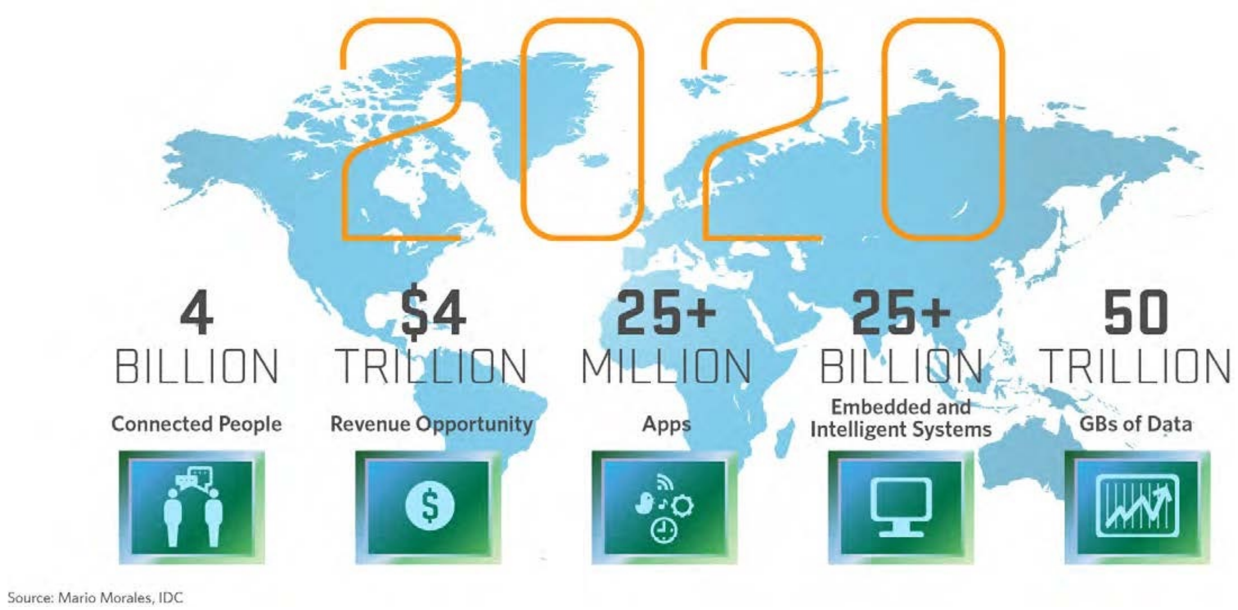
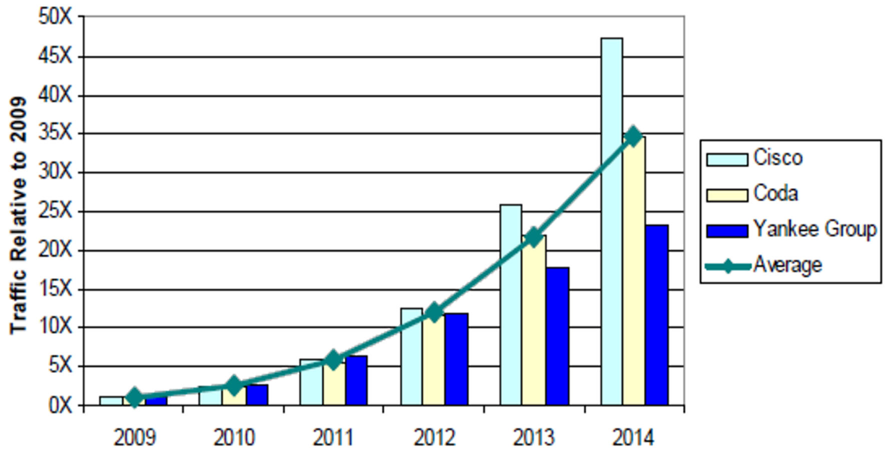
Wireless Communication Systems
@CS.NCTU

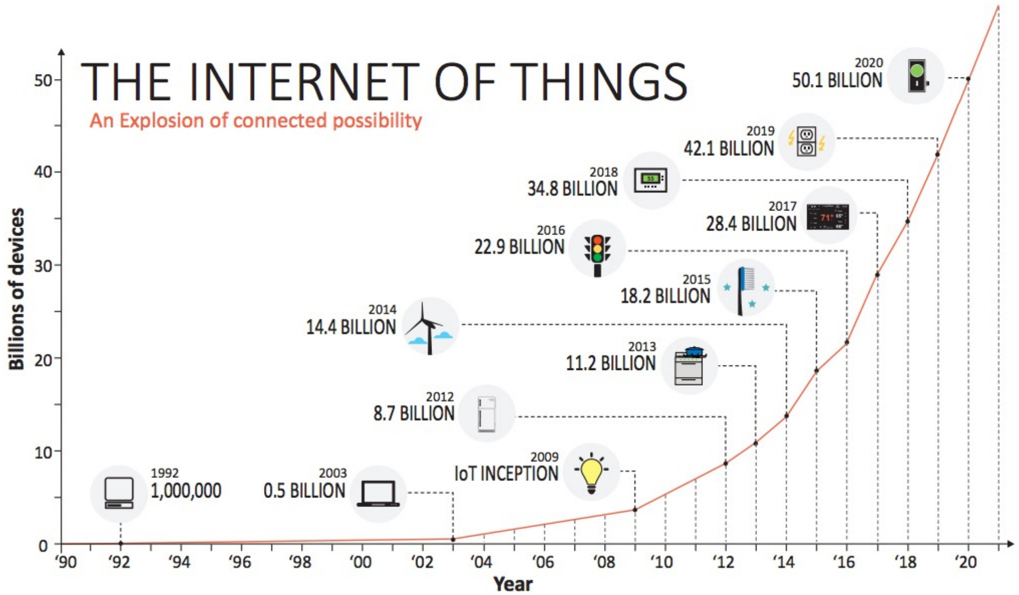
Lecture 8: 5G and mmWave

Lecturer: Kate Ching-Ju Lin (林靖茹)

Increasing Demand for Wireless Connectivity





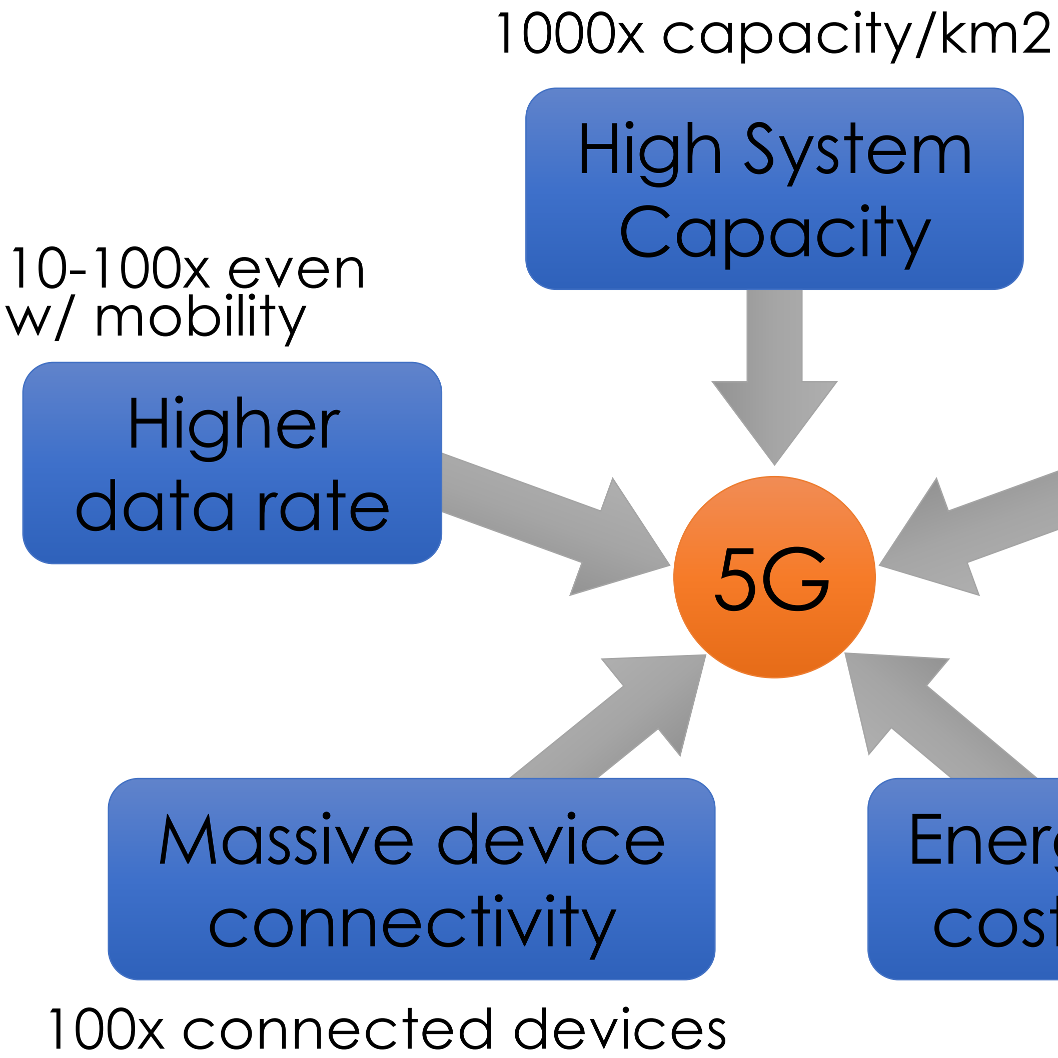


Key Trend (2013-2025)

- Exponential traffic growth
- Wireless traffic dominated by video multimedia
- Expectation of ubiquitous broadband access
- Expectation of Gbps, low latency access
- Emerging internet of things devices

source: Intel, Sept. 2013

5G Targets



source: NTT DoCoMo, Inc. 2014

Disruptive Technologies

- Massive MIMO
- Device-to-device (D2D) communications
- Heterogeneous networks
- Full-duplex communication
- Millimeter wave (mmWave)

Disruptive Technologies

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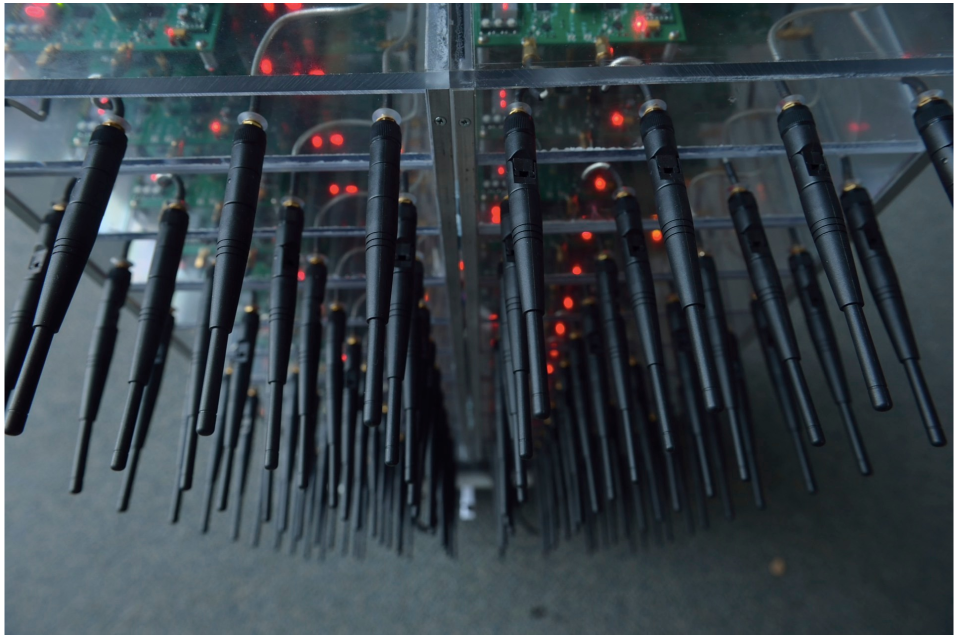
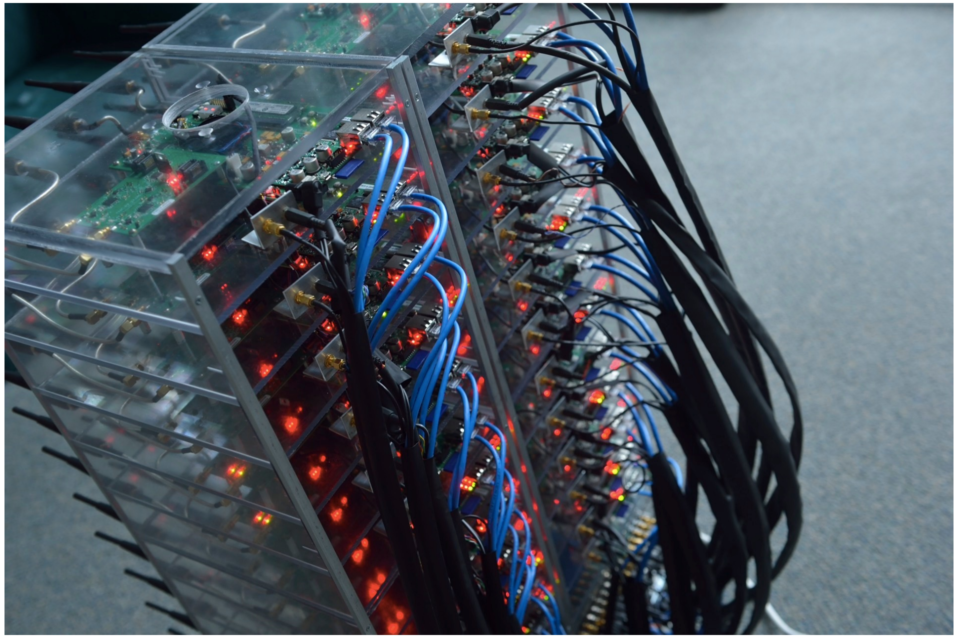
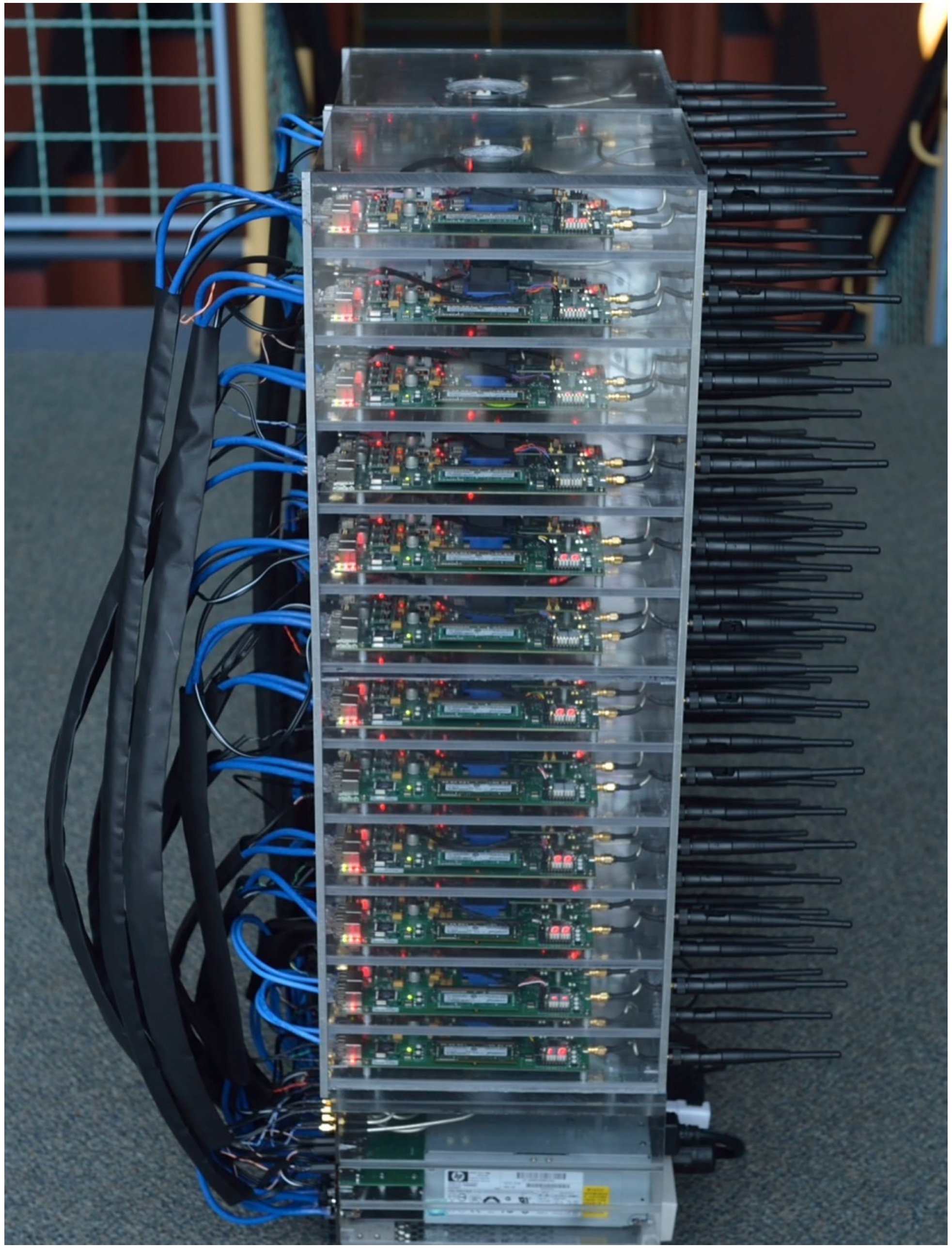






http://argos.rice.edu/

Massive MIMO

- Support a much larger number of antennas, e.g., one hundred or more
- Also known as Large-Scale Antenna Systems, Very Large MIMO, Hyper MIMO, Full-Dimension MIMO
- If N grows large and all other system parameters are assumed constant, the transmit power per user can be reduced proportionally to $1/N$ and $1/\sqrt{N}$ for perfect and imperfect CSI knowledge, respectively

H. Q. Ngo, E.G. Larsson, T.L. Marzetta, "Energy and Spectral Efficiency of Very Large Multiuser MIMO Systems," IEEE Trans. on Comm., vol. 61, no. 4, pp. 1436--1449, Apr. 2013.

Massive MIMO: Challenges

- Scalability of precoding and detection
  - Traditional zero-forcing beamforming requires non-trivial baseband processing
- CSI estimation
  - How to efficiently collect full CSI?
- Accurate synchronization
- Cost, size, and power consumption

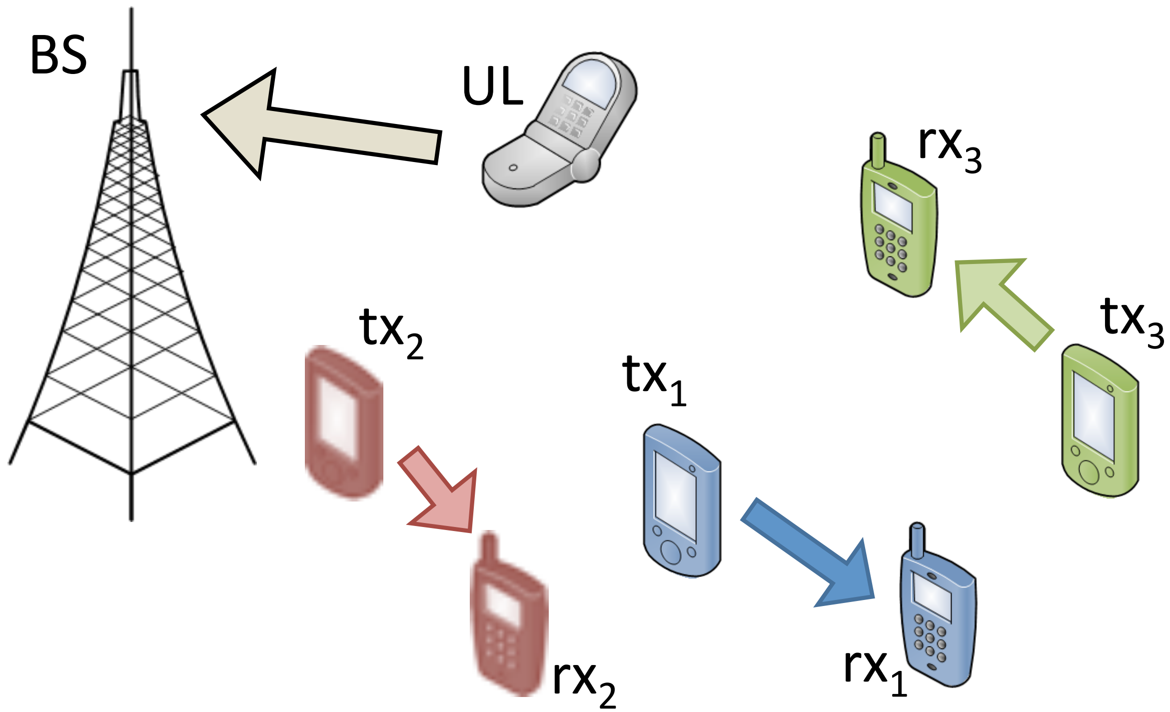
Reading list

- http://www.idc.lnt.de/en/forschung/massive-mimo-systems/
- http://www.massivemimo.eu/research-library
- http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6798744
- http://www.comsoc.org/best-readings/topics/massive-mimo

Disruptive Technologies

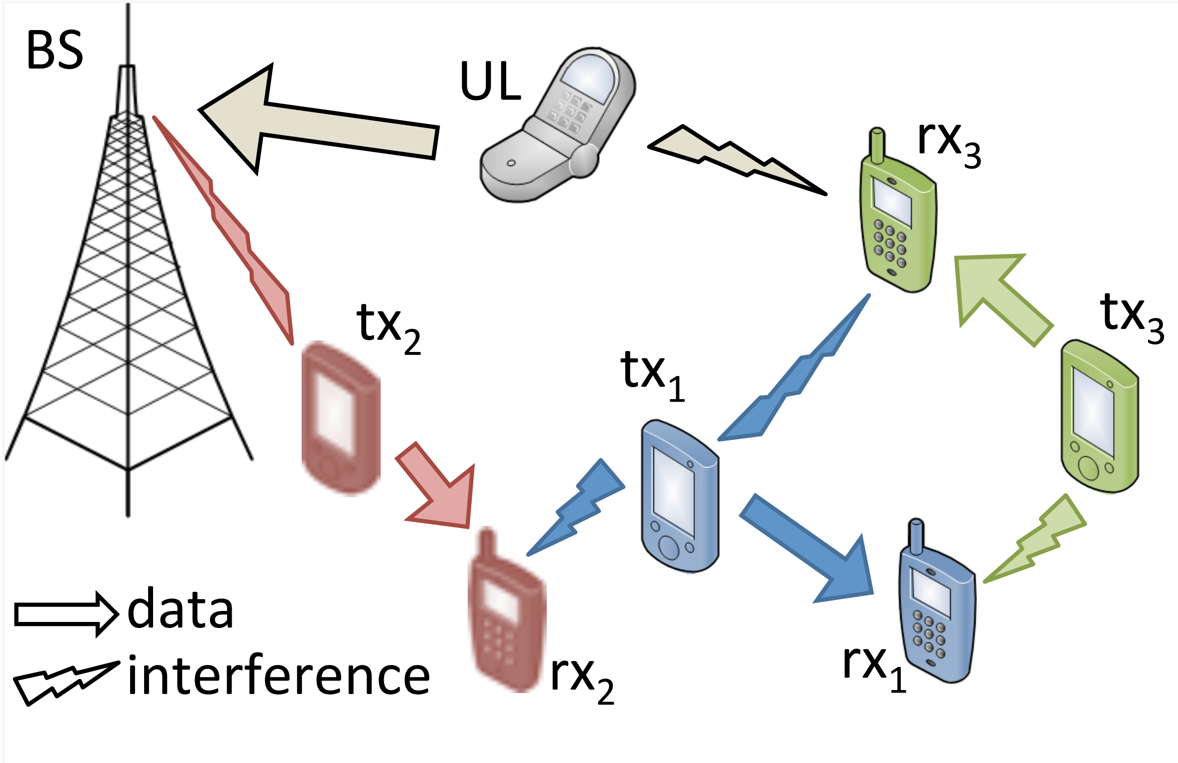
- Massive MIMO
- **Device-to-device (D2D) communications**
- Heterogeneous networks
- Full-duplex communication
- Millimeter wave (mmWave)

D2D Communications



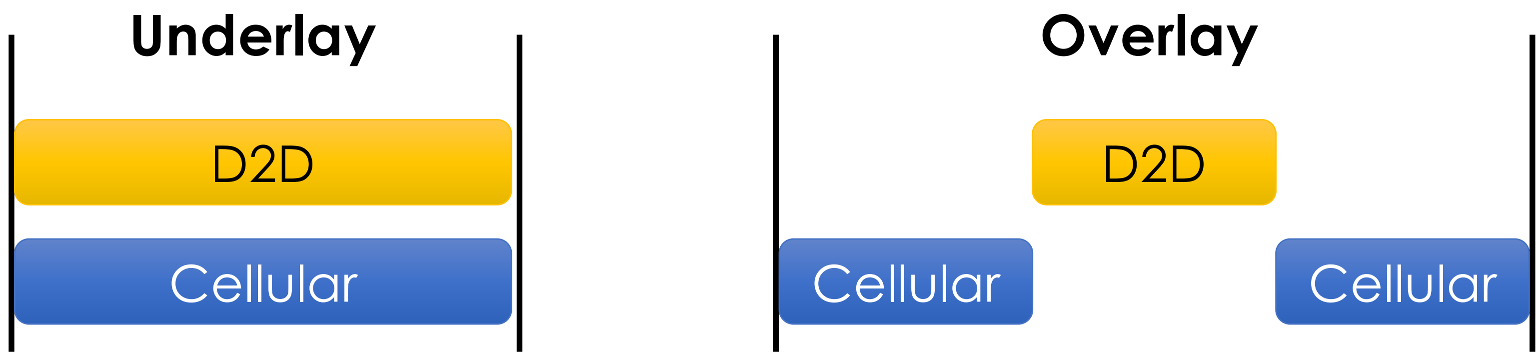
- Co-located devices share content directly, without going through a base station
- Offload proximity data exchange from a congested cellular system

Inter-link Interference in D2D



- D2D links might interfere with each other
- D2D clients might also interfere cellular transmissions

Overlay and Underlay D2D



- Higher spectrum efficiency by spatial reuse
- Need to cope with interference

- Dedicated resources for D2D
- Reduce the concern about interference
- Need explicit resource allocation

D2D Interference Management

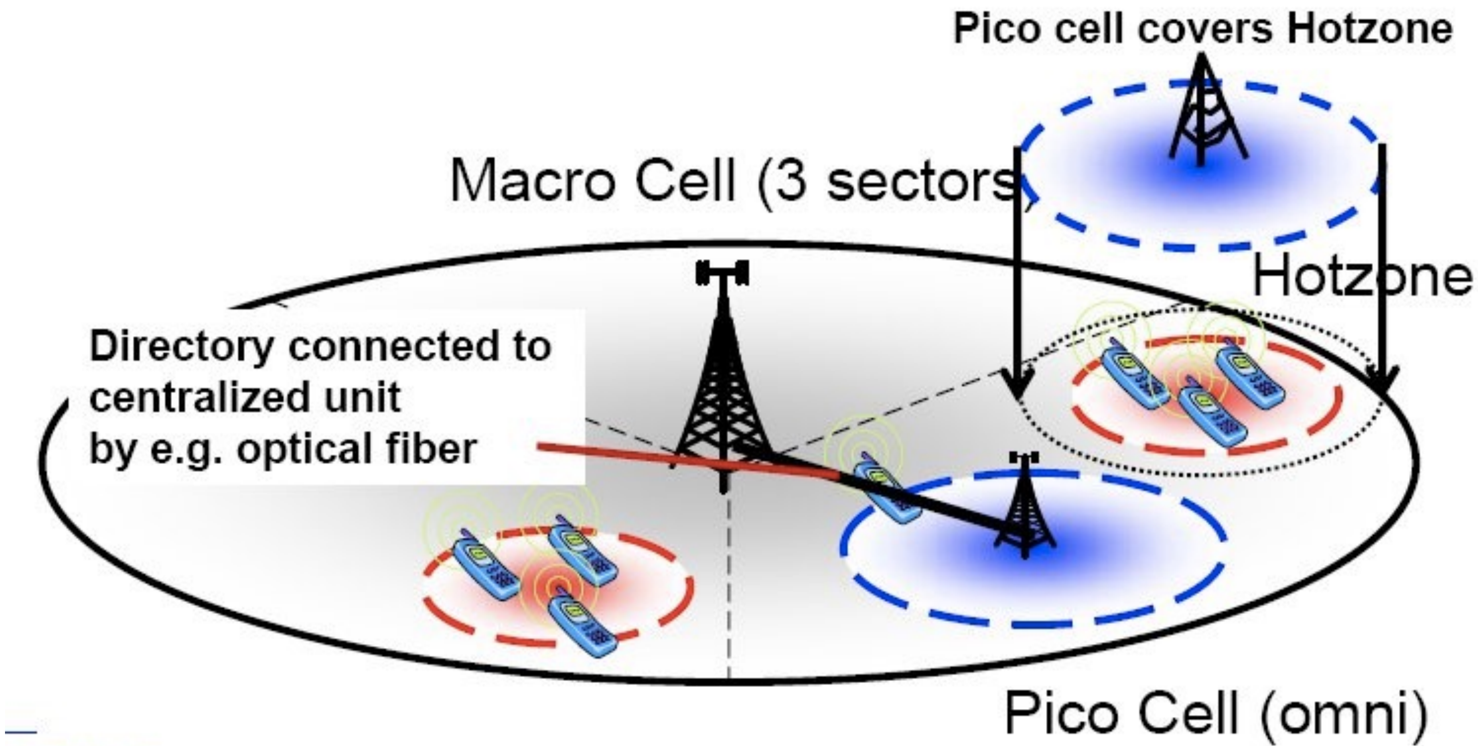
- Possible solutions
  - Resource allocation (OFDMA)
    - Throughput maximization
    - Revenue maximization
    - Energy consumption
    - Incentive
  - MIMO techniques, such as interference alignment

Disruptive Technologies

- Massive MIMO
- Device-to-device (D2D) communications
- **Heterogeneous networks**
- Full-duplex communication
- Millimeter wave (mmWave)

Heterogeneous Networks

macro cell + pico cell + femto cell



source: http://blog.3g4g.co.uk/

Comparison

Aspect	**Picocell**	**Femtocell**
Installation	Operator	Customer
Transmission to operator's network	Operator	Customer
Frequency/radio parameters	Centrally planned	Locally determined
Site rental	Operator	Customer

Source: https://www.thinksmallcell.com/FAQs/whats-the-difference-between-picocells-and-femtocells.html

Advantages and Challenges

- Reduce the cell size, and improve spatial reuse
  - larger capacity per device
- Challenges
  - Resource allocation and interference management
  - Backhaul bandwidth management
  - Latency and QoS guarantee
  - Pricing

Disruptive Technologies

- Massive MIMO
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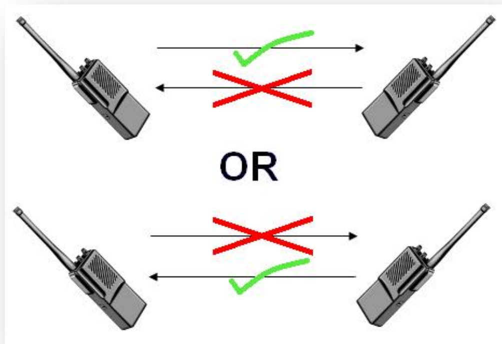
- Heterogeneous networks
- **Full-duplex communication**
- Millimeter wave (mmWave)

What is Duplex?

- Simplex

- Half-duplex



- Full-duplex

Disruptive Technologies

- Massive MIMO
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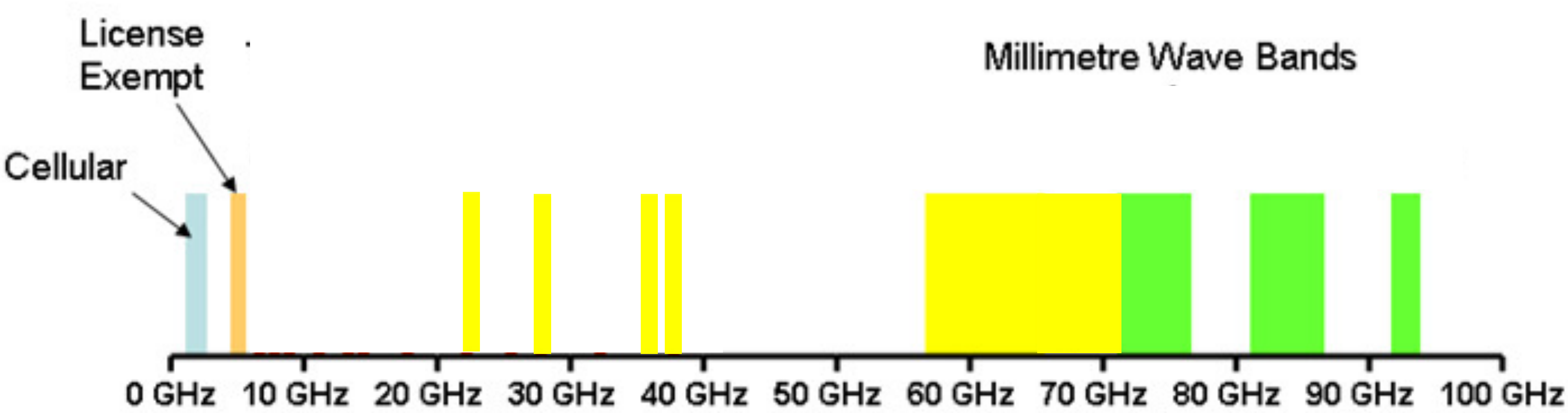
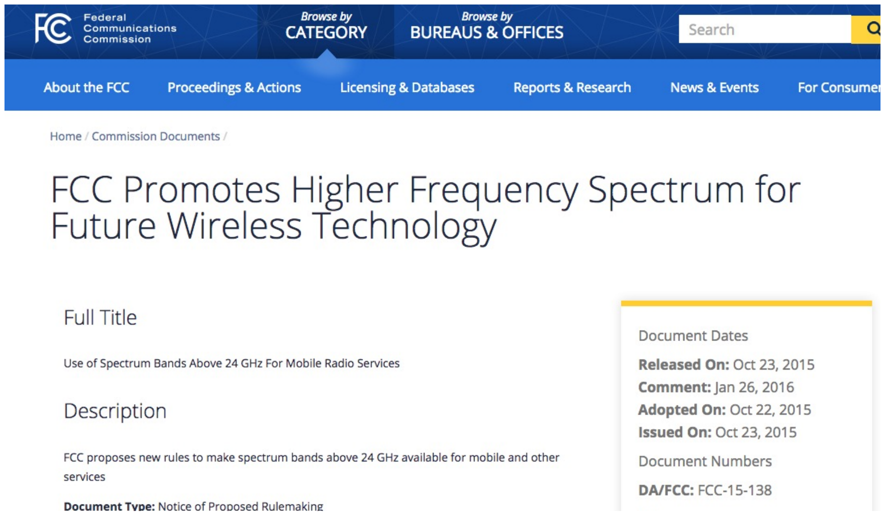
- Full-duplex communication
- **Millimeter wave (mmWave)**

Millimeter Wave Bands

- Huge amount of available bandwidth ($\lambda = C/f$)





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FCC Promotes Higher Frequency Spectrum for Future Wireless Technology

Full Title

Use of Spectrum Bands Above 24 GHz For Mobile Radio Services

Description

FCC proposes new rules to make spectrum bands above 24 GHz available for mobile and other services

Document Type: Notice of Proposed Rulemaking

Document Dates

Released On: Oct 23, 2015
Comment: Jan 26, 2016
Adopted On: Oct 22, 2015
Issued On: Oct 23, 2015

Document Numbers

DA/FCC: FCC-15-138

National Science Foundation
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Advanced Wireless Research Initiative @ NSF

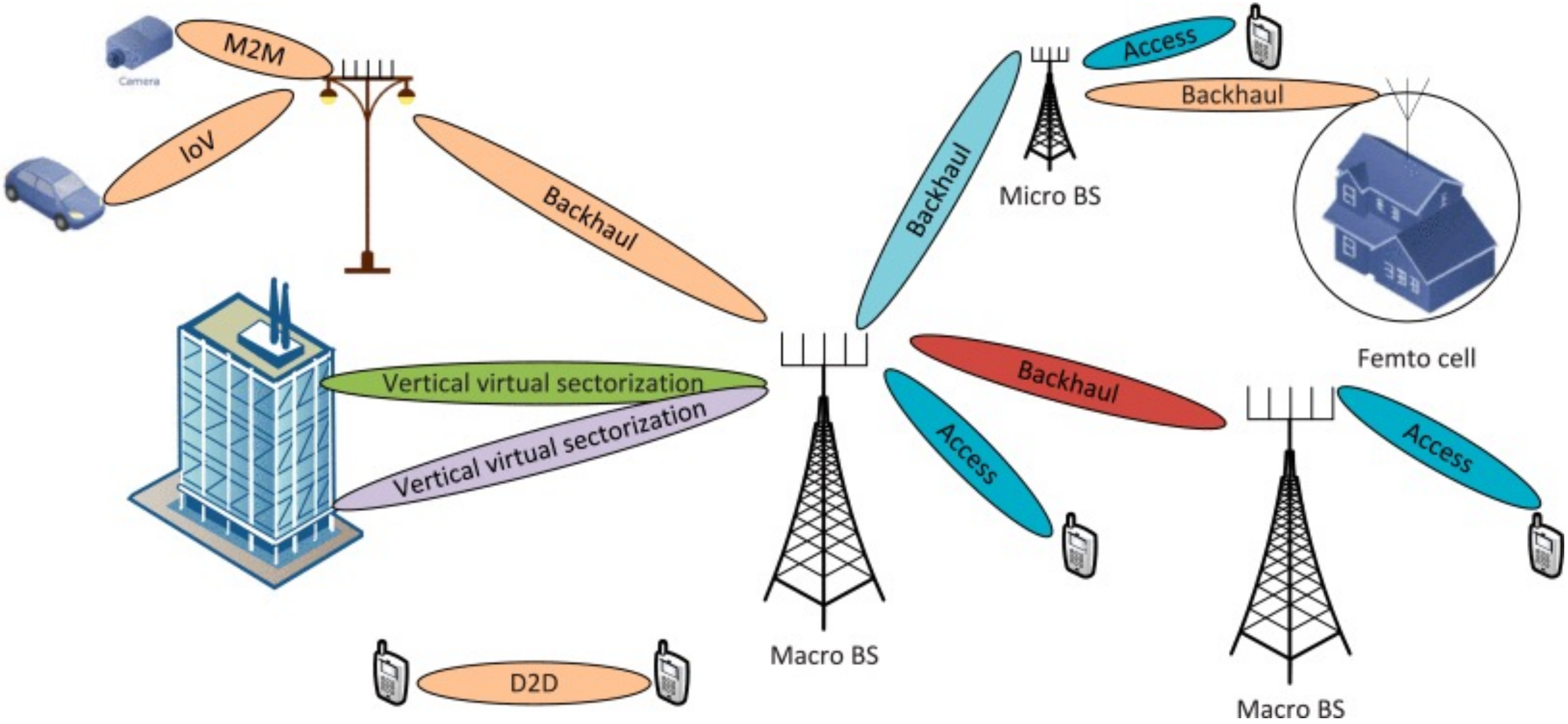
The Advanced Wireless Research Initiative will sustain United States leadership in wireless communications and tech and development.

The National Science Foundation's (NSF) leadership of this Initiative has three intertwined components:

- Establishing **platforms for advanced wireless research** enabled by a new industry consortium and engagem
- Supporting **fundamental research enabling advanced wireless technologies**; and
- Catalyzing **academic, industry, and community leaders** to work together to prototype innovative wireless app

These efforts will provide new insights capable of making wireless communication faster, smarter, more responsive, a

mmWave Massive MIMO Beamforming



mmWave Wireless Applications

5G Cellular Networks

Wireless Data Centers

Wireless LANs 802.11ad

Wireless Virtual/ Augmented Reality

Connected Vehicles

Gesture Recognition

Challenges

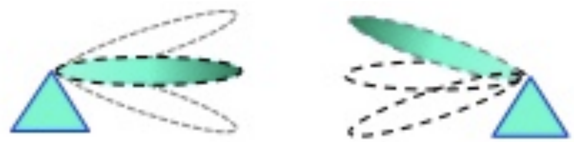
- Directional communications
- Shadowing
- Channel fluctuation
- Multiuser coordination
- Power consumption

Directional Transmissions

- Path loss grows with the square of the frequency

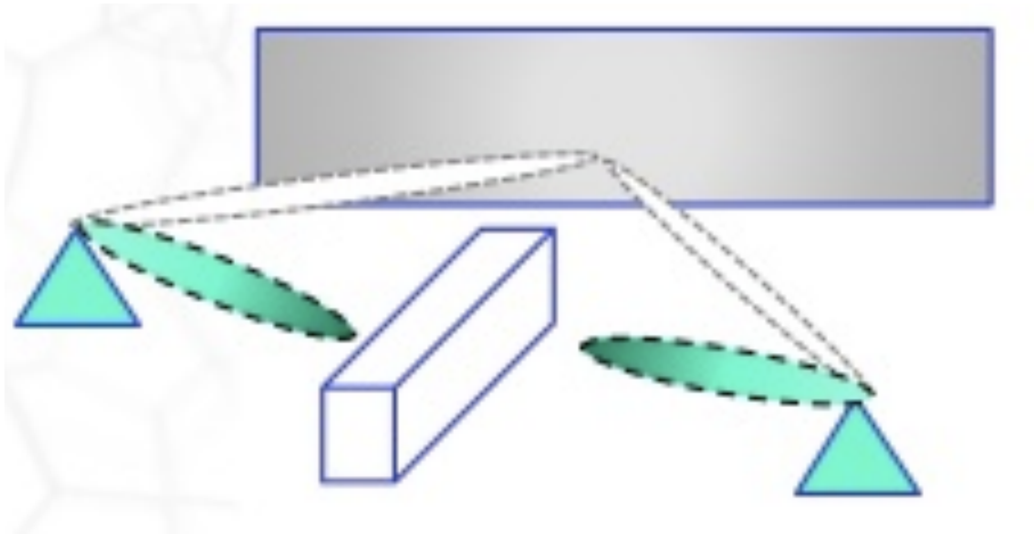
$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi R}\right)^2$$

- Small wavelength → Large path loss → Short transmission range
- Leverage antenna array and beamforming to steer directional beam with a stronger power
- Deafness occurs when the main lobes at both Tx and Rx do not point to each other



Shadowing

- mmWave signals are extremely susceptible to shadowing
  - High penetration loss due to obstacles
  - Brick can attenuate signals by as much as 40–80 dB

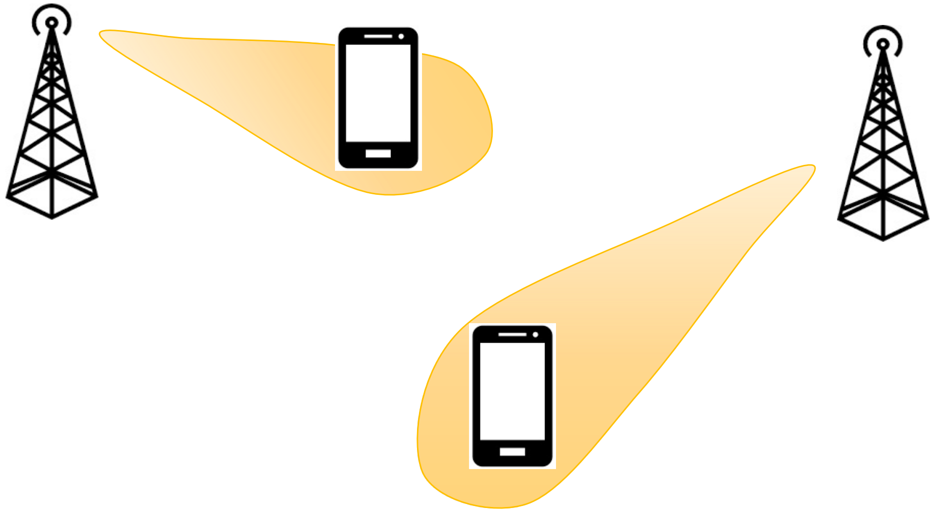


Channel Fluctuation

- For a given mobile velocity, channel coherence time is linear in the carrier frequency → higher frequency, shorter coherence time
  - Connectivity will be highly intermittent and communication will need to be rapidly adaptable
  - Channel estimation should be performed frequently → large overhead

Multiuser Coordination

- Directional transmissions imply more spatial reuse opportunities



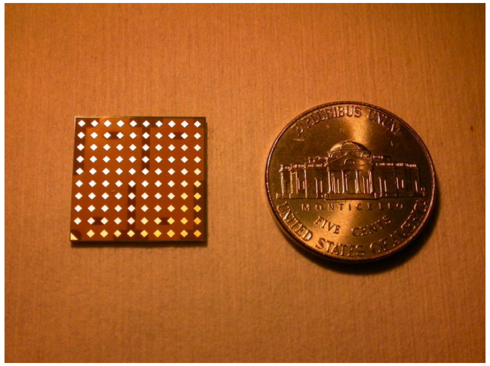
- Challenges
  - How to locate users?
  - How to quickly switch the beam directions and widths?

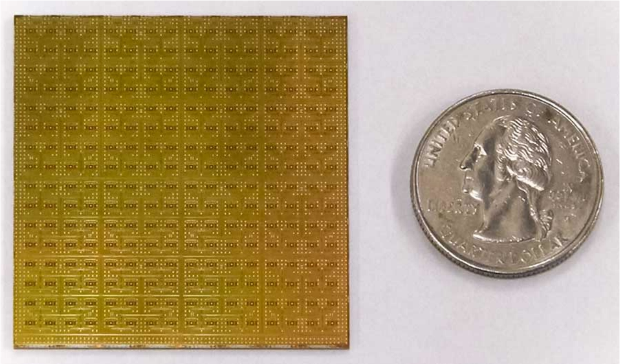
Power Consumption

- Power consumption generally scales
  - linearly in the sampling rate
  - exponentially in the number of bits per samples
- Hard to achieve high-resolution quantization at wide bandwidths and large numbers of antennas
- Efficient RF power amplification and combining will be needed for phased array antennas

Phase Array

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



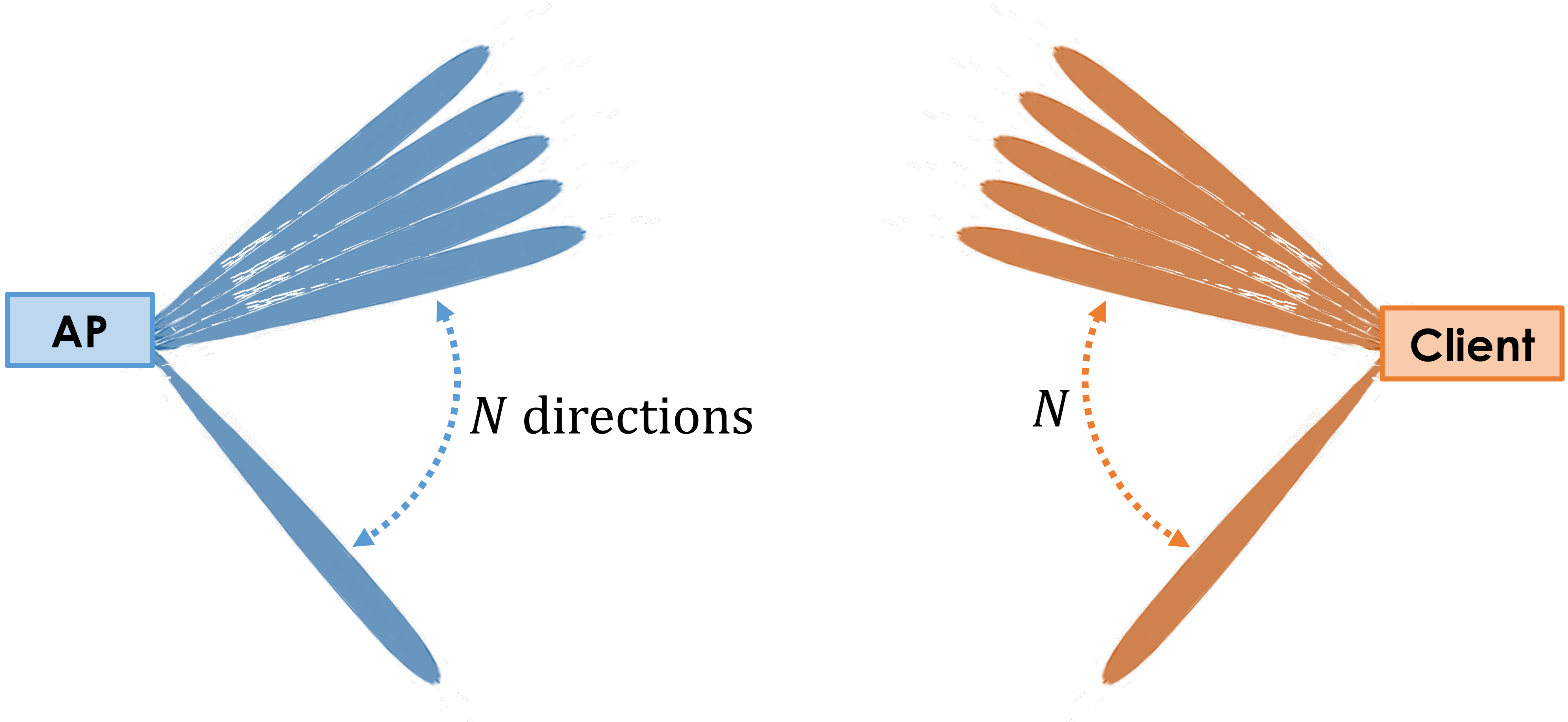


Small Wavelength enables thousands of antennas to be packed into small space

Analog beamforming
→ Extremely narrow beams

Beam Searching

N : number of possible directions



Naïve solution: Exhaustive search

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

802.11ad: Multi-Stage Scan

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

802.11ad: Multi-Stage Scan

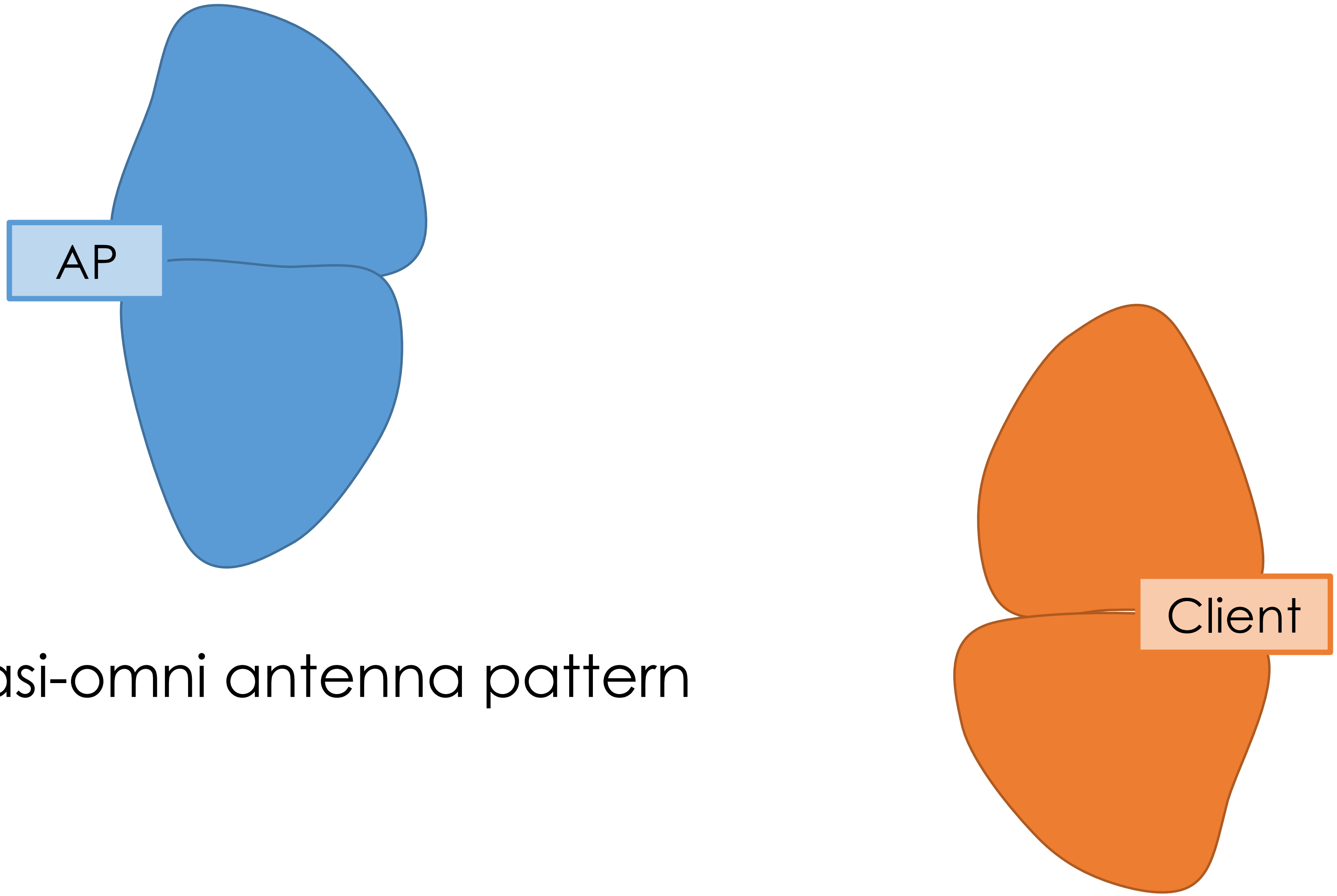
- Stage 2: AP uses omni directional; client scans directions

O(N) Beacon Packets

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

Hierarchical Scanning

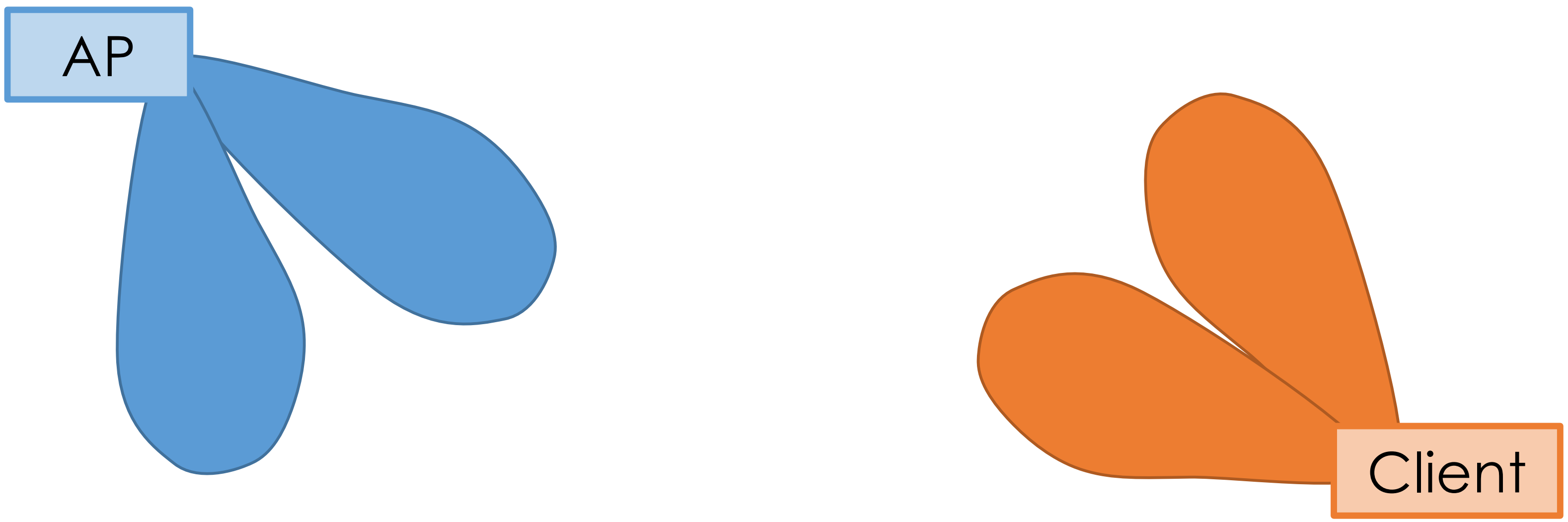
- Iteratively reduce the size of lobes as scanning



quasi-omni antenna pattern

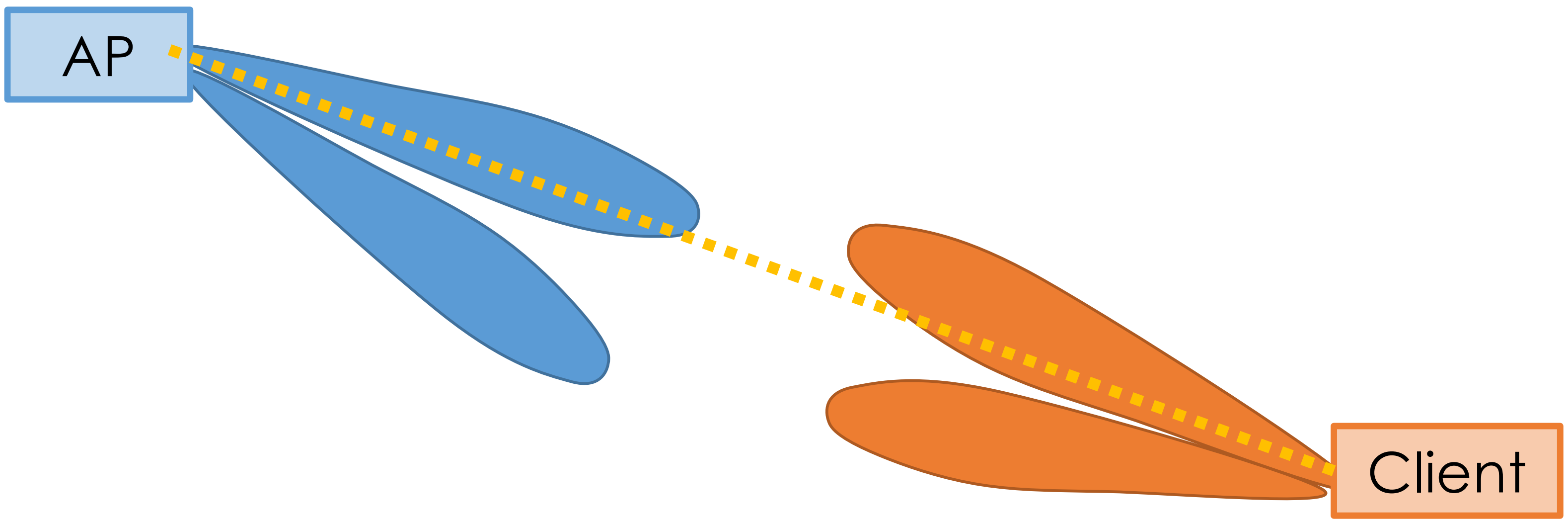
Hierarchical Scanning

- Iteratively reduce the size of lobes as scanning



Hierarchical Scanning

- Iteratively reduce the size of lobes as scanning
- Until the narrowest beam pointing to each other

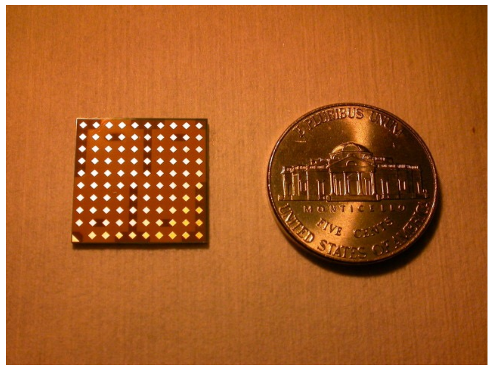


Open problem: wider beam → shorter range
How to avoid misdetection in the beginning?

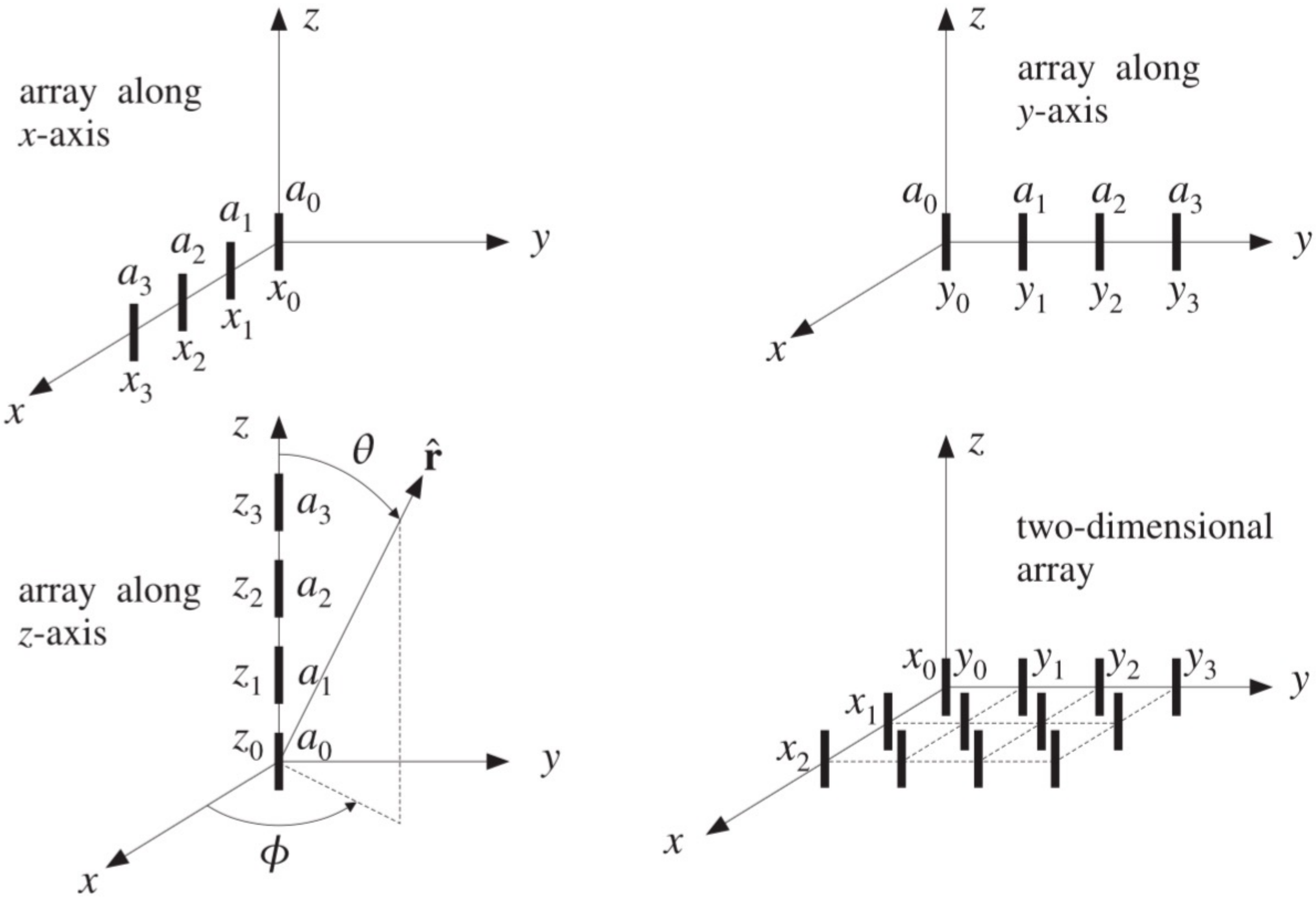
Analog Beamforming

Beam Steering

- Direct radiated power towards a desired angular sector
- Does not need to know the channel state information
- How? Phase array
  - By changing the phase of each antenna
  - Also known as switched-beam antenna or adaptive antenna
- Beam pattern is determined by
  - the number of antennas
  - the arrangement of antennas



Array Configuration

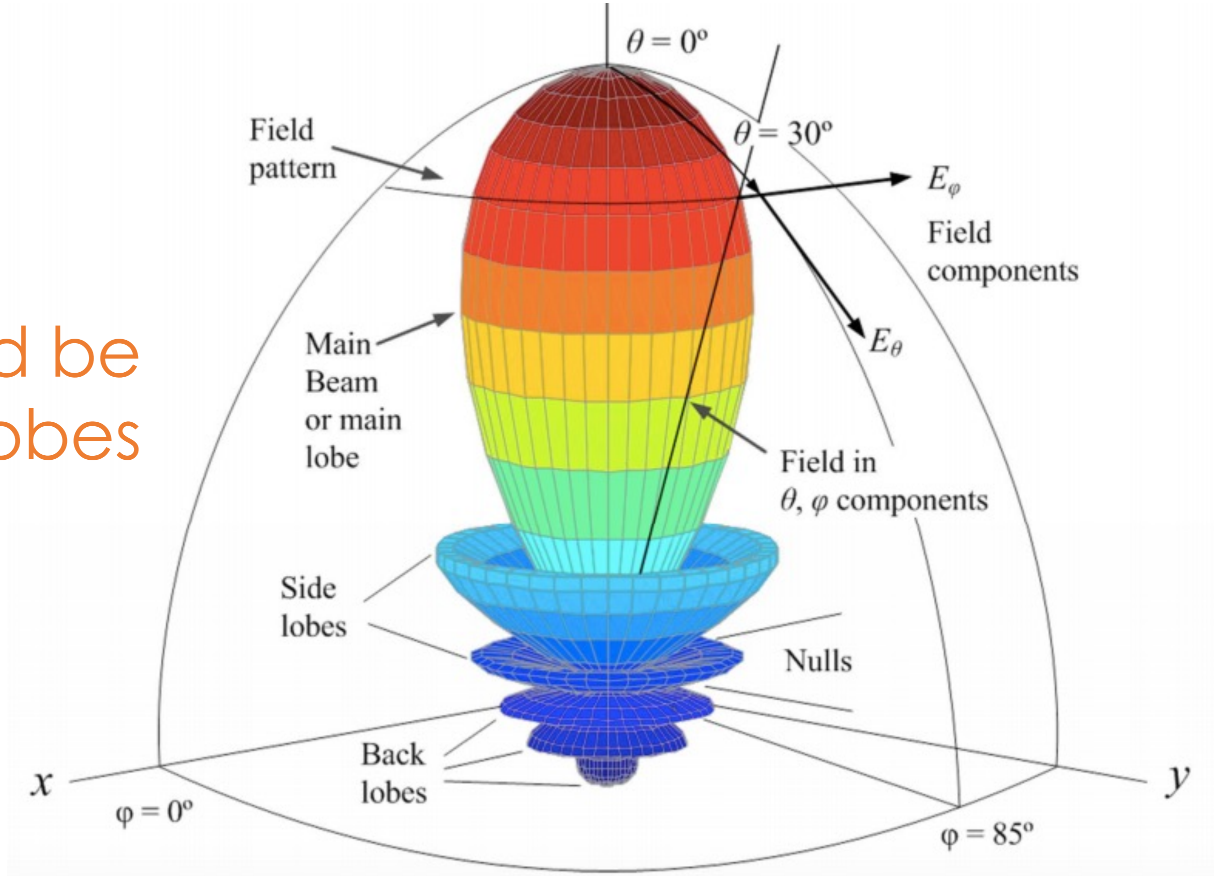


Can be 1D or 2D

Main lobe and Side lobe

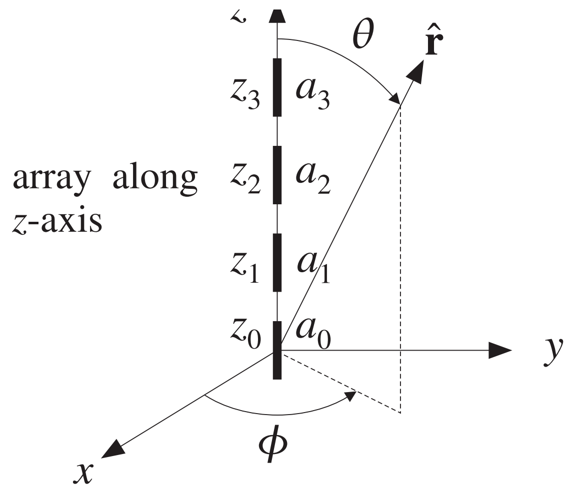
- Main lobe: the beam with the strongest power
- Side lobe: leakage power toward undesirable direction

There could be multiple side lobes



Reference: https://www.youtube.com/watch?v=V8bqxBywvjc

Array Factor



- φ: Azimuth angle
- θ: Zenith angle
- G(θ, φ): power gain of a signal toward (θ, φ)
- How to manipulate the gain?
  - Change the phase of each antenna via a phase shift a_i

$h_1 + h_2 + \cdots + h_N$ Original channel

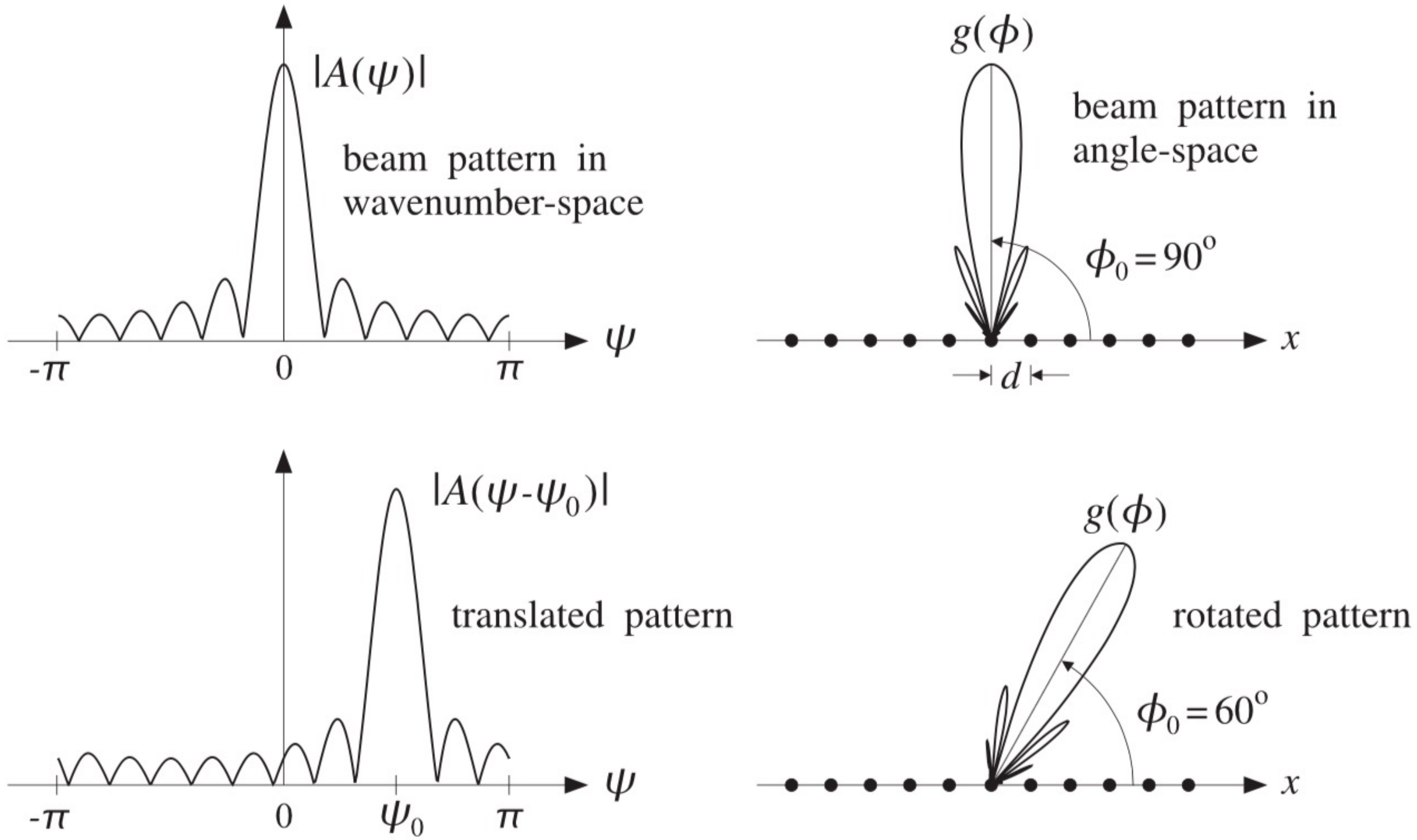
$a_1 h_1 + a_1 h_2 + \cdots + a_N h_N$ Channel of steering signals

$$\boxed{h = e^{-2j\pi f t} \leftrightarrow ah = e^{-2j\pi f t} * e^{\delta} = e^{-2j\pi f t + \delta}}$$

G(θ, φ) is independent of the original channel *h*

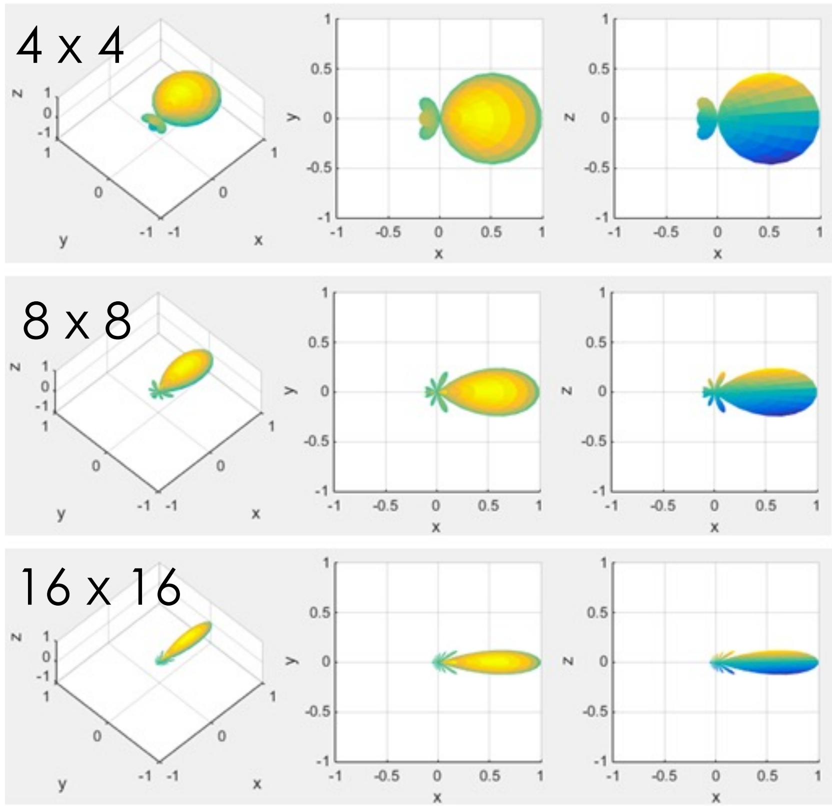
Array Steering

- Change the direction of the main lobe by channel the array factor A
- Usually, A can only be selected from a fixed-sized codebook (limited number of directions)



Beam Width

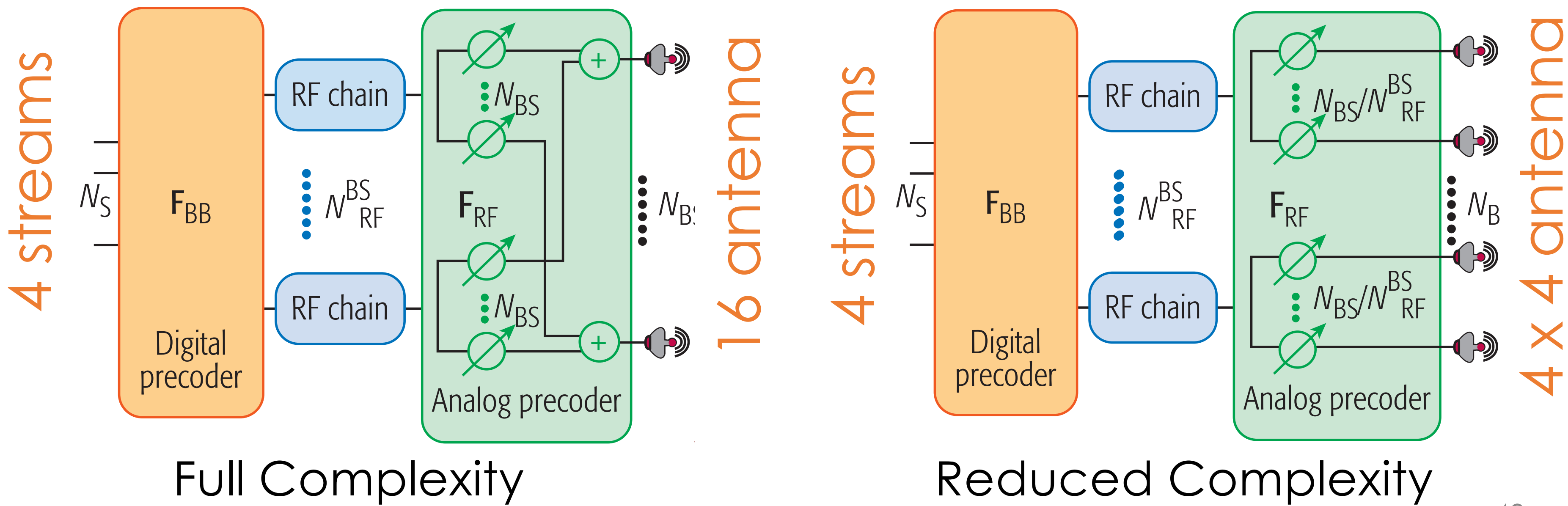
- The more antennas we have, the narrower beam we can generate
  - Intuition: more array factors *a* we can control to get a better resolution



Hybrid Beamforming

Hybrid Beamforming Structure

- Combine digital beamforming with analog beamforming
- Number of streams = number of RF chains
  - RF chains (e.g., ADC/DAC) are power consuming)
- Each stream is further steered by phased array antennas using analog beamforming



Hybrid Beamforming Model

Analog beamforming matrix

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

Digital beamforming matrix

Identify a analog beam and digital precoder W such that

$$\mathbf{F}\mathbf{H}\mathbf{W} = G(\theta, \phi)\mathbf{I}$$