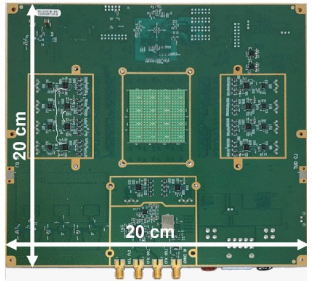


Nokia & National Instruments

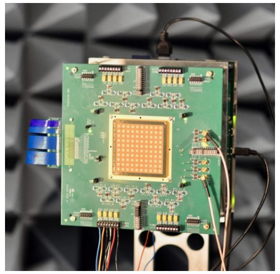


UCSD
256 elements

UCSD
64 elements

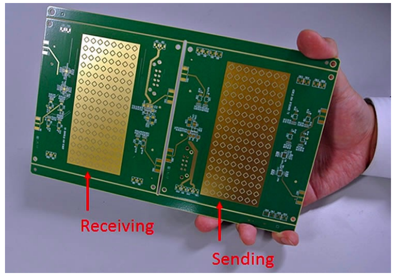


Bell Labs
384 elements



IBM
64 elements

Anokiwave
256 elements



Fujitsu
64 elements

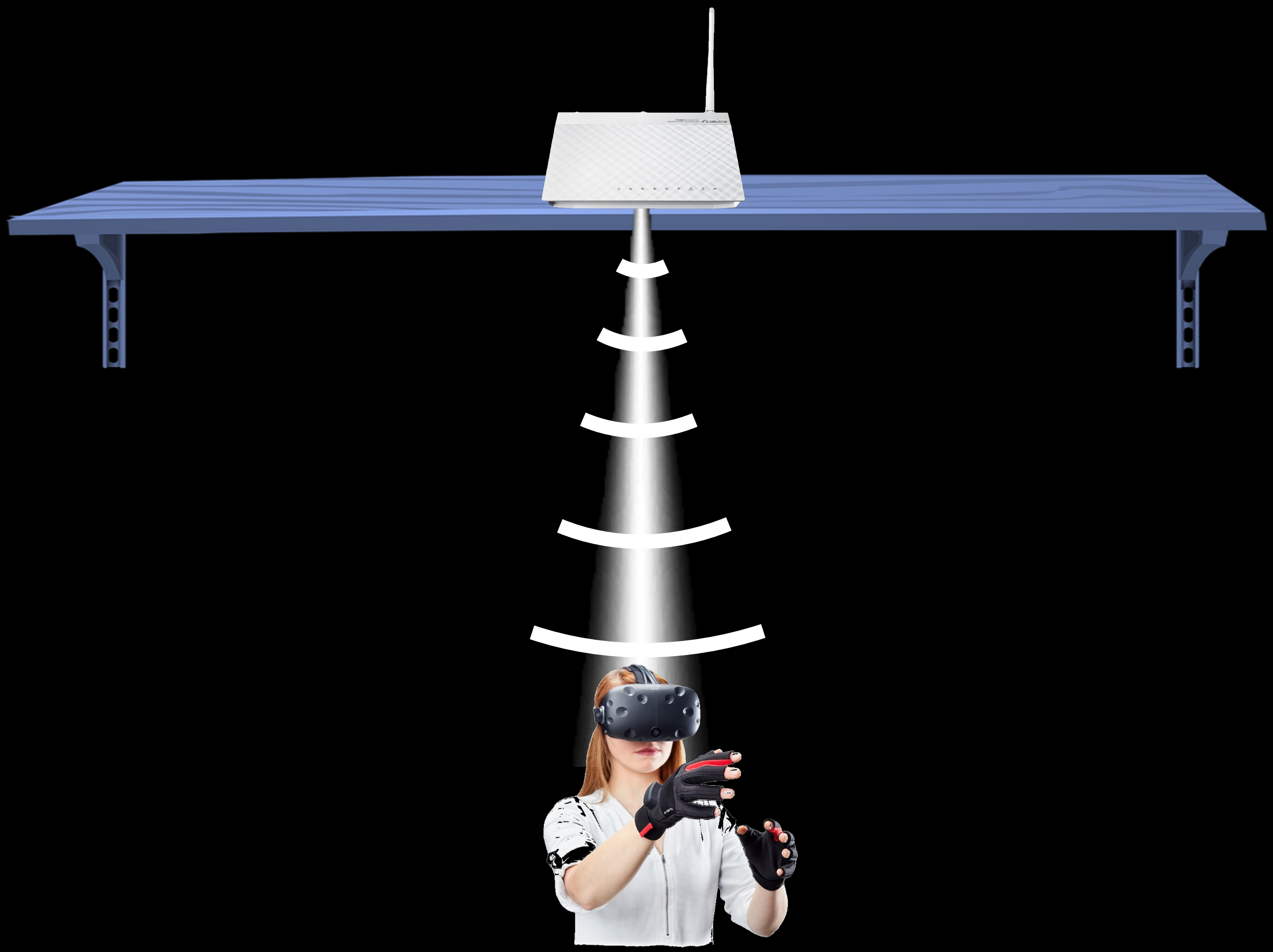
Small Wavelength enables thousands of antennas to be packed into small space

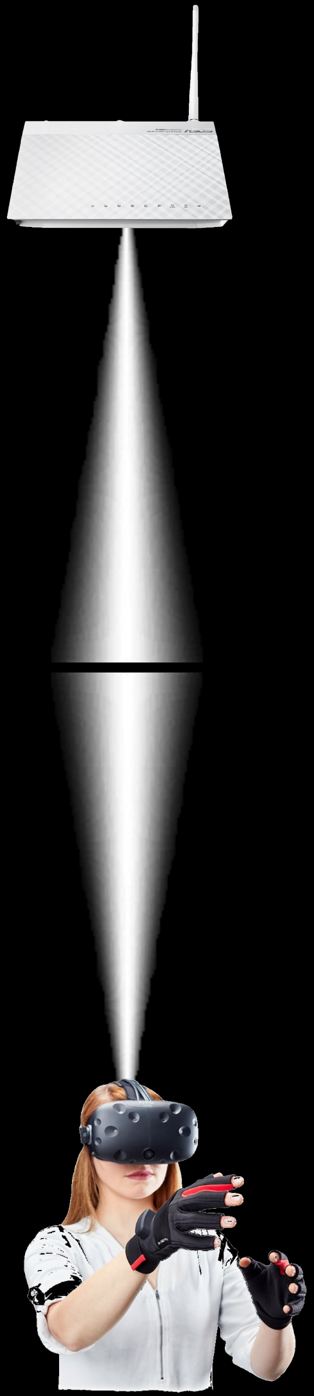
→ Extremely narrow beams

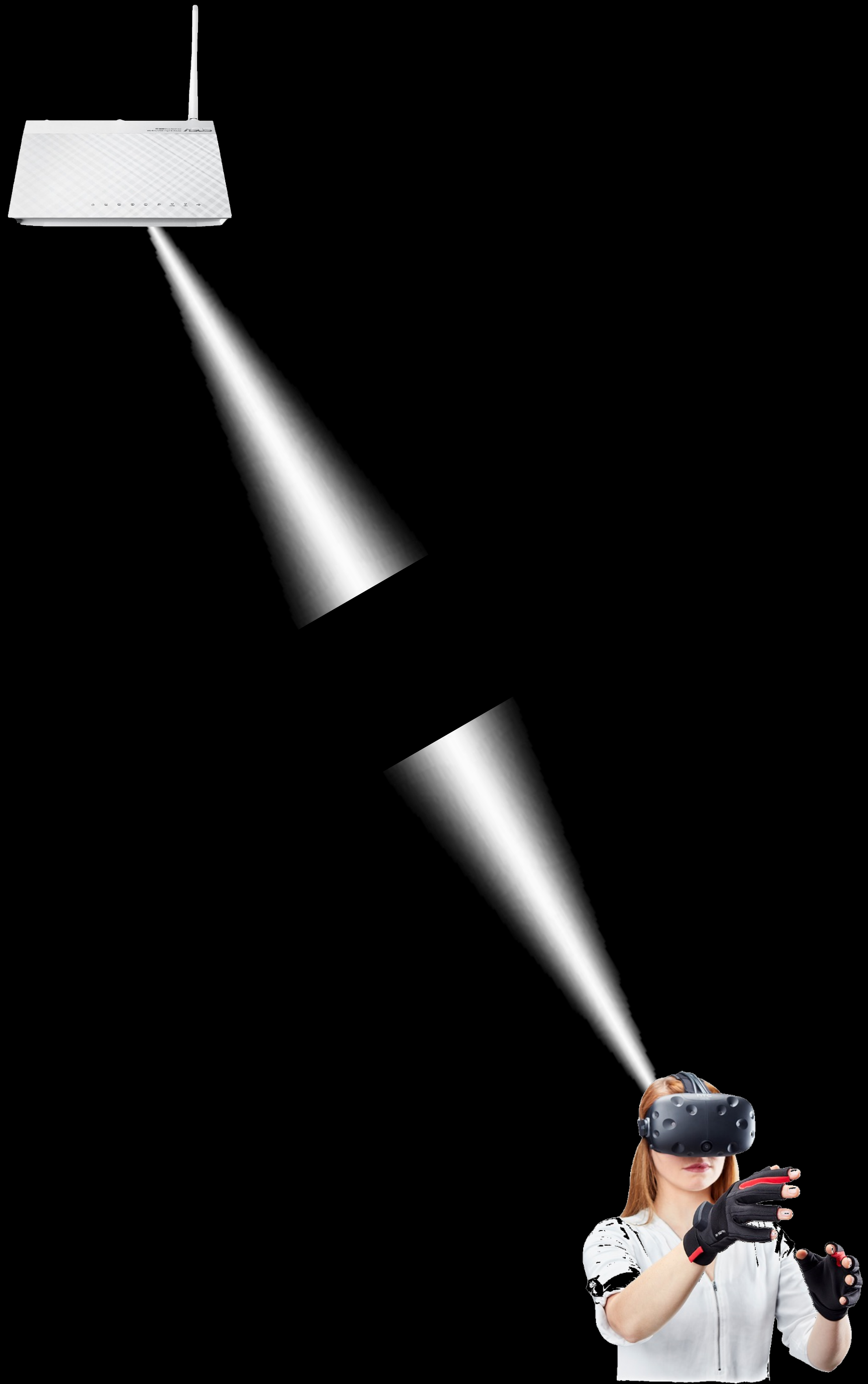
Today's Networks : Broadcast

mmWave changes how wireless systems operate

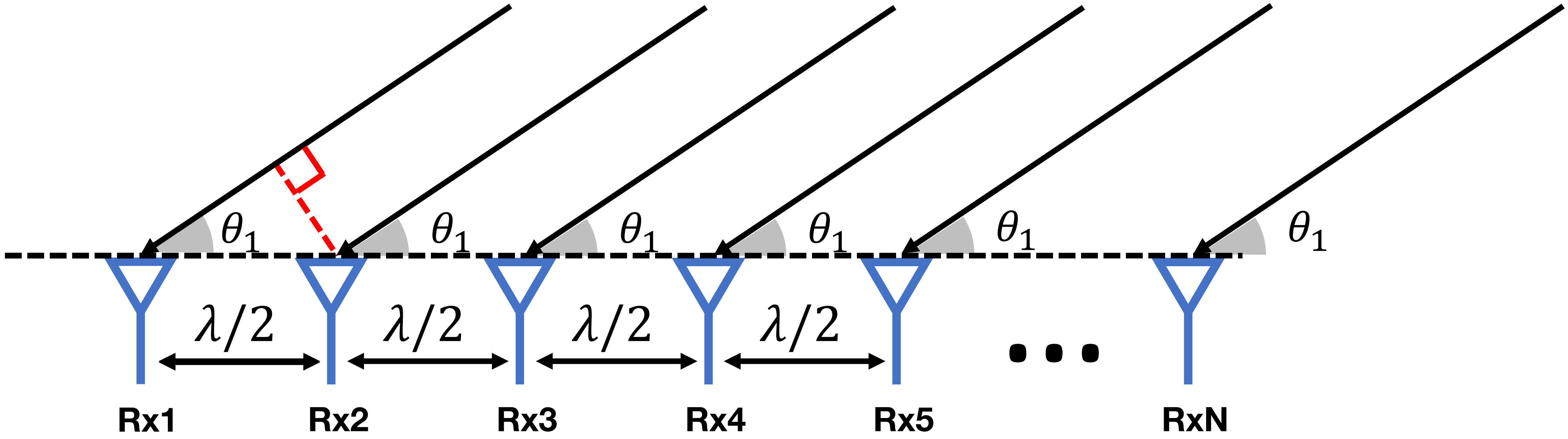
mmWave: Narrow-beam Antennas





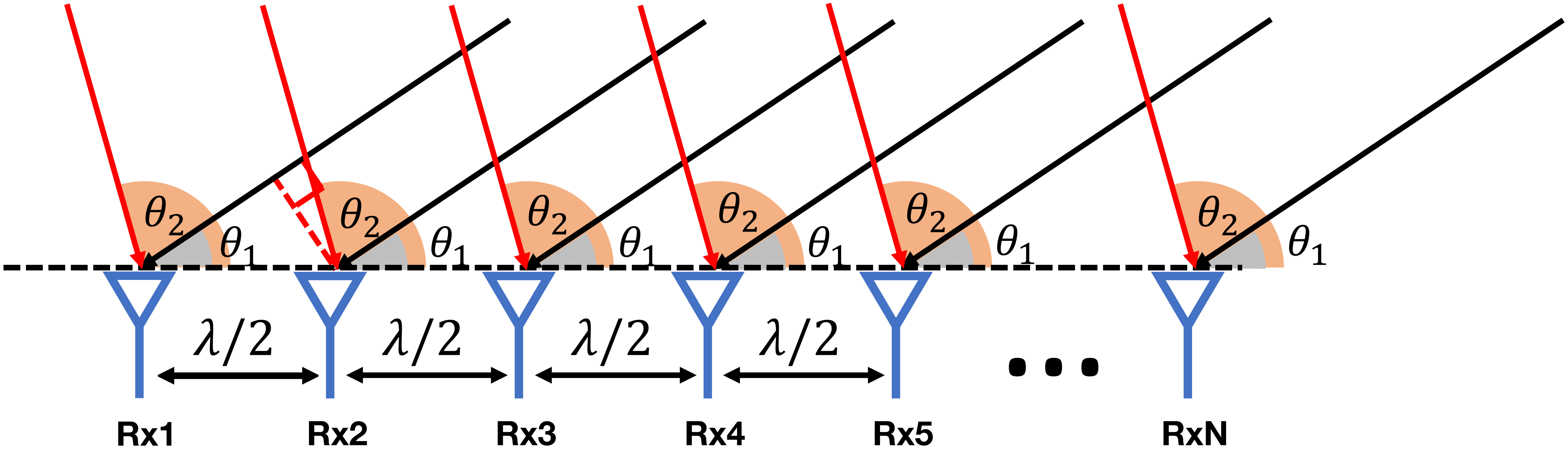


Antenna Arrays



$$h_k = \alpha_1 e^{-j2\pi\frac{d_1 - k\ s \cos\theta_1}{\lambda}} = \alpha_1 e^{-j\phi_1 + k\pi\cos\theta_1}$$

Antenna Arrays

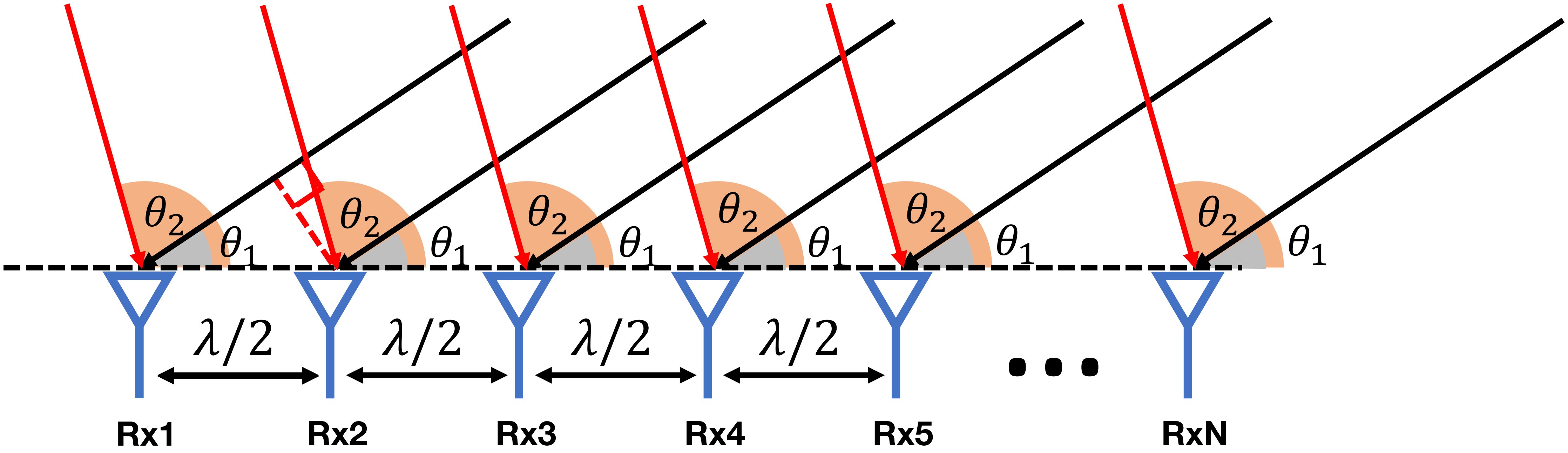


$$h_k = \alpha_1 e^{-j2\pi\frac{d_1 - k\,s\cos\theta_1}{\lambda}} = \alpha_1 e^{-j\phi_1 + k\pi\cos\theta_1}$$

$$+\alpha_2 e^{-j2\pi\frac{d_2 - k\,s\cos\theta_2}{\lambda}} \quad +\alpha_2 e^{-j\phi_2 + k\pi\cos\theta_2}$$

For L paths → $h_k = \sum_{l=1}^{L} \alpha_l e^{jk\pi\cos\theta_l - j\phi_l}$

Antenna Arrays



$$h_k = \sum_{l=1}^{L} \alpha_l e^{jk\pi \cos\theta_l - j\phi_l}$$

Multipath Profile: $P(\theta) = \left| \sum_{k=1}^{N} h_k e^{-jk\pi \cos\theta} \right|^2$

Antenna Arrays

$$P(\theta) = \left| \sum_{k=1}^{N} h_k e^{-jk\pi \cos\theta} \right|^2 \qquad h_k = \sum_{l=1}^{L} \alpha_l e^{jk\pi \cos\theta_l - j\phi_l}$$

$$P(\theta_1) = \left| \sum_{k=1}^{N} h_k e^{-jk\pi \cos\theta_1} \right|^2$$

$$= \left| \sum_{k=1}^{N} \left(\sum_{l=1}^{L} \alpha_l e^{jk\pi \cos\theta_l - j\phi_l} \right) e^{-jk\pi \cos\theta_1} \right|^2$$

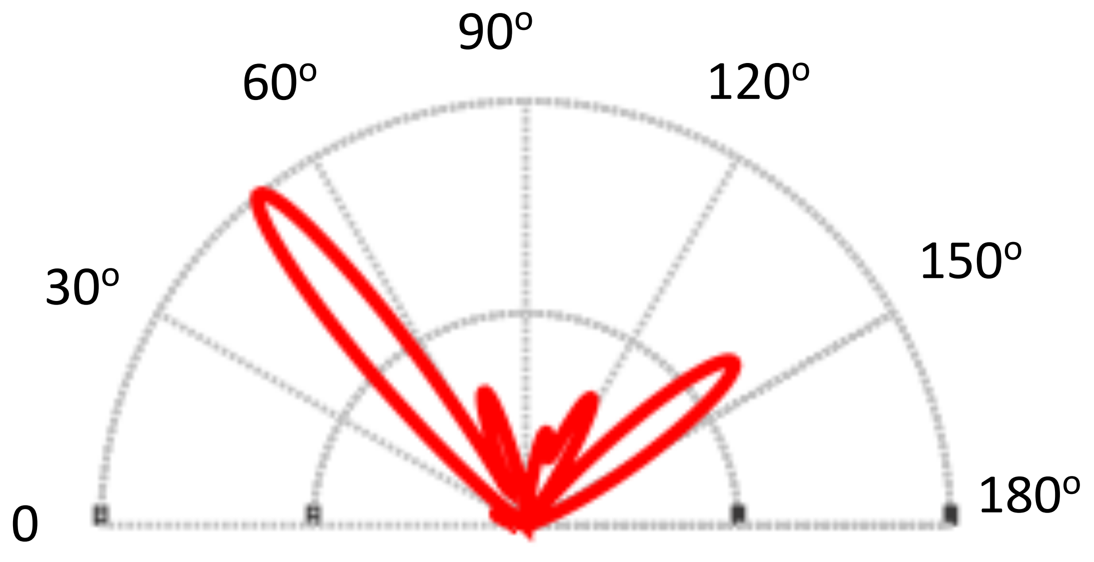
$$= \left| \sum_{k=1}^{N} \alpha_1 e^{-j\phi_1} + \sum_{k=1}^{N} \left(\sum_{l=2}^{L} \alpha_l e^{jk\pi(\cos\theta_l - \cos\theta_1) - j\phi_l} \right) \right|^2$$

$$= \left| N\alpha_1 e^{-j\phi_1} + \sum_{l=2}^{L} \alpha_l e^{-j\phi_l} \left(\sum_{k=1}^{N} e^{jk\pi(\cos\theta_l - \cos\theta_1)} \right) \right|^2 \approx N^2 \alpha_1^2$$

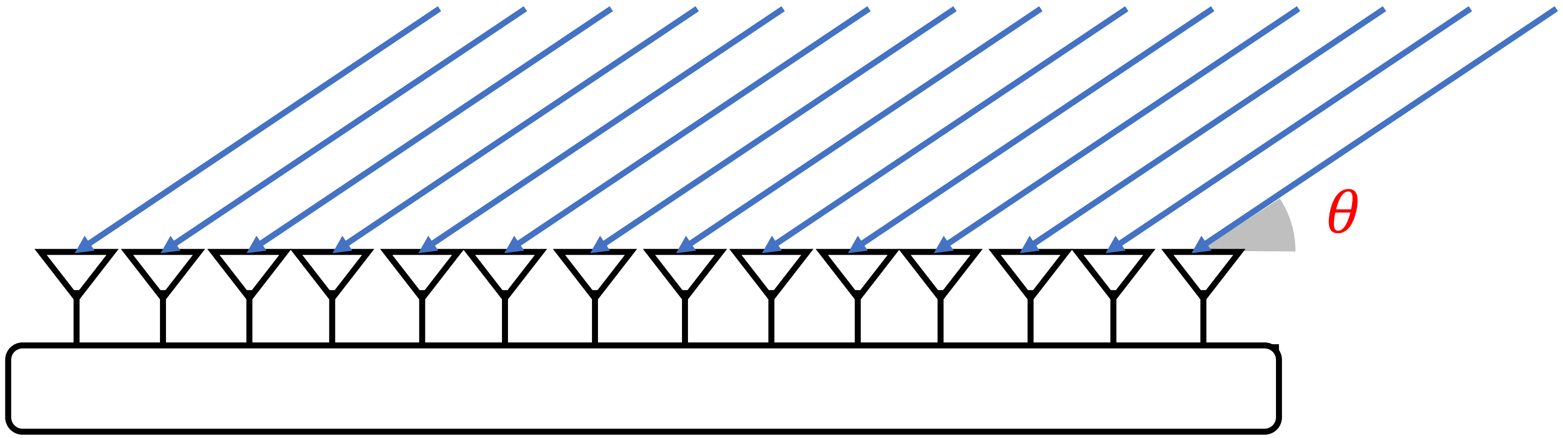
Antenna Arrays

$$h_k = \sum_{l=1}^{L} \alpha_l e^{jk\pi \cos\theta_l - j\phi_l}$$

$$Multipath\ Profile\colon\ P(\theta) = \left| \sum_{k=1}^{N} h_k e^{-jk\pi\cos\theta} \right|^2$$

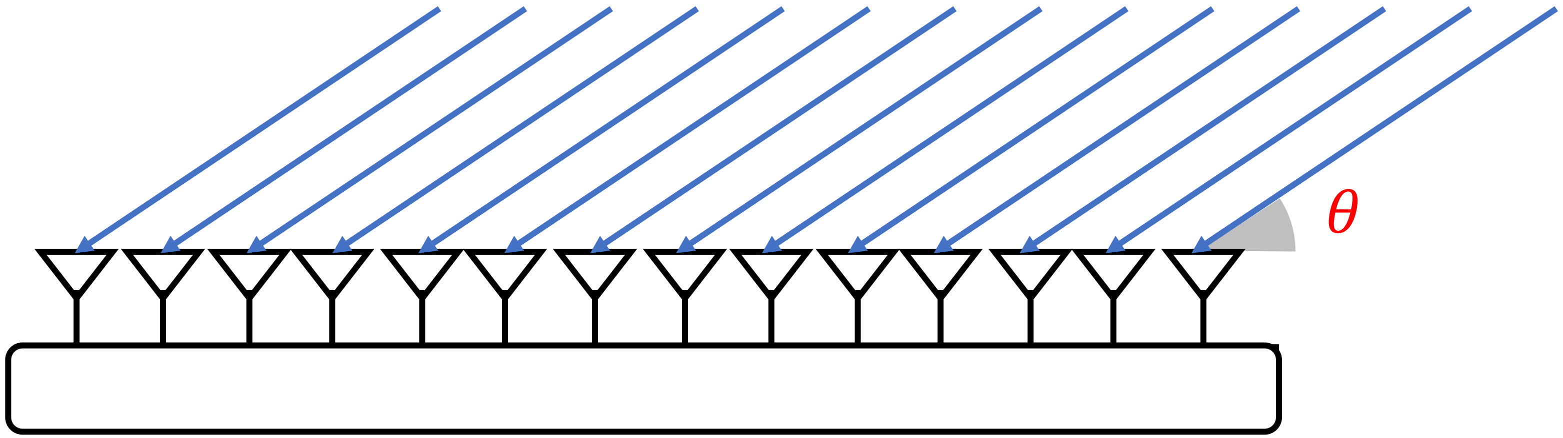


Antenna Arrays



$$h_k = \alpha_1 e^{-j2\pi\frac{d_1 - k\, s \cos\theta_1}{\lambda}}$$

Antenna Arrays



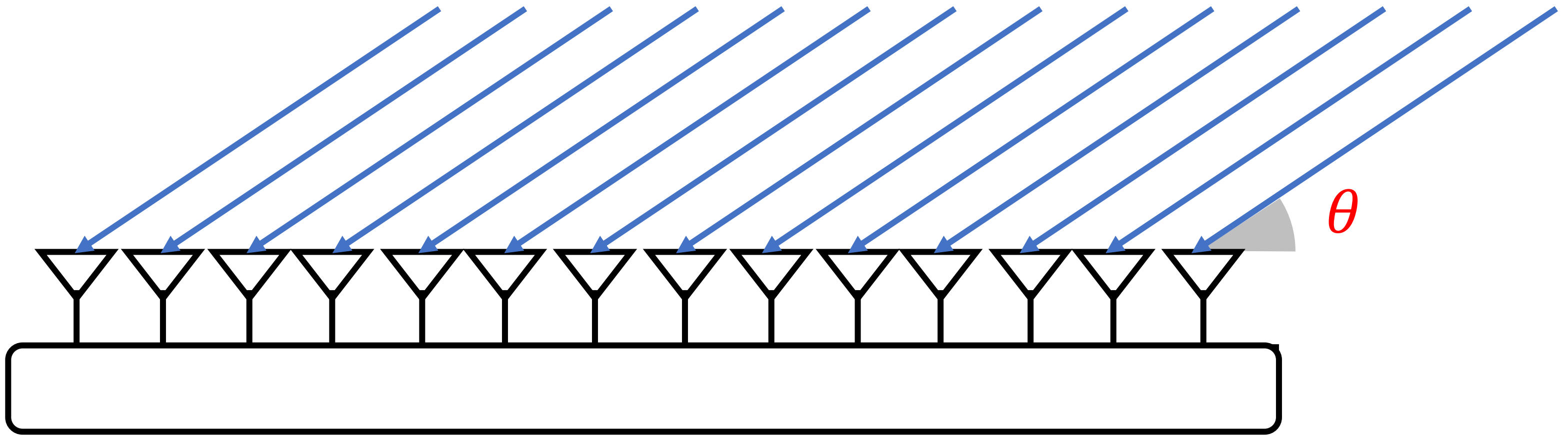
$$h_k = \sum_{l=1}^{L} \alpha_l e^{-j\phi_l} e^{j2\pi \frac{ks \cos\theta_l}{\lambda}}$$

Let: $f = \cos\theta\,, t = ks/\lambda\,,$
$P_{\cos\theta} = \alpha_l e^{-j\phi_l}$

$$h_t = \sum_f P_f e^{j2\pi f t} \quad \Longleftrightarrow \quad x(t) = \sum_f X(f) e^{j2\pi f t}$$

Antenna Arrays are a Fourier Transform

Antenna Arrays



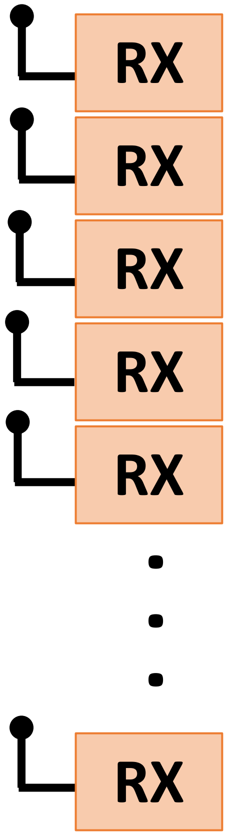
$$h_k = \sum_{l=1}^{L} \alpha_l e^{-j\phi_l} e^{j2\pi \frac{ks \cos\theta_l}{\lambda}} \quad \Longleftrightarrow \quad x(t) = \sum_f X(f) e^{j2\pi f t}$$

Antennas ⟺ Time Samples

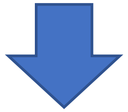
FFT ↓ FFT ↓

AoA Directions ⟺ Frequencies

Why can't we estimate the direction of the signal?

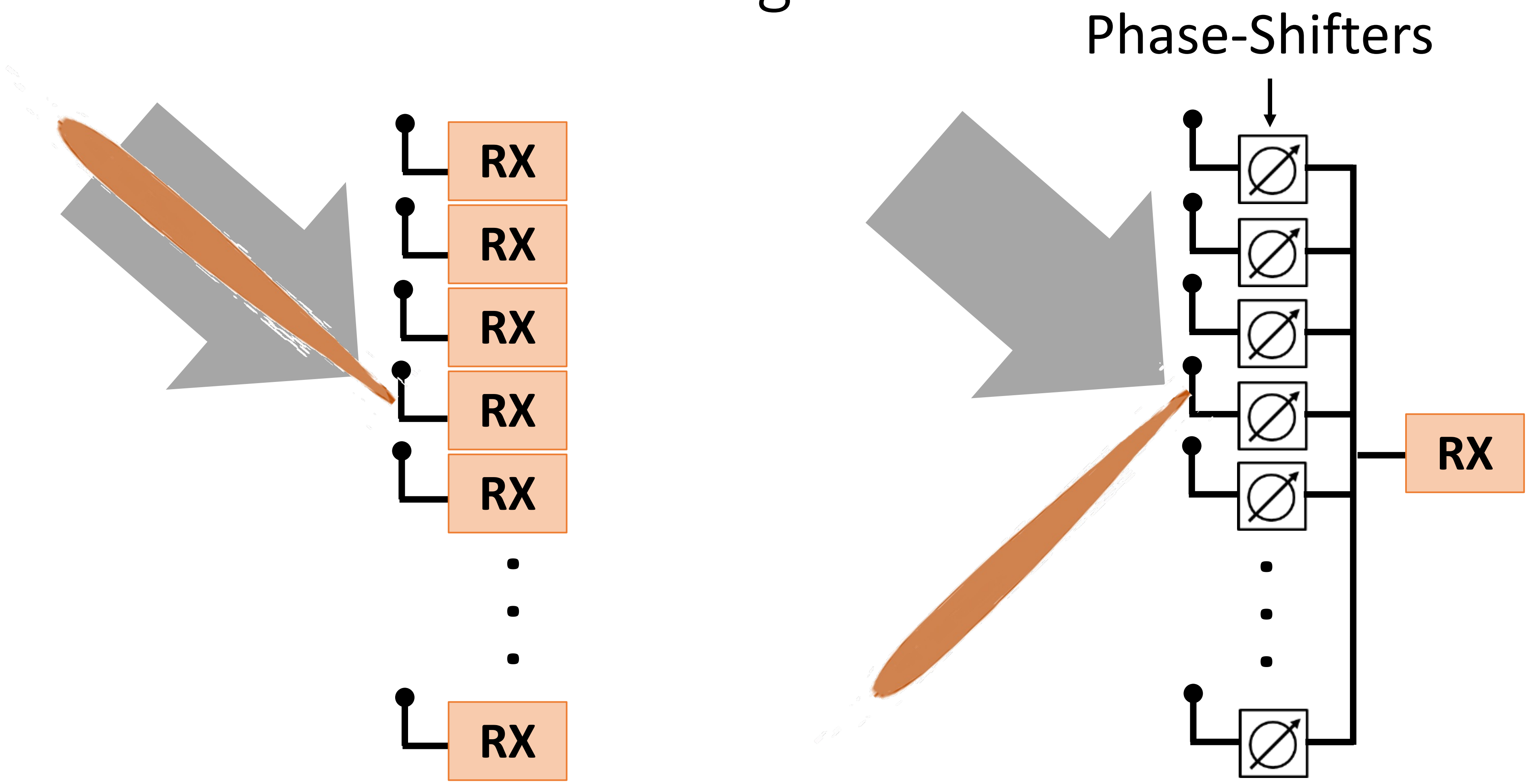


Cannot have a TX/RX chain per antenna!



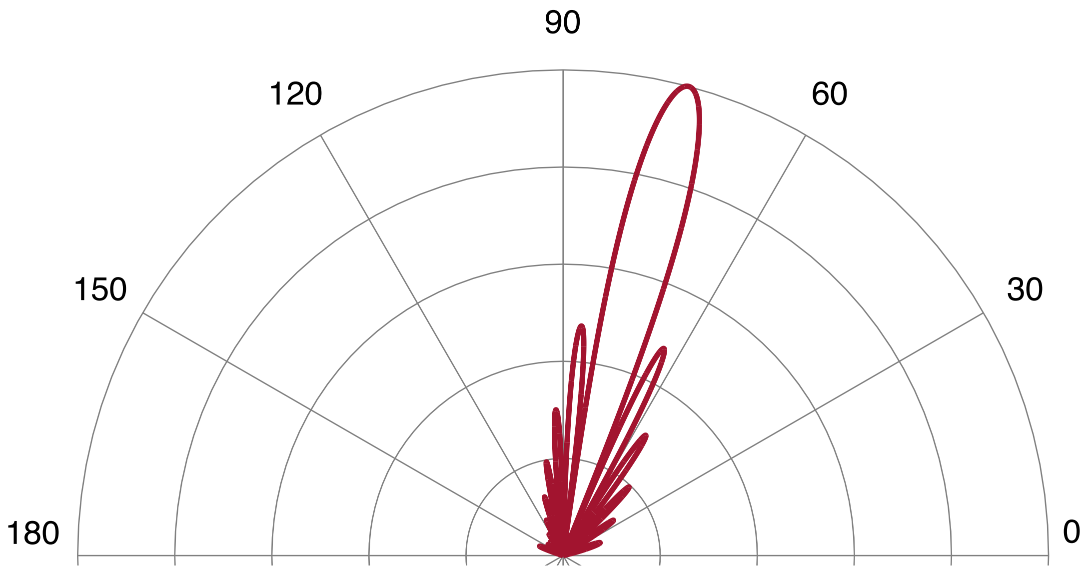
Cannot do digital beamforming

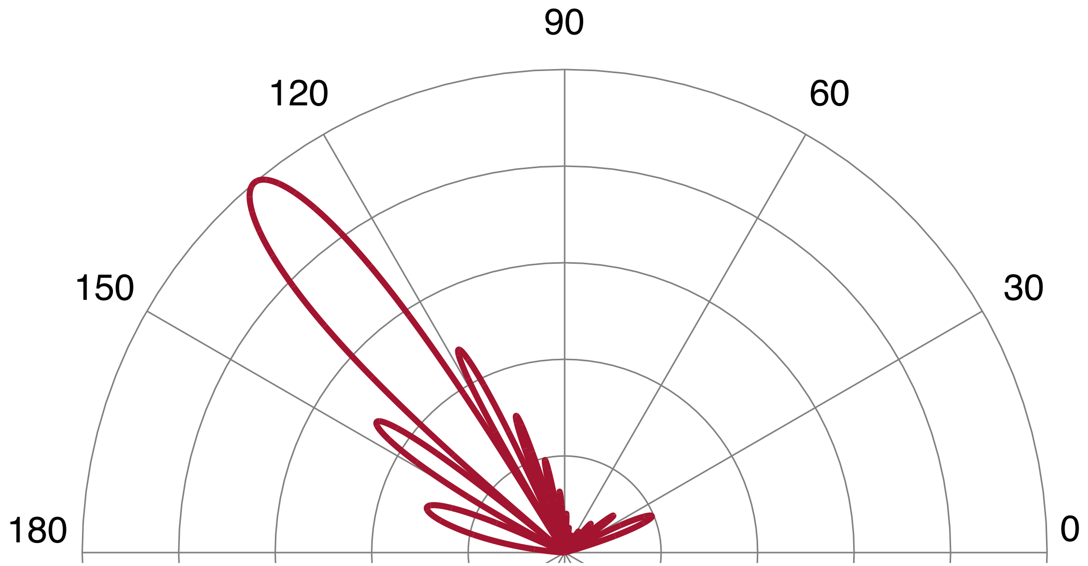
Why can't we estimate the direction of the signal?

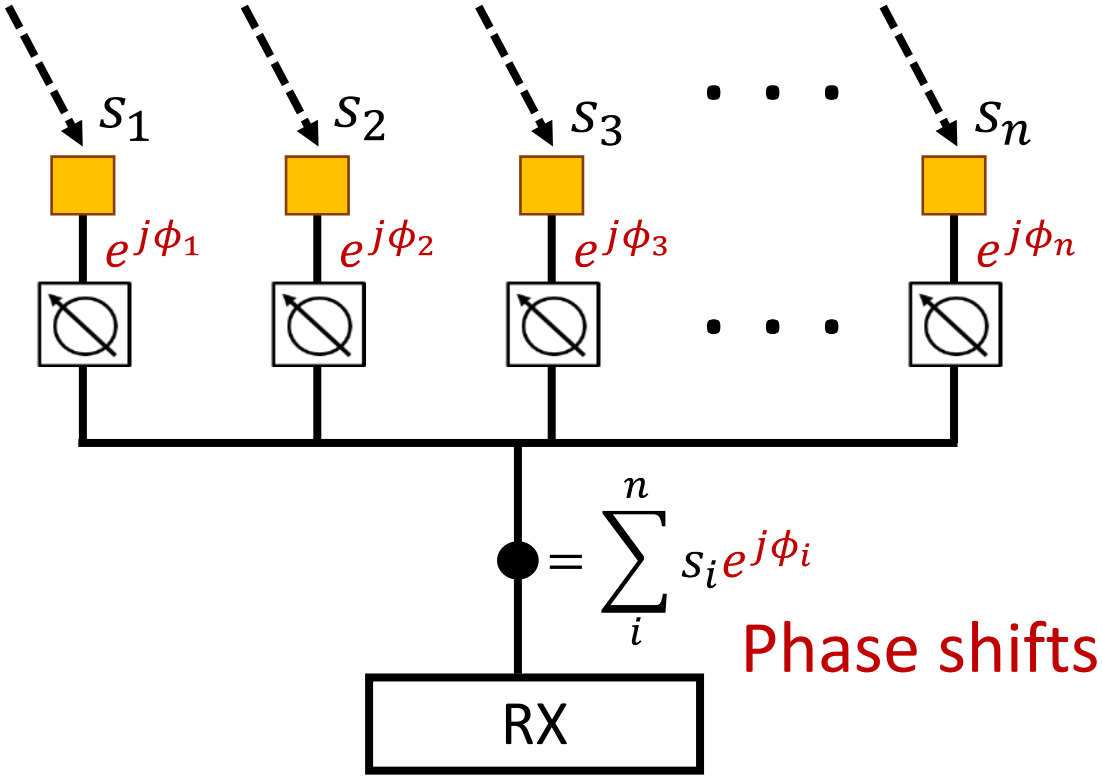


Need to scan the space and search for the direction of the signal→ takes time!

How to control the beam pattern?



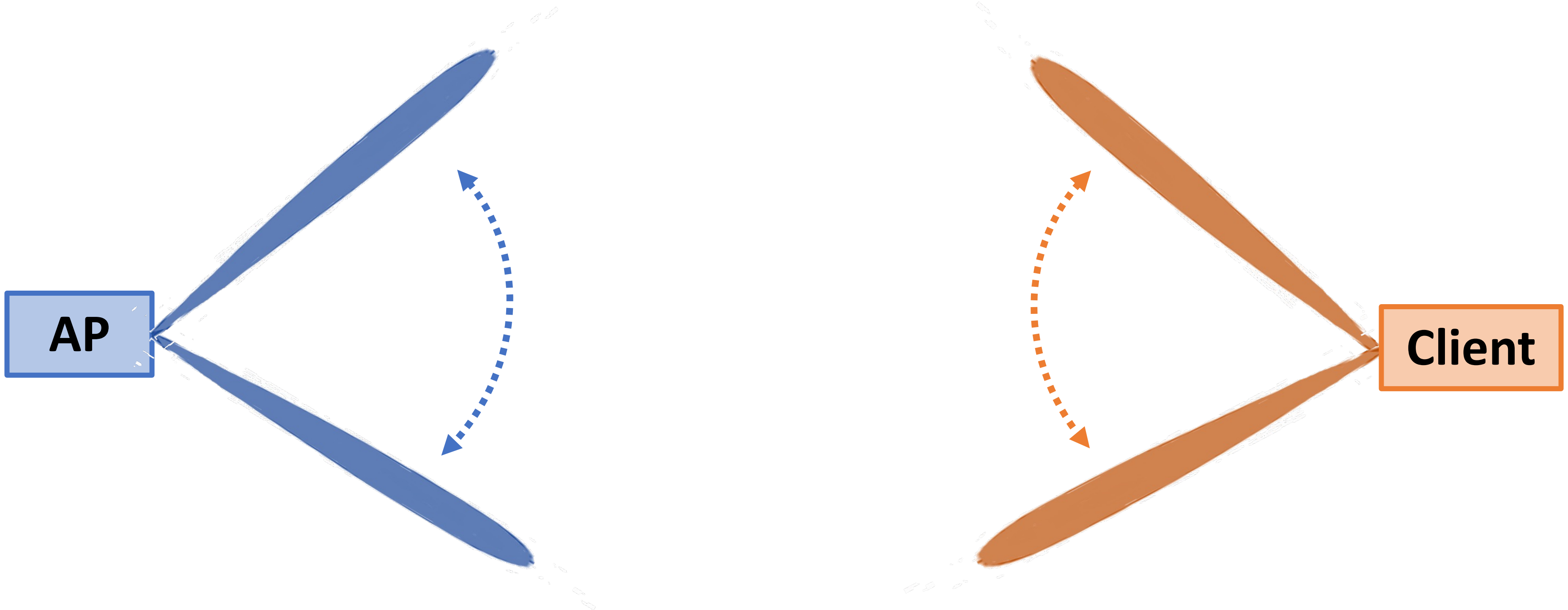




Phase shifts

How to align the beams of the AP and Client?

N : number of possible directions



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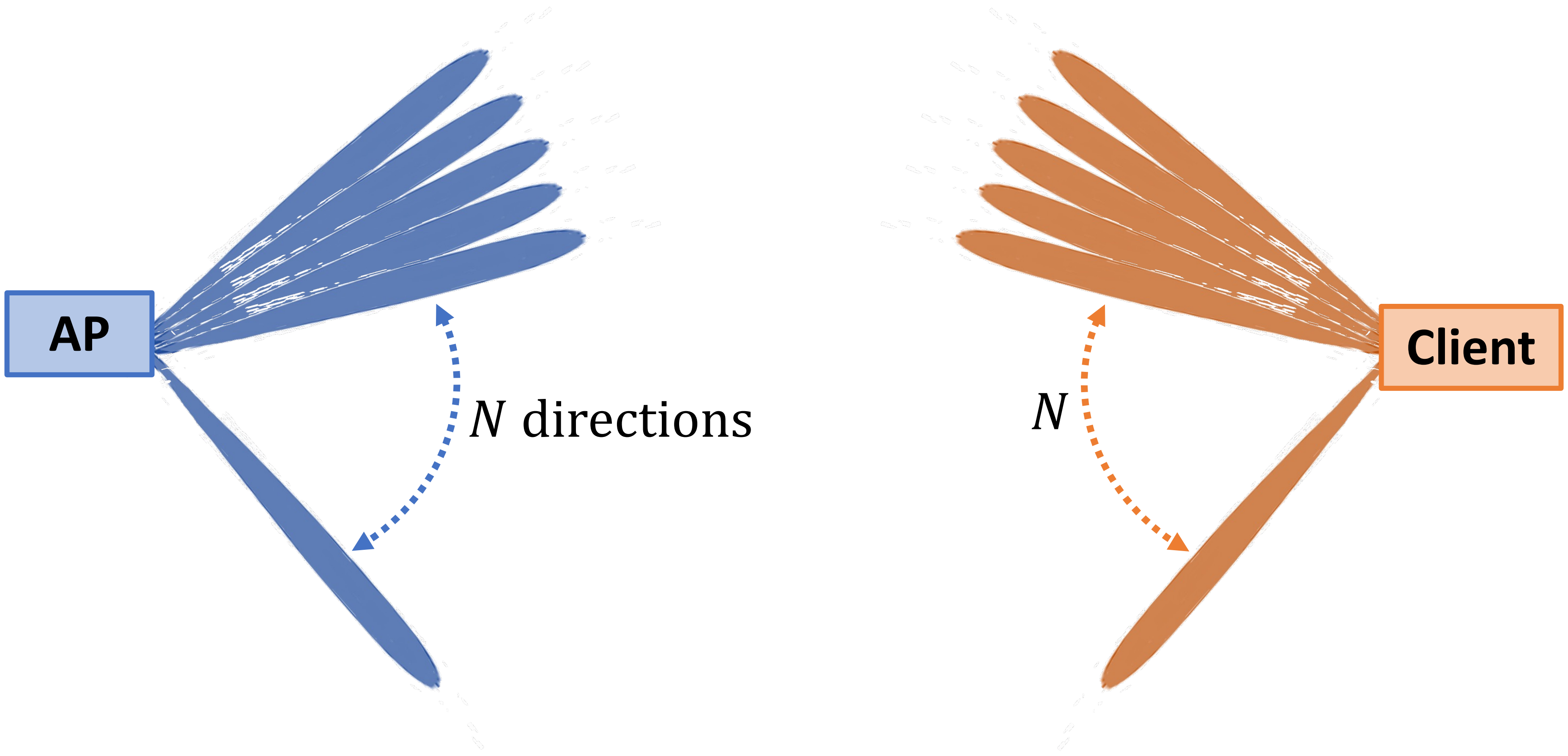
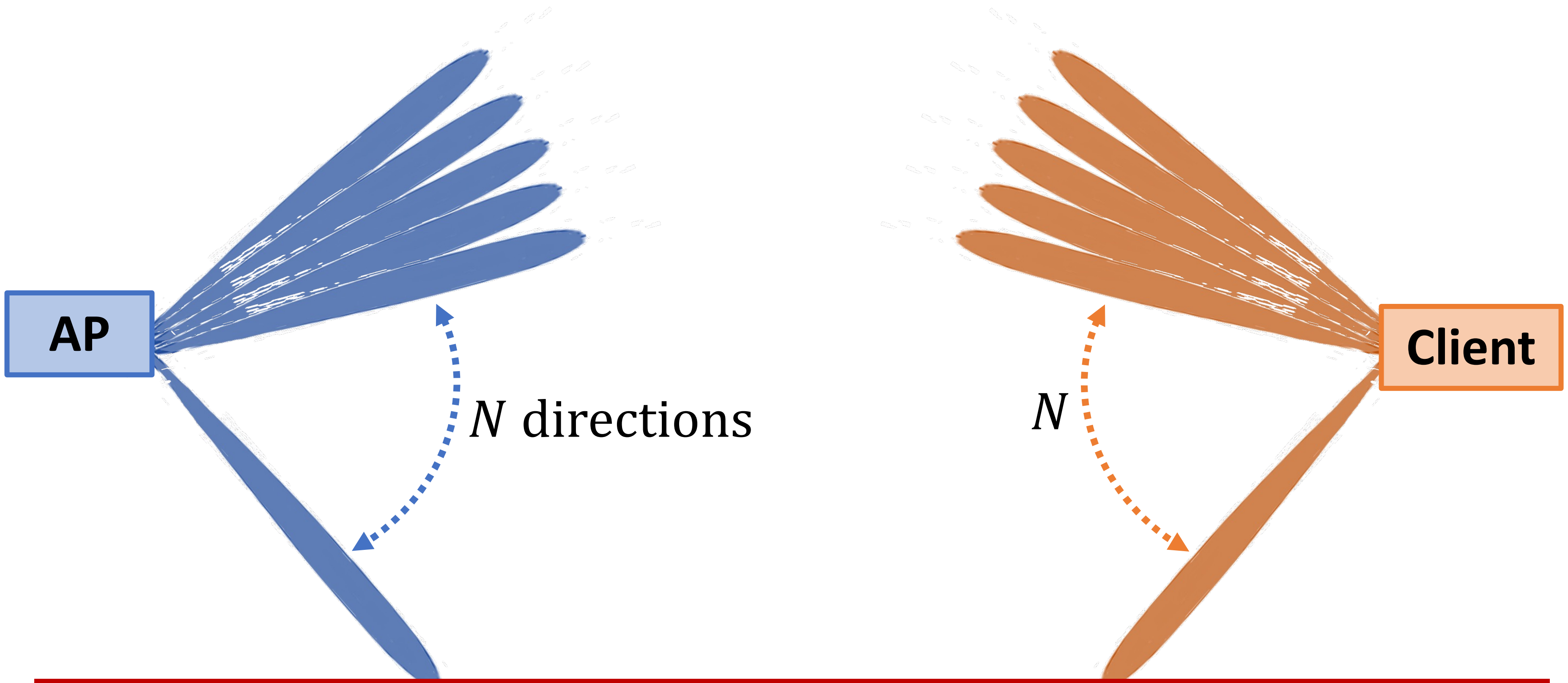


Naïve Algorithm: Exhaustive Scan

N : number of possible directions



$O(N^2)$ Beacon Packets → Too expensive

Multi-Stage Scan

Stage 1: Client uses omni-directional; AP scans directions

Multi-Stage Scan

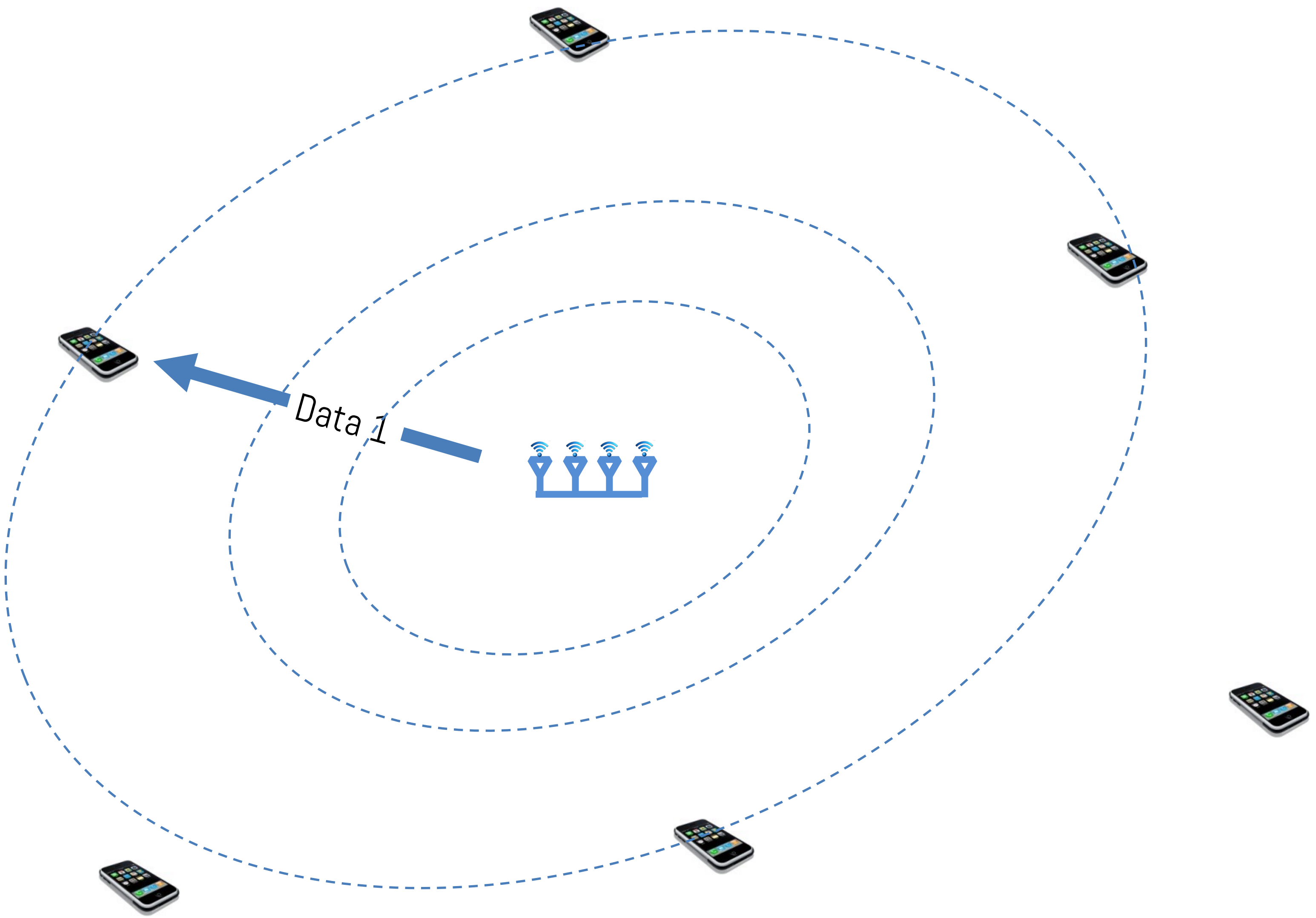
Stage 2: AP uses omni directional; client scans directions

$O(N)$ Beacon Packets

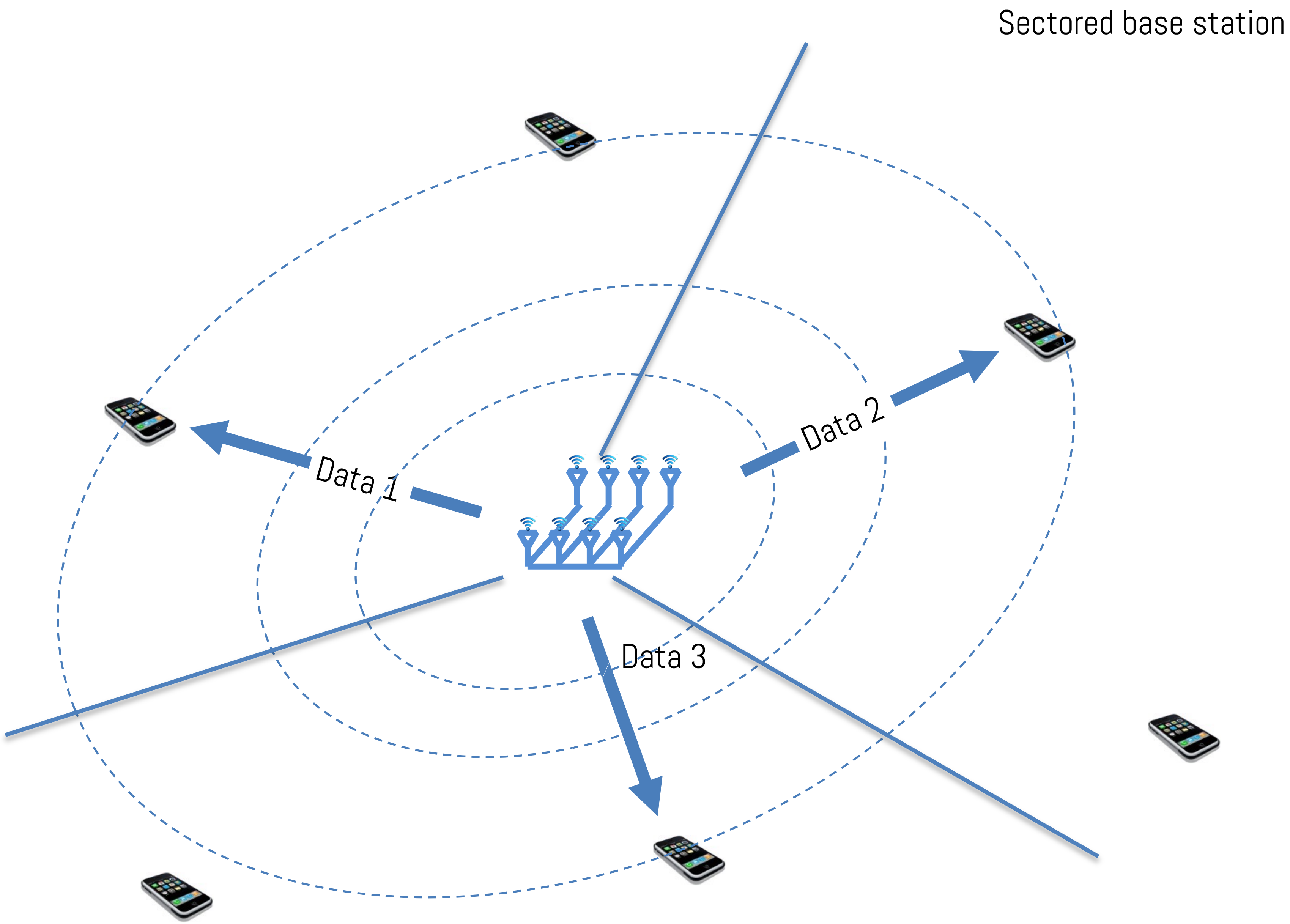
→ Still Too Slow [MOBICOM'14, SIGMETRICS'15, NSDI'16]

Massive MIMO

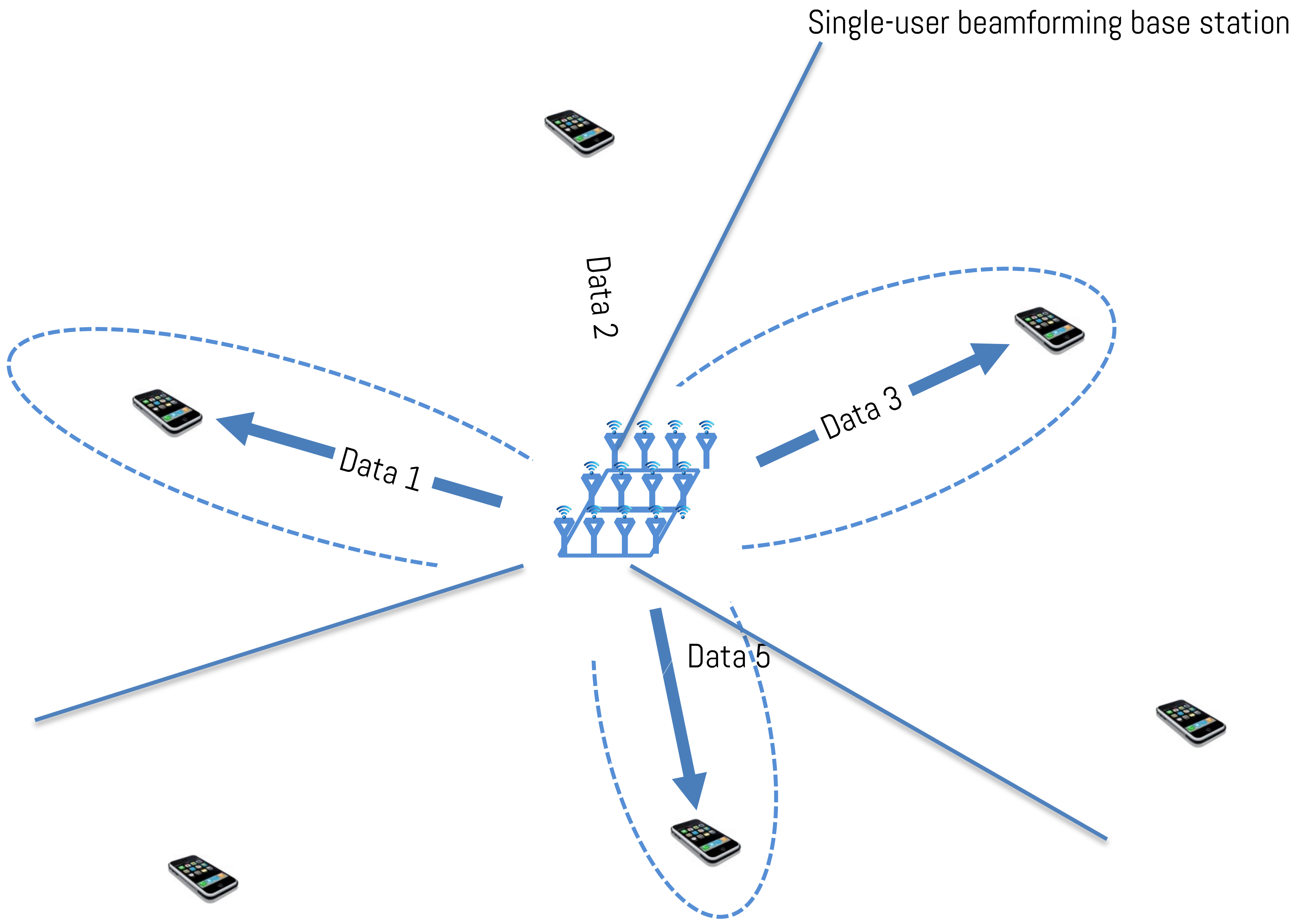
Omni-directional base station



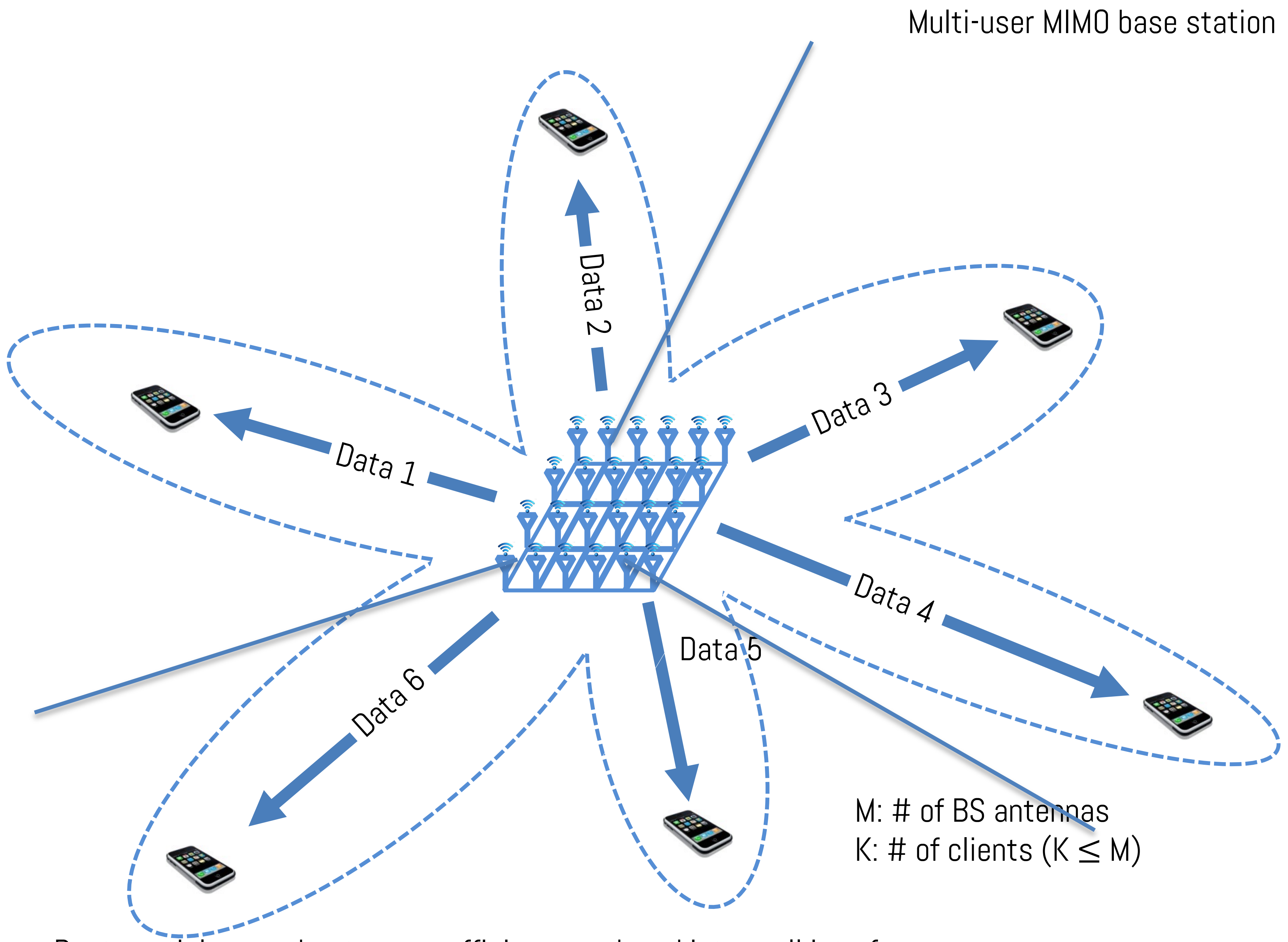
Poor spatial reuse; poor power efficiency; high inter-cell interference



Better spatial reuse; better power efficiency; high inter-cell interference

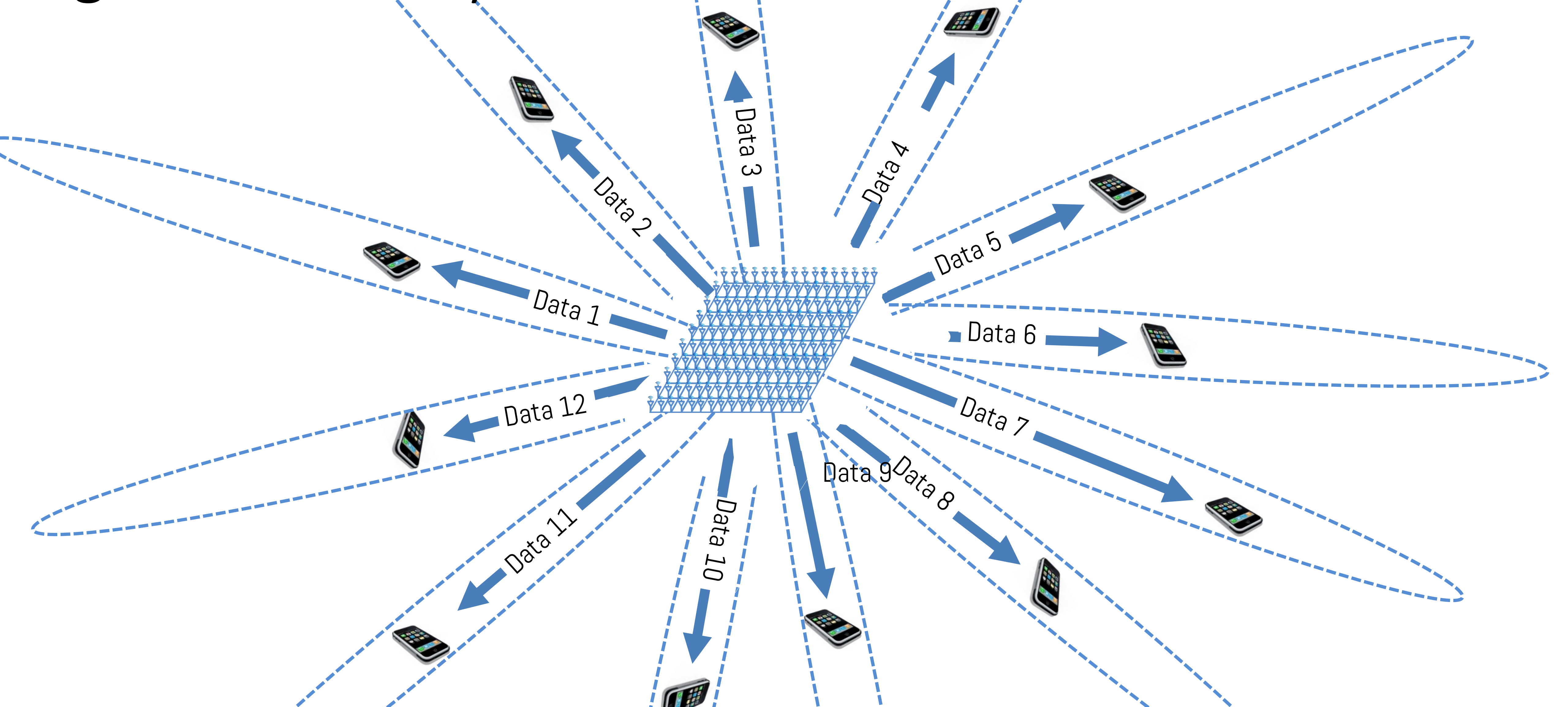


Better spatial reuse; best power efficiency; reduced inter-cell interference

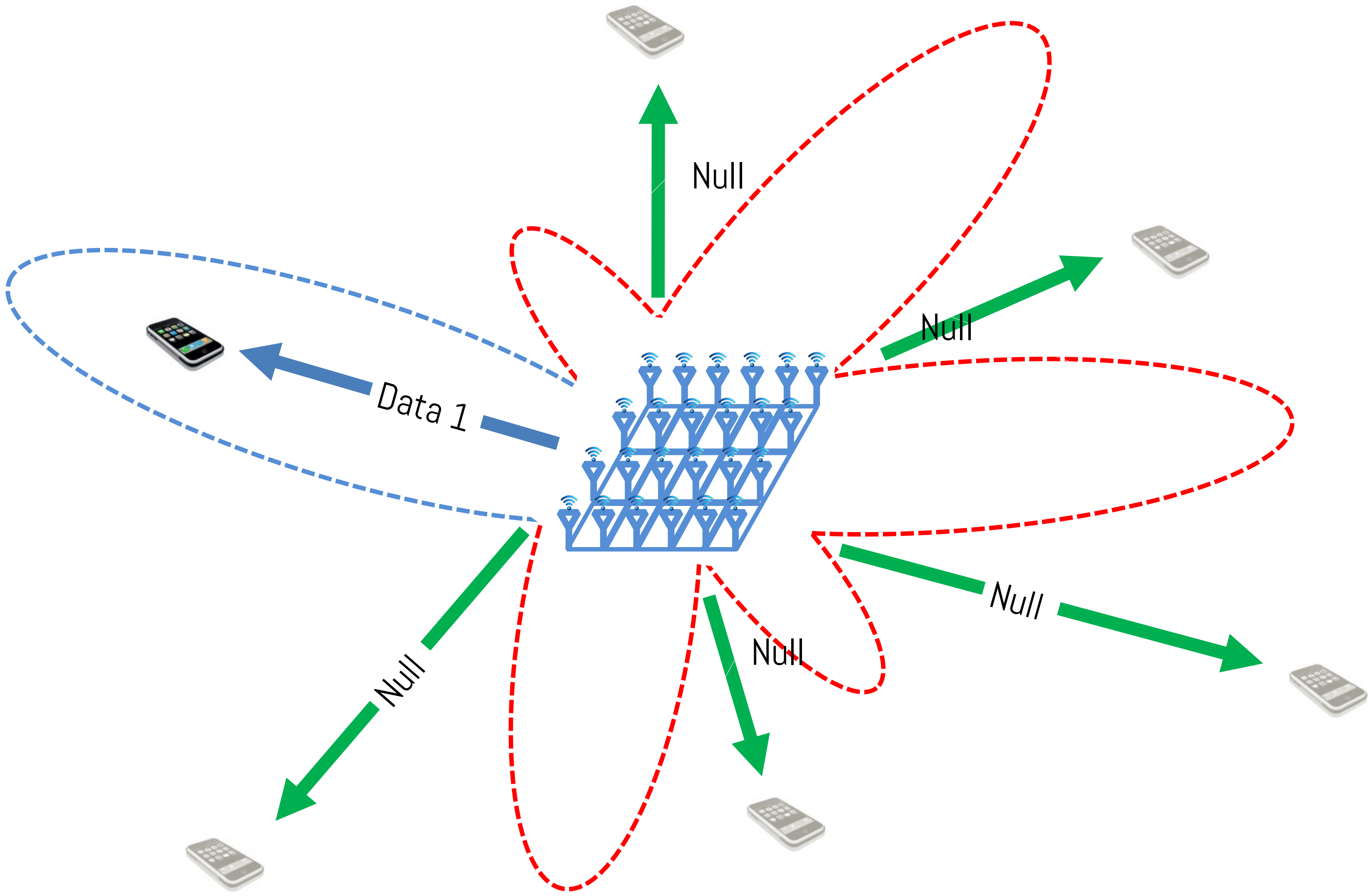


Best spatial reuse; best power efficiency; reduced inter-cell interference

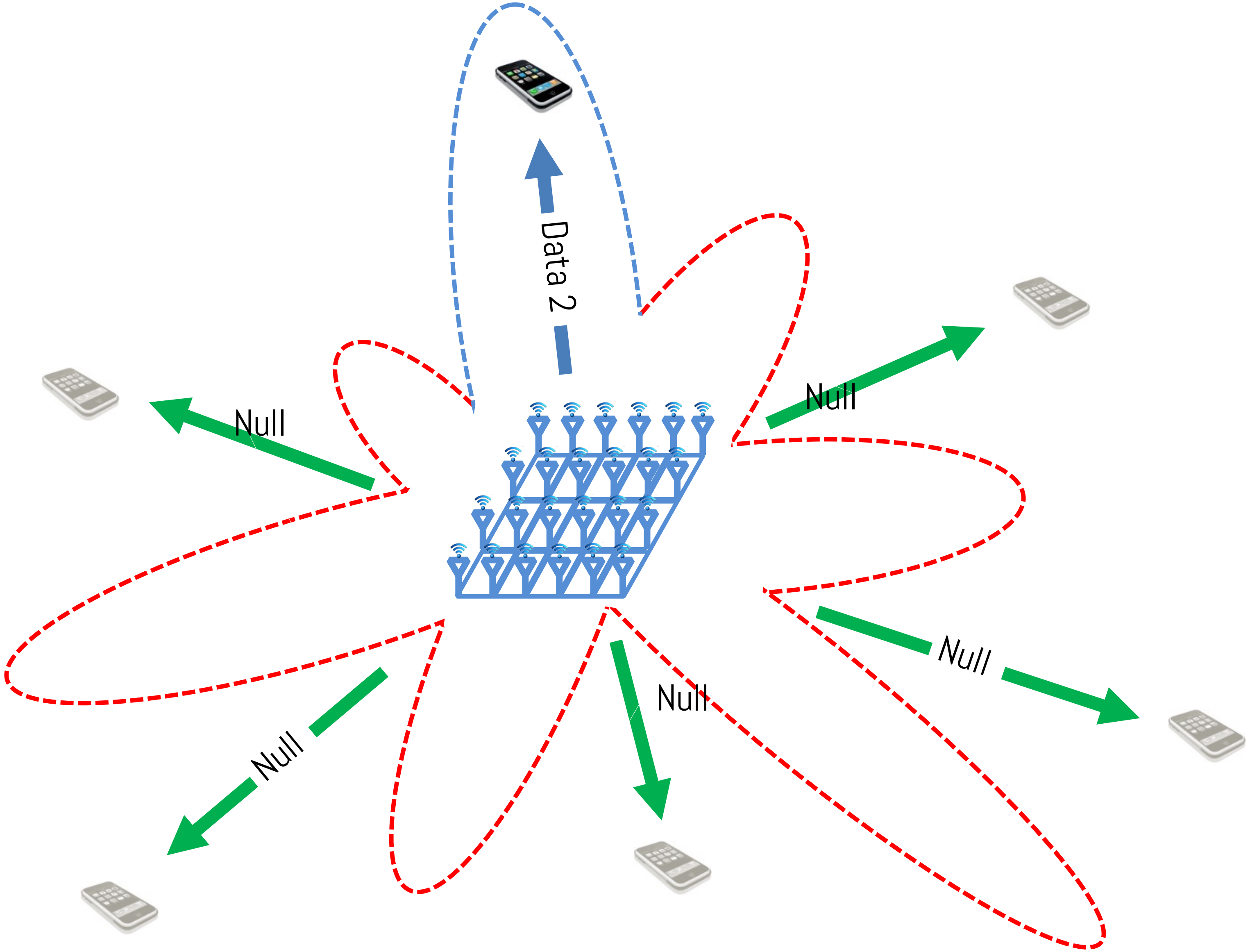
More BS antennas + MU-MIMO ➔ Higher efficiency & lower interference



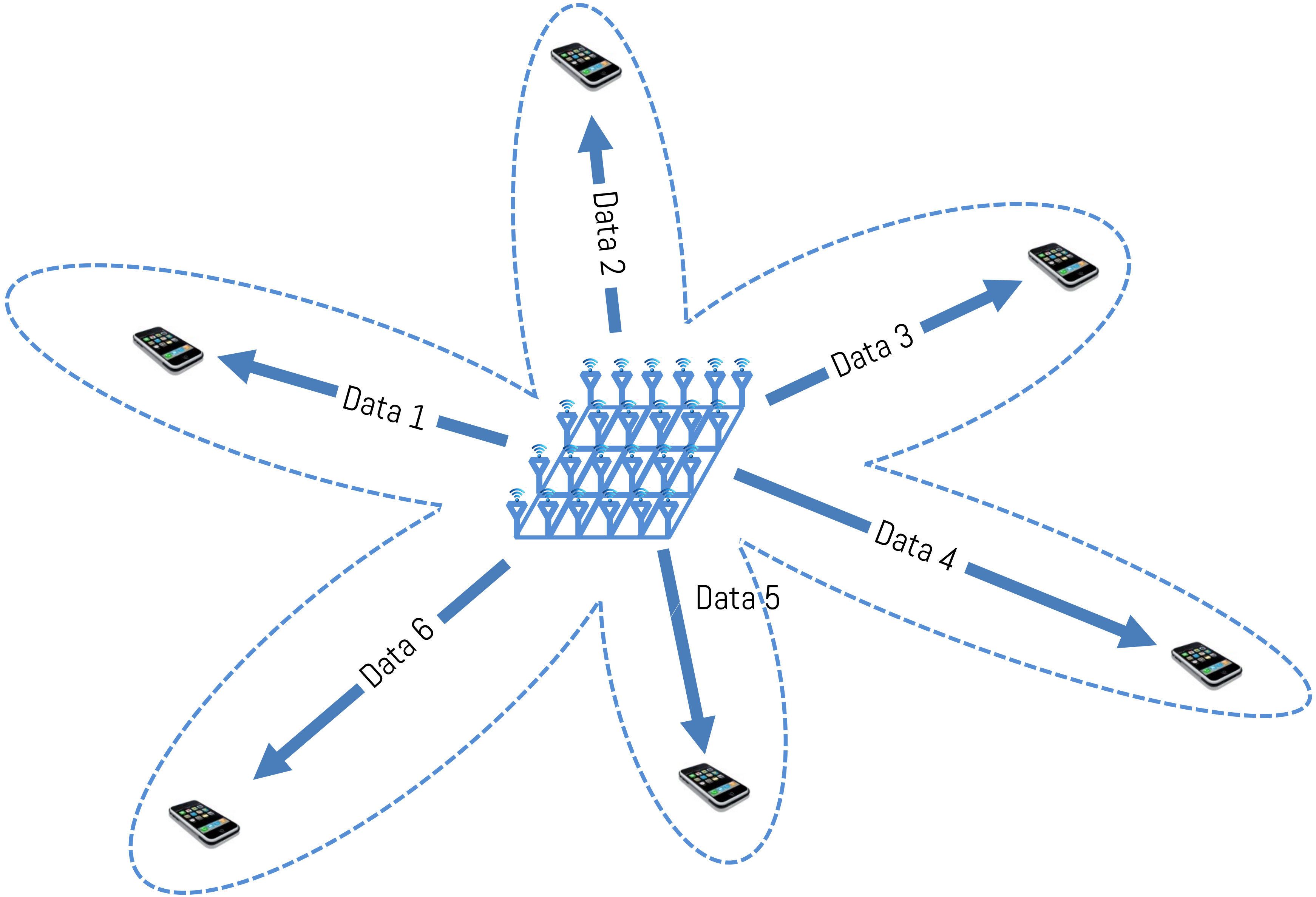
Zeroforcing precoder



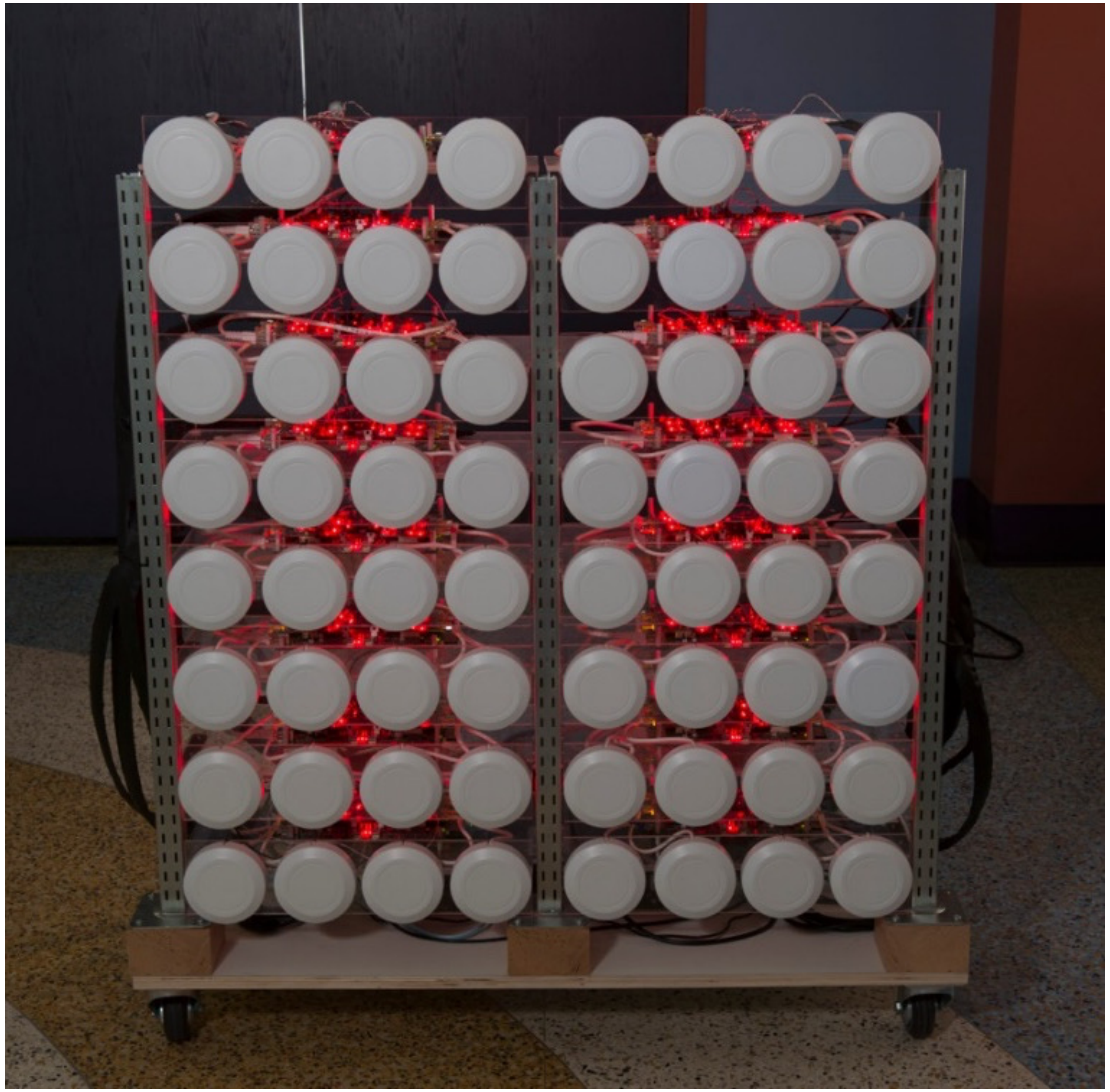
Zeroforcing precoder

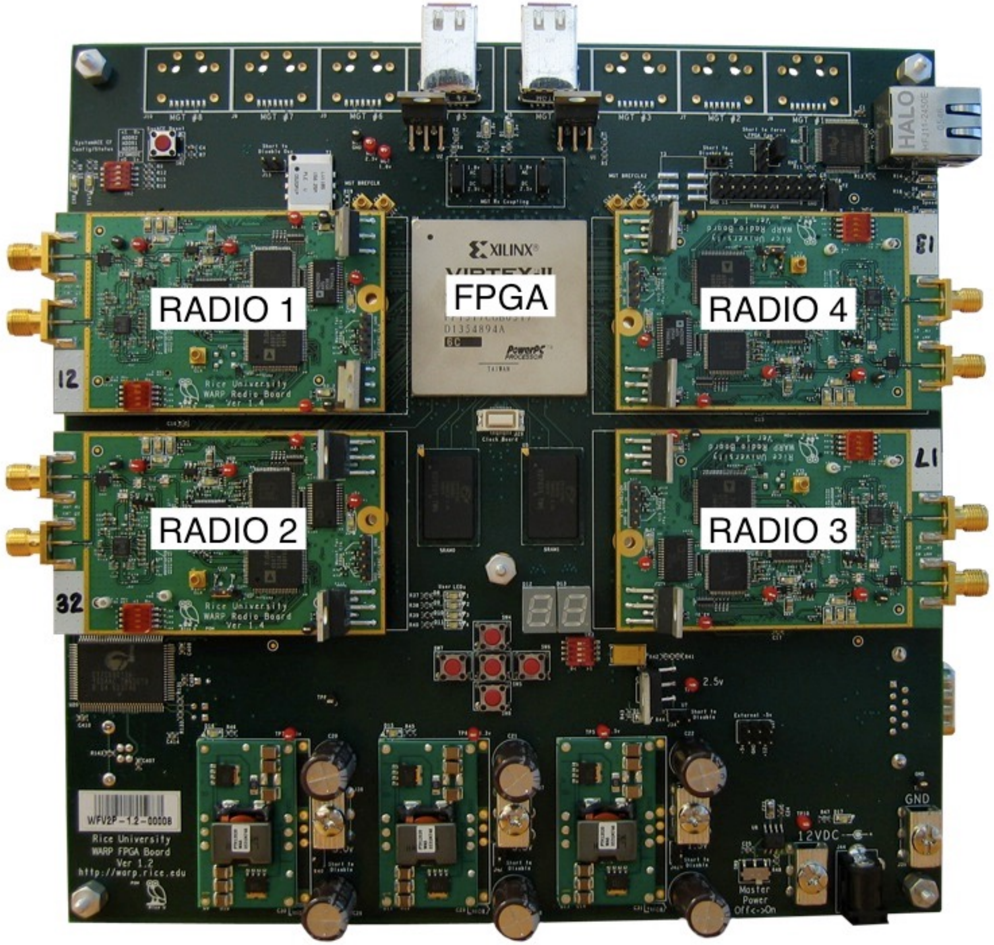


Zeroforcing precoder

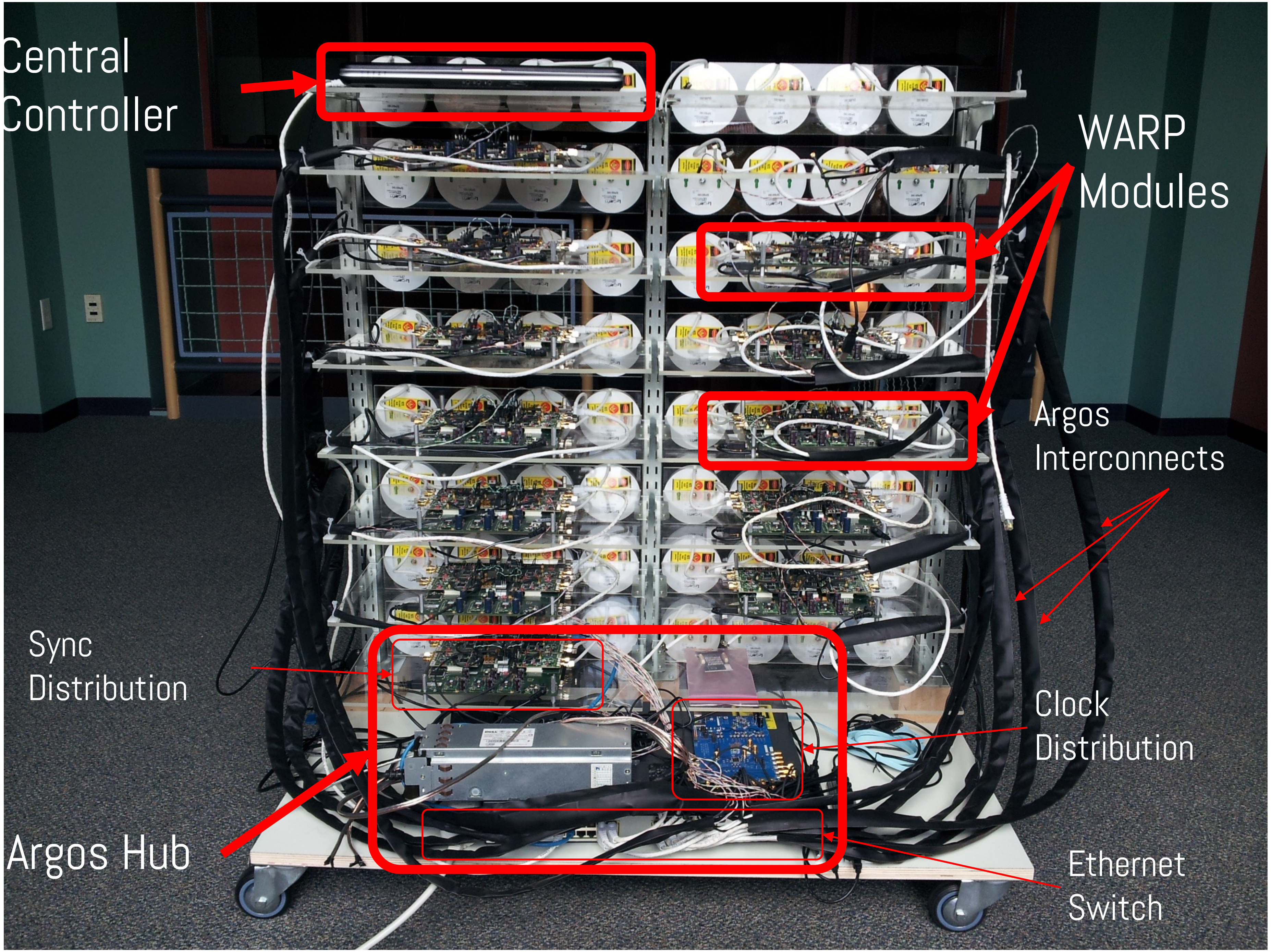


Argos V1 (2011): World's first Massive MIMO Testbed





WARP v1 as Module


Central
Controller
WARP
Modules
Argos
Interconnects
Sync
Distribution
Clock
Distribution
Argos Hub
Ethernet
Switch

Argos V2 (2013)
World's first largest real-time massive MIMO testbed