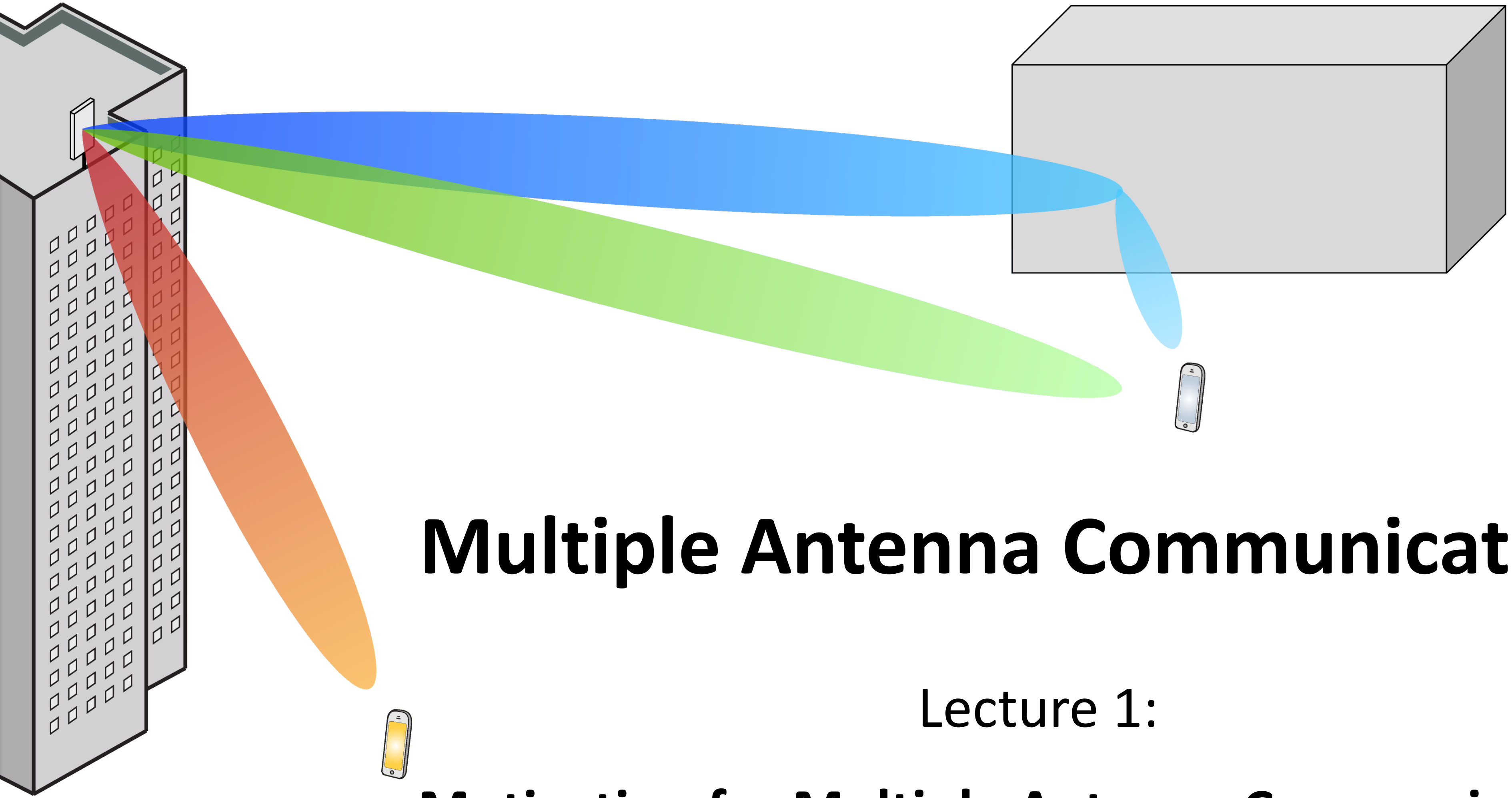


Multiple Antenna Communications

Lecture 1:

Motivation for Multiple Antenna Communications

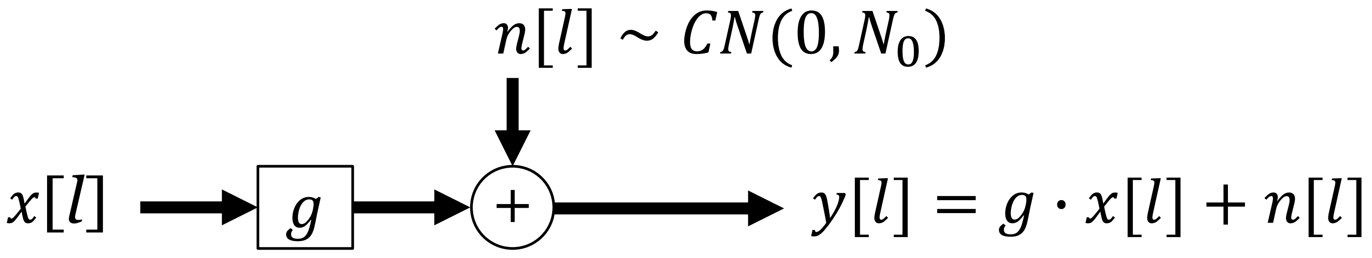
Emil Björnson

Outline

- Capacity dependence on power and bandwidth
  - Basic wave propagation and antennas
  - Frequency bands

- Three ways that multiple antennas improve wireless communications

Discrete memoryless channel



- Assumptions:
  - B symbols per second (B = bandwidth)
  - Signal power P Watt, energy per symbol $q = P/B$

Channel capacity depends on P and B:

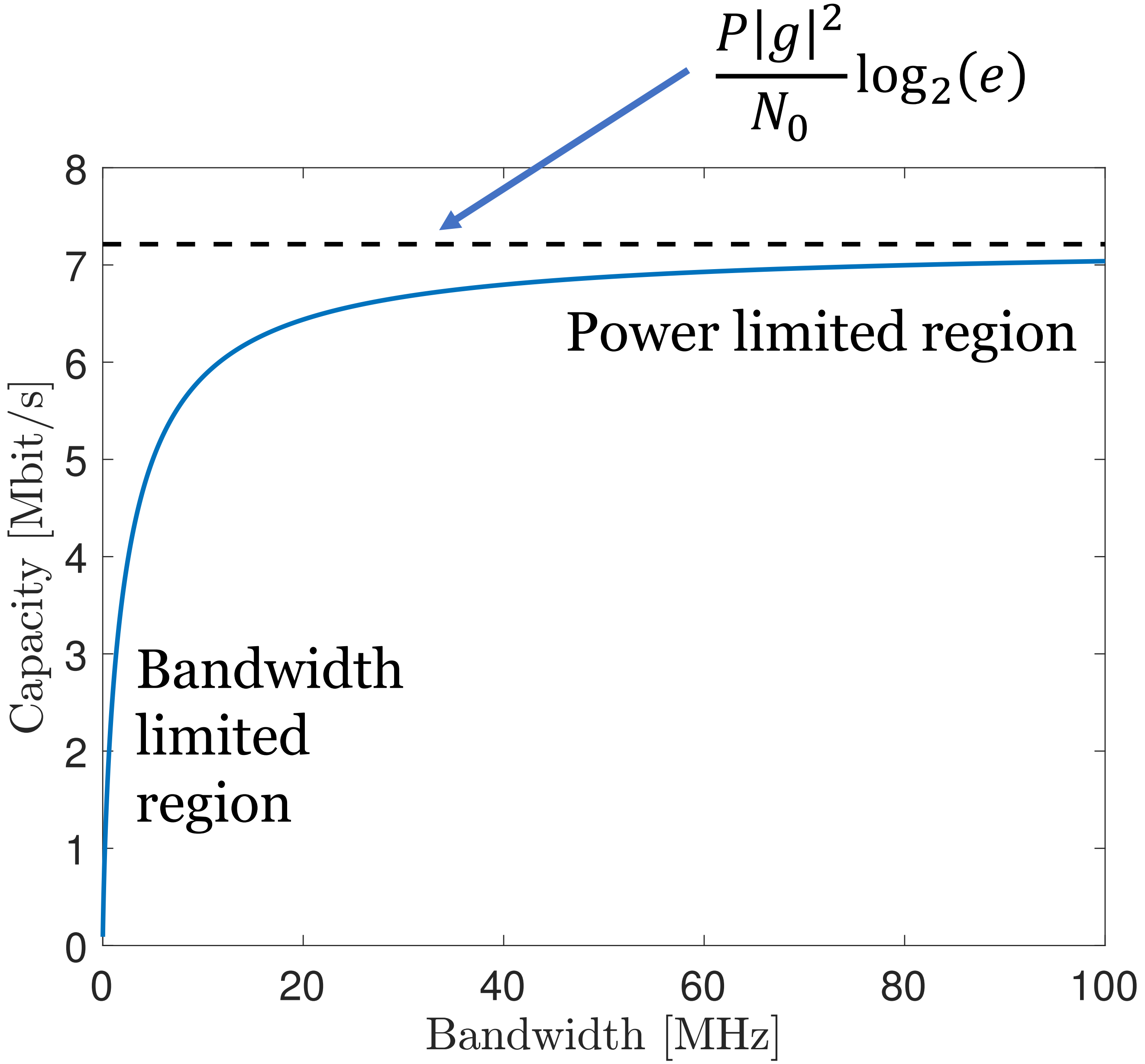
$$C = B \cdot \log_2\left(1 + \frac{P|g|^2}{BN_0}\right) \text{ bits per second}$$

Capacity behaviors

- Signal-to-noise ratio (SNR):
$$\frac{P|g|^2}{BN_0}$$

- $B\log_2(1+\mathrm{SNR})$
  - Linear for small SNR
  - Almost flat for large SNR

Assumption: $\frac{P|g|^2}{N_0} = 5 \cdot 10^6$ Hz

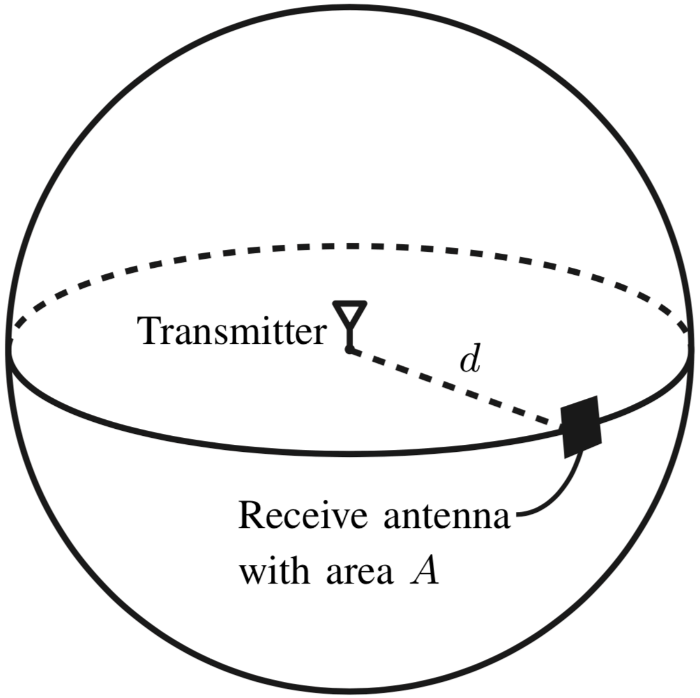


Basic wave propagation

- Electromagnetic waves travel at speed of light
  - Spreads out in all directions

- Friis' propagation formula:

$$\text{Receive power} = \text{Transmit power} \cdot \frac{A}{4\pi d^2}$$



Example: $A = \frac{\lambda^2}{4\pi}$, $\quad \frac{A}{4\pi d^2} = \left(\frac{\lambda}{4\pi d}\right)^2$

$\lambda = 0.1$ m (3 GHz)
0.006% received at 1 m $\quad (-42$ dB$)$
0.00006% received at 10 m $\quad (-62$ dB$)$

Only a tiny fraction of transmit power is received!

Different types of antennas

- Channel capacity $B \cdot \log_2(1 + \text{SNR})$

$$\text{SNR} = \frac{P}{BN_0}|g|^2$$

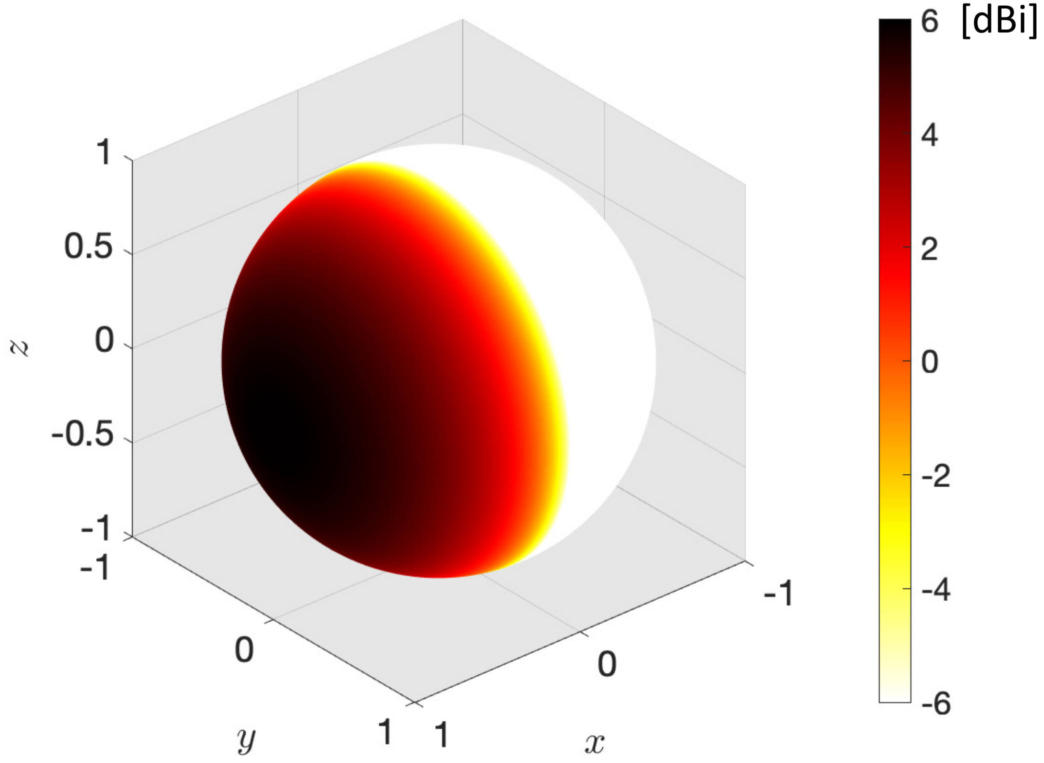
  - Omni-directional (isotropic) antennas:

$$|g|^2 = \left(\frac{\lambda}{4\pi d}\right)^2$$

  - Directive antennas:

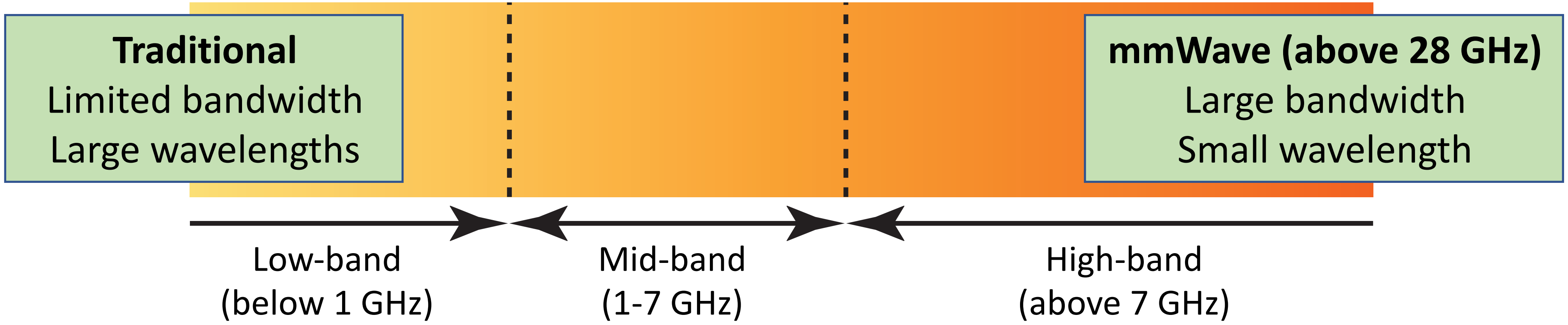
$$|g|^2 = \left(\frac{\lambda}{4\pi d}\right)^2 G_t\underbrace{(\text{angle})}_{\text{to receiver}} G_r\underbrace{(\text{angle})}_{\text{to transmitter}}$$

Example:



Effective area: $A = \left(\frac{\lambda}{4\pi d}\right)^2 G$

Frequency spectrum in wireless communications



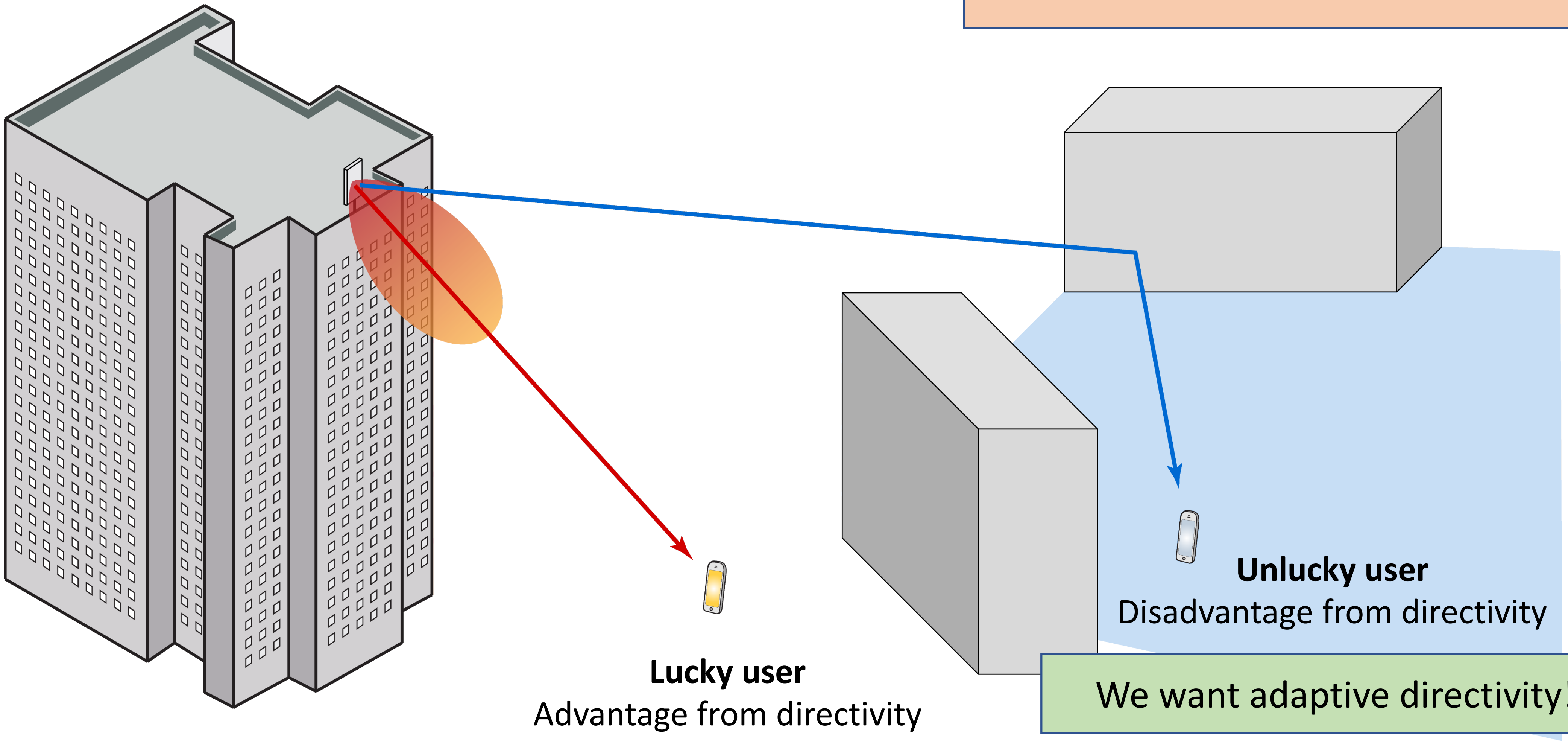
- Approximate size of an isotropic antenna
  - Low-band (800 MHz): 1 dm x 1 dm
  - Mid-band (3 GHz): 3 cm x 3 cm
  - High-band (30 GHz): 3 mm x 3 mm

Directive antennas
in fixed infrastructure

Directive antennas
also in handheld devices

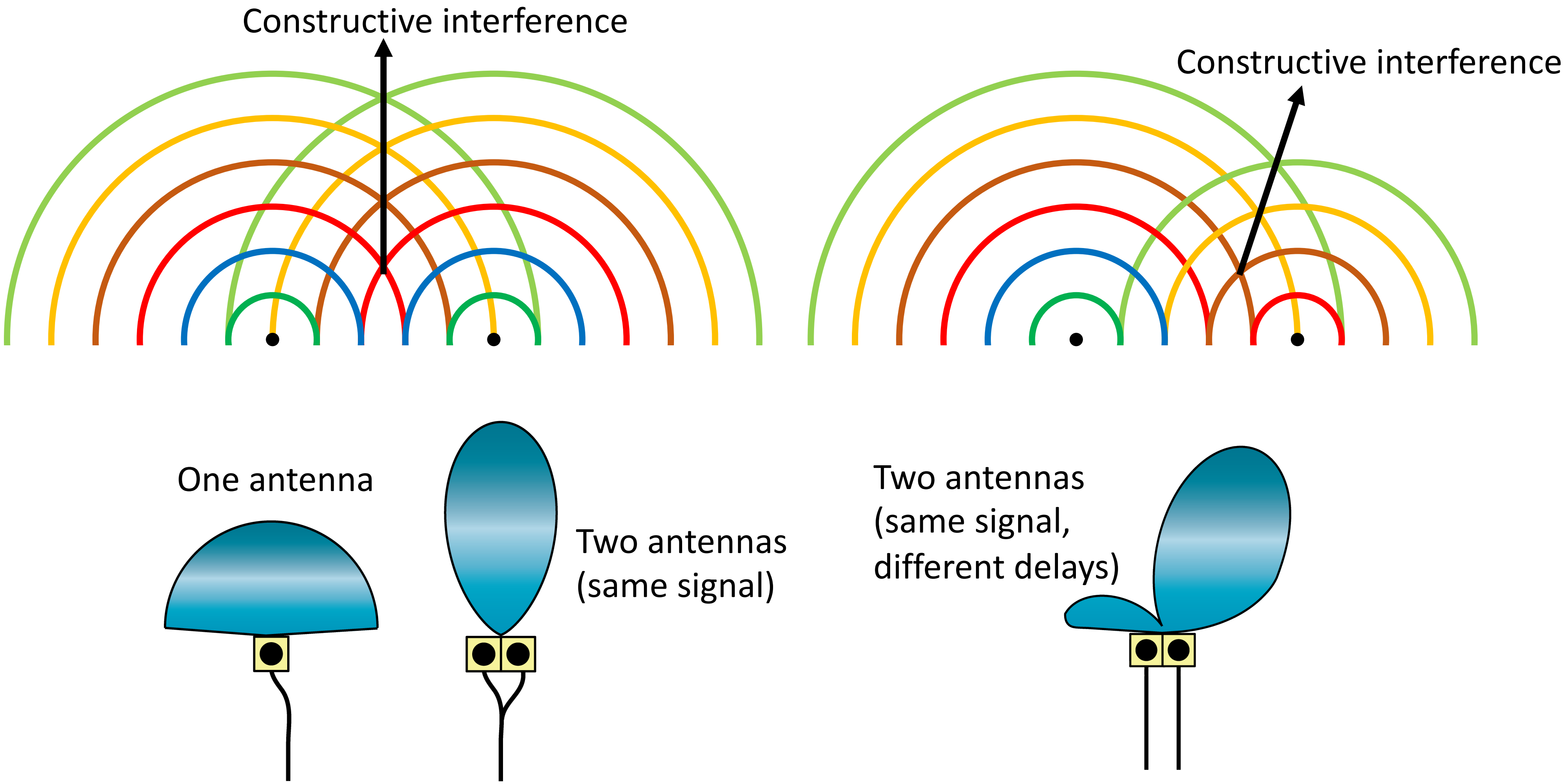
Mobile wireless communications

Directive antenna not useful in handset:



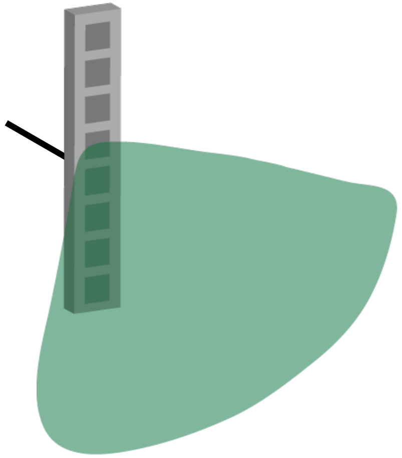
We want adaptive directivity!

How can we adapt directivity?



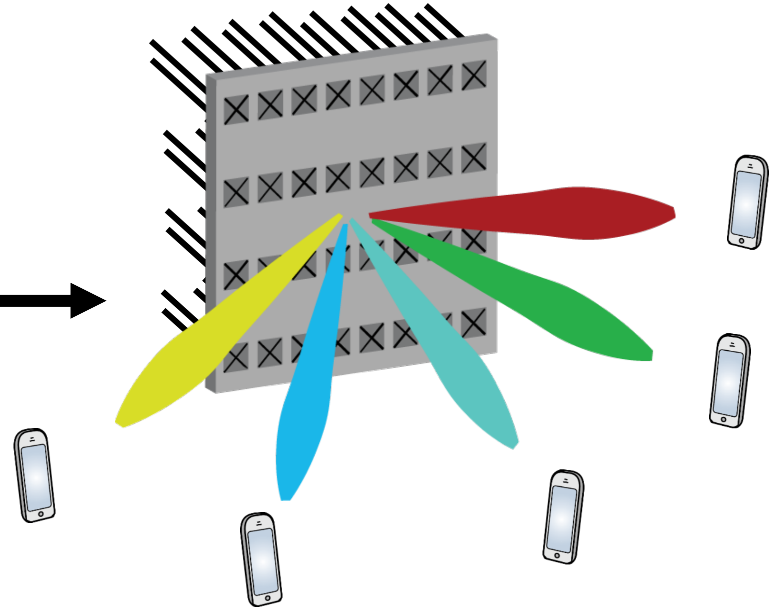
From passive antennas to active antenna arrays

1 strongly directive antenna



Passive antenna
Constant directivity

64 weakly directive antennas



Active antenna array
Antenna-integrated radios
Strong but *adaptive* directivity
Multiple directions at same time

Three main benefits of multiple antenna communications

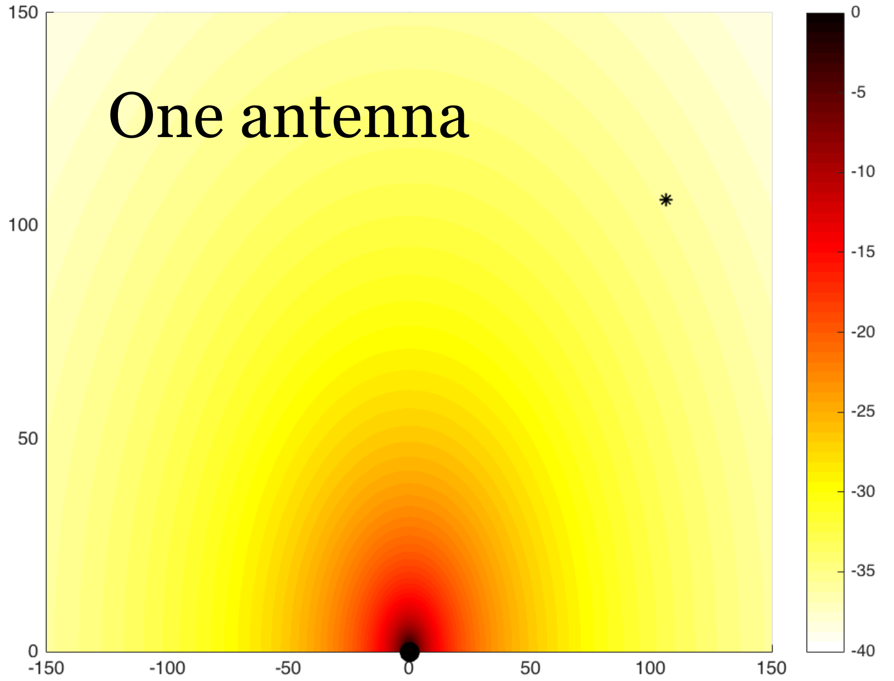
1. Beamforming gain
2. Spatial diversity
3. Spatial multiplexing

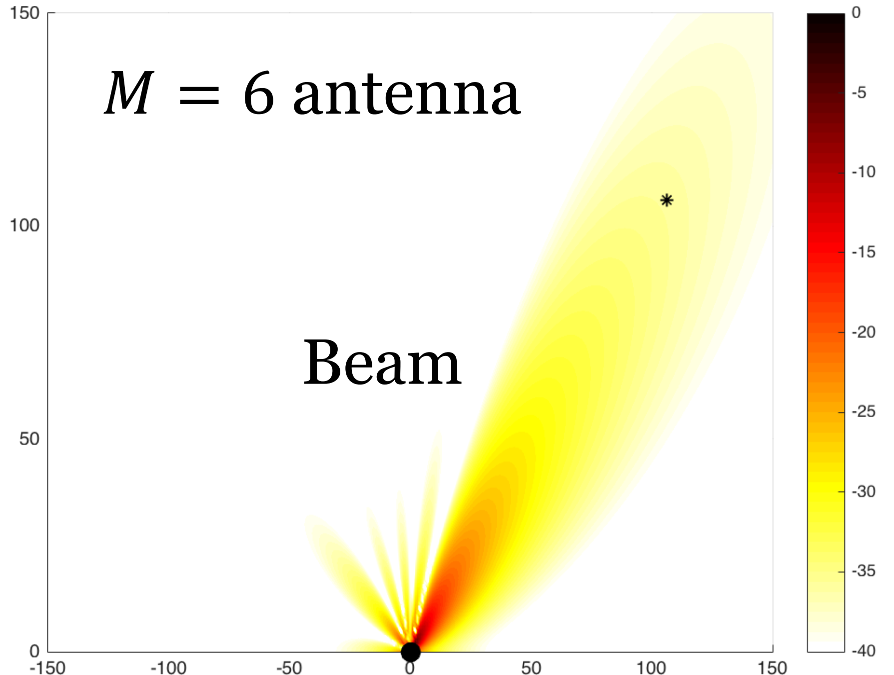
The course will cover all of them:

- First historical perspective
- Then the theory behind them

Adaptive beamforming

- Power directed towards receiver
  - Constructive interference
  - Send signals with time delays
  - Needs to know "direction"





We can use directivity in any band

Two options:

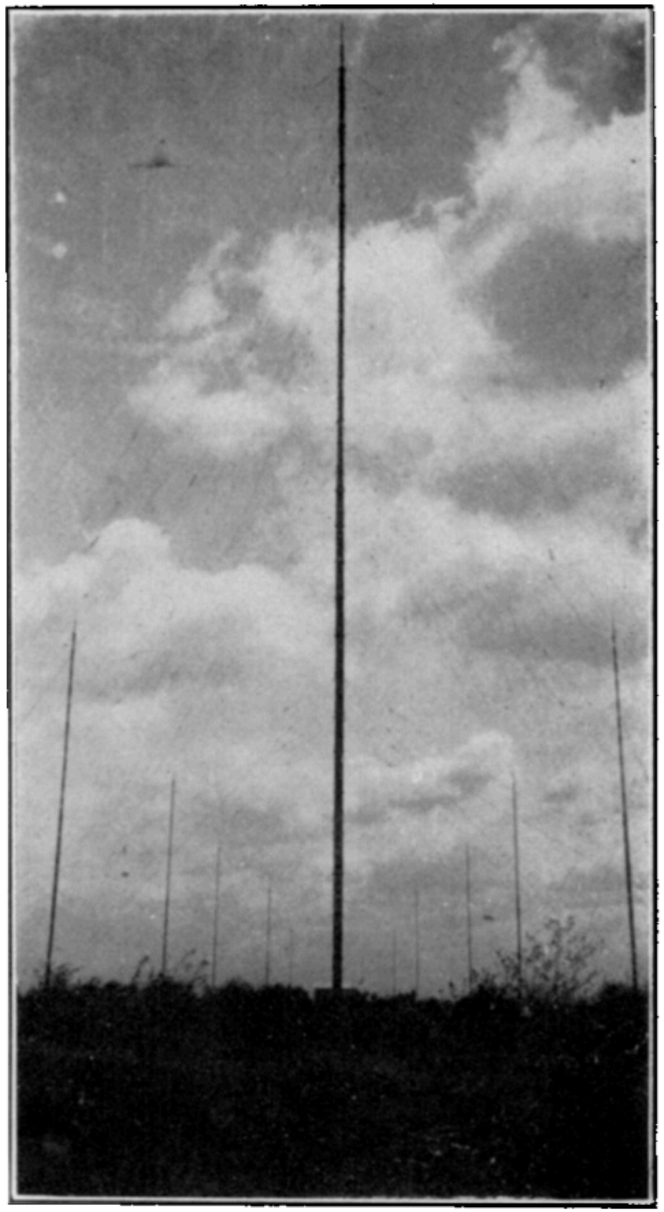
- M times larger received power
- Use $1/M$ of power to achieve same received power

History: Beamforming

- Directional communication
  - E.F.W. Alexanderson, ”Transatlantic Radio Communication”, Trans. AIEE, 1919.

- Directive radiation pattern
  - Constructive/destructive interference patterns
  - Energy savings or better performance

Called *beamforming gain*



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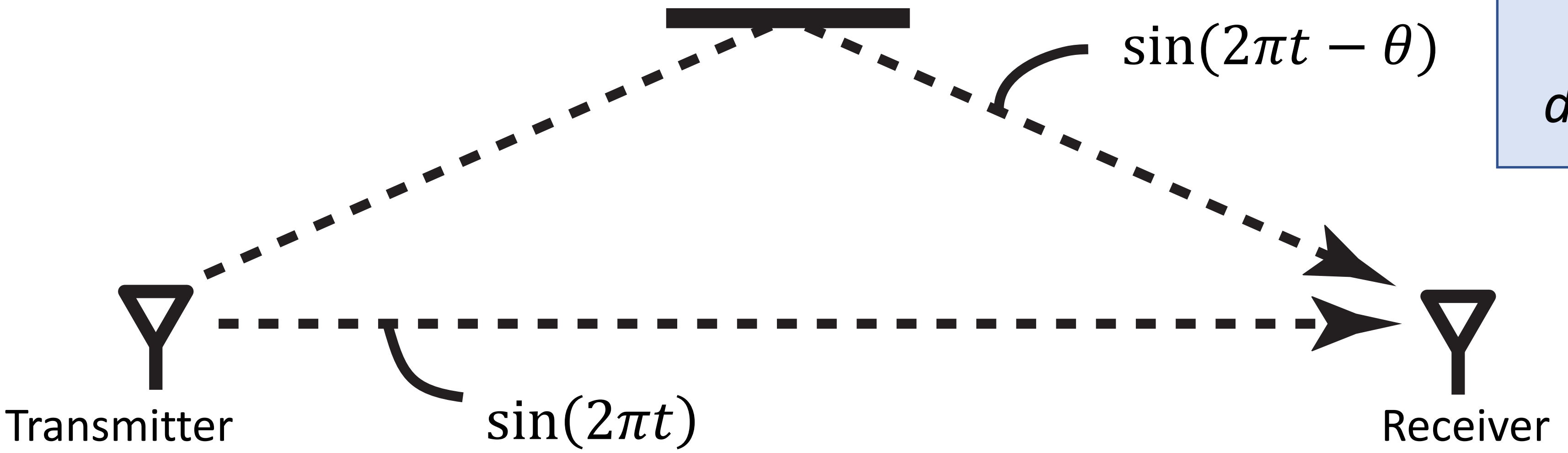
Multipath Propagation



Add construtively or destructively depending on θ

Received signal: $\sin(2\pi t) + \sin(2\pi t - \theta) = \underbrace{2\cos\left(\frac{\theta}{2}\right)}_{\text{Amplitude from 2 to 0}} \sin\left(2\pi t - \frac{\theta}{2}\right)$

History: Spatial diversity

- Diversity combining
    - D.G. Brennan, “Linear diversity combining techniques,” Proc. IRE, 1959

- Protect against fading/noise
    - Multiple antennas with independent observations
    - Small risk multiple observations are all bad
    - Improve reliability

Called *diversity gain*

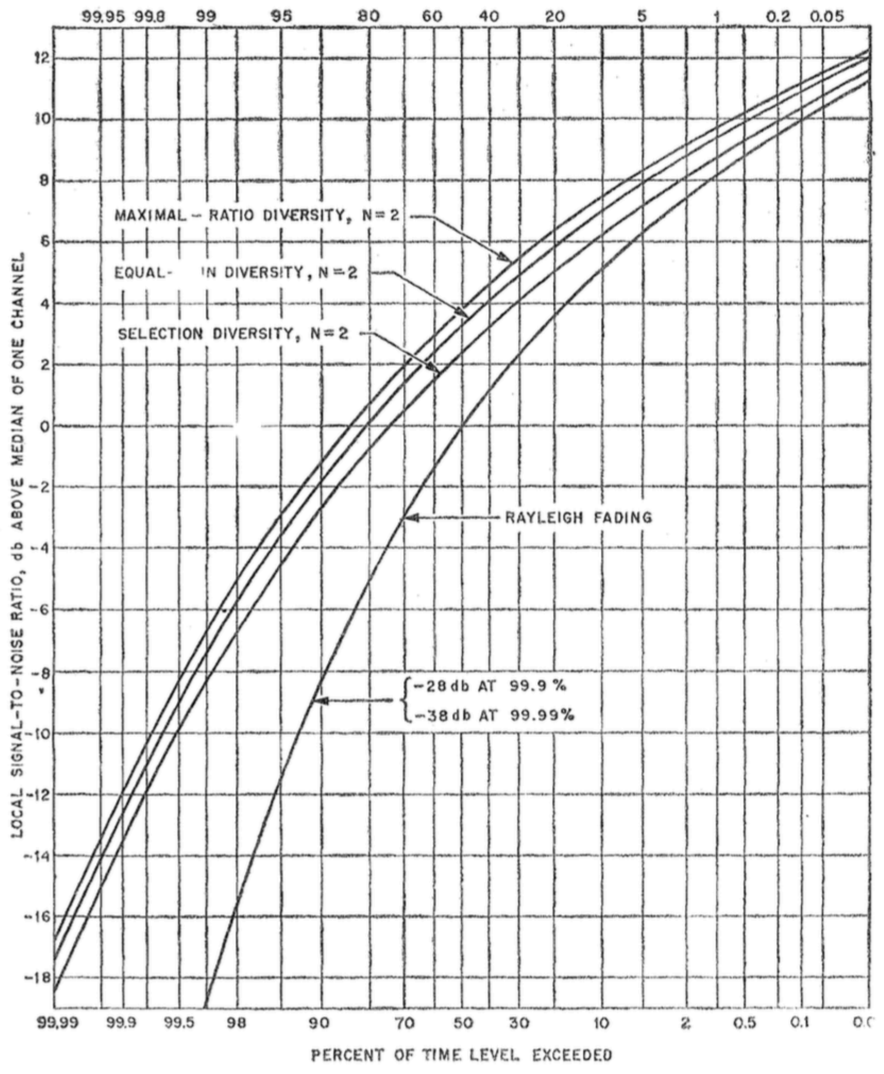
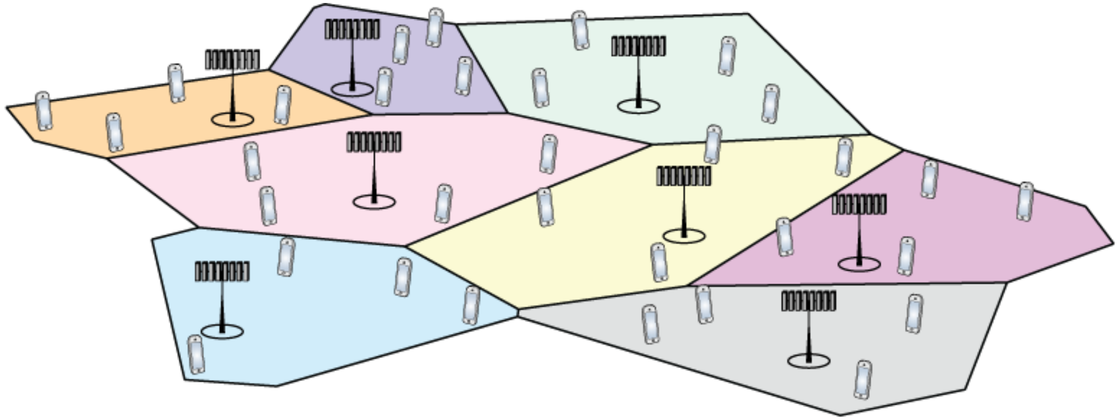
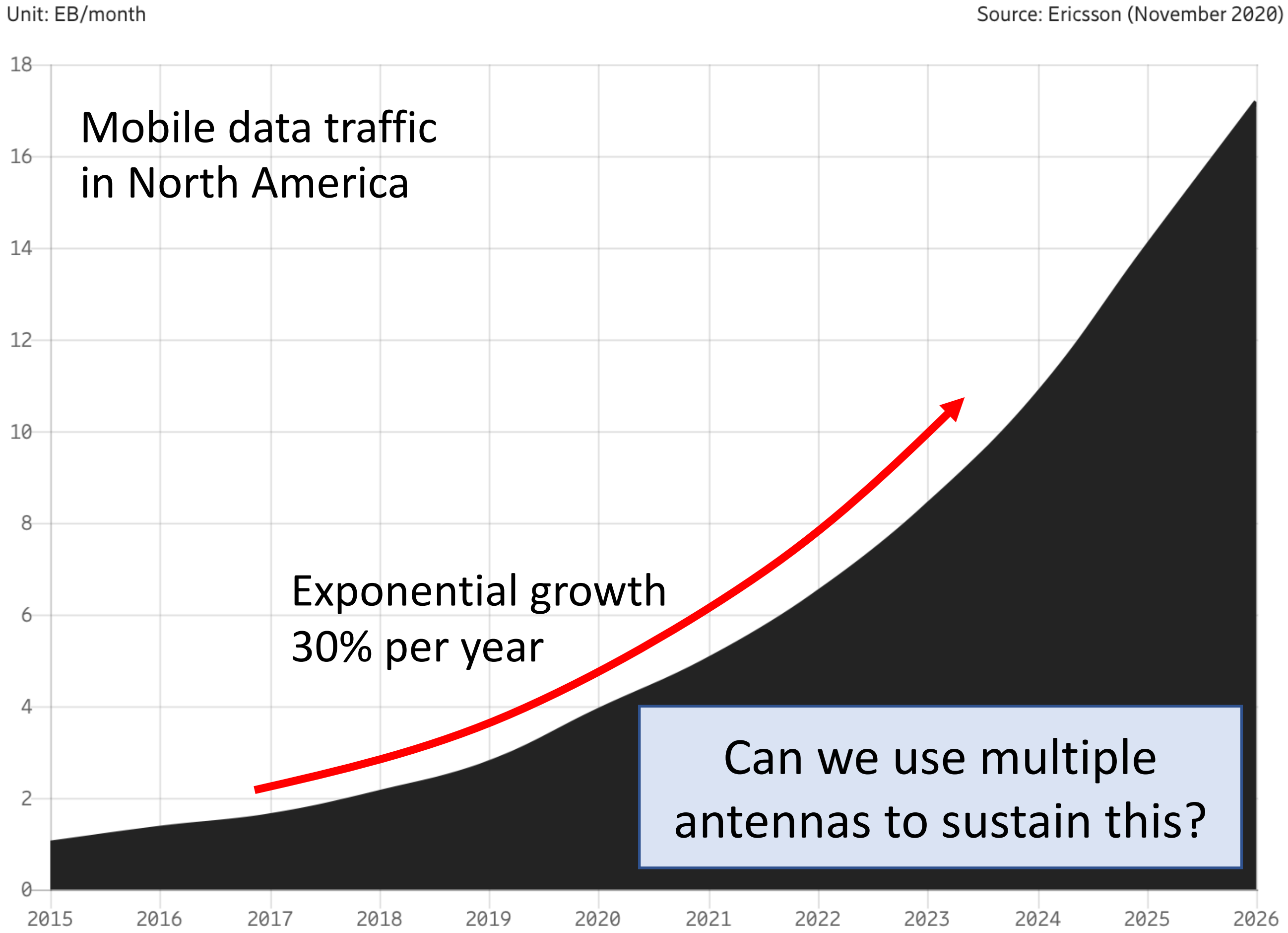


Fig. 9—Dual diversity distributions, conditions of Fig. 8.

Cellular networks

- Designed for mobile telephony
  - Bullington, K. (1953). “Frequency economy in mobile radio bands”. The Bell System Technical Journal.
  - Schulte, H. J. and W. A. Cornell (1960). “Multi-area mobile telephone system”. IEEE Trans. Veh. Technol.
- Reuse of spectrum in space:
  - Densify as usage increases
  - Control interference by fractional spectrum reuse, power control





History: Space division multiple access (SDMA)

- Multiple user communication
  - S. C. Swales et al., “The Performance Enhancement of Multibeam Adaptive Base-Station Antennas for Cellular Land Mobile Radio Systems” Trans. on Vehicular Technology, 1990.
- Spatial multiplexing of users
  - Serve multiple users on same time and frequency
  - Handle more users per base station
  - Supported by 4G, 5G and Wi-Fi 5, 6

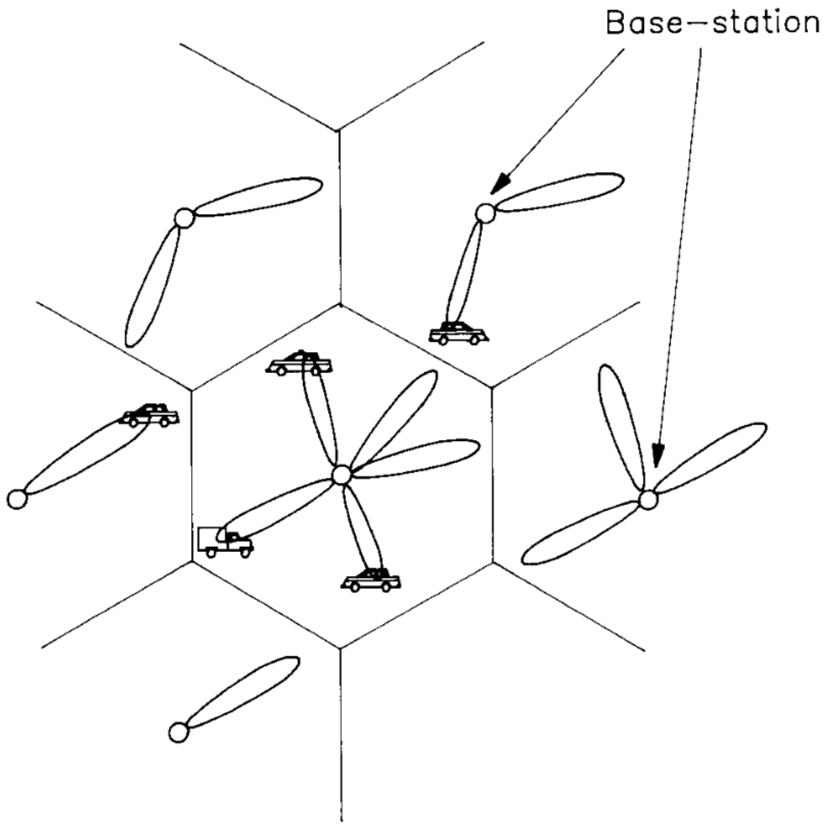


Fig. 2. Tracking of mobiles with multiple beams.

Called *multiplexing gain*

History: Point-to-point multi-antenna links

- Point-to-point multiple-input multiple-output (MIMO)
  - G. G. Raleigh and J. M. Cioffi, "*Spatio-temporal coding for wireless communications*," Globecom 1996.

- Multiple streams per user
  - Increase capacity (bit/s) per user
  - Requires multiple paths
  - Supported by 4G, 5G and Wi-Fi 5, 6

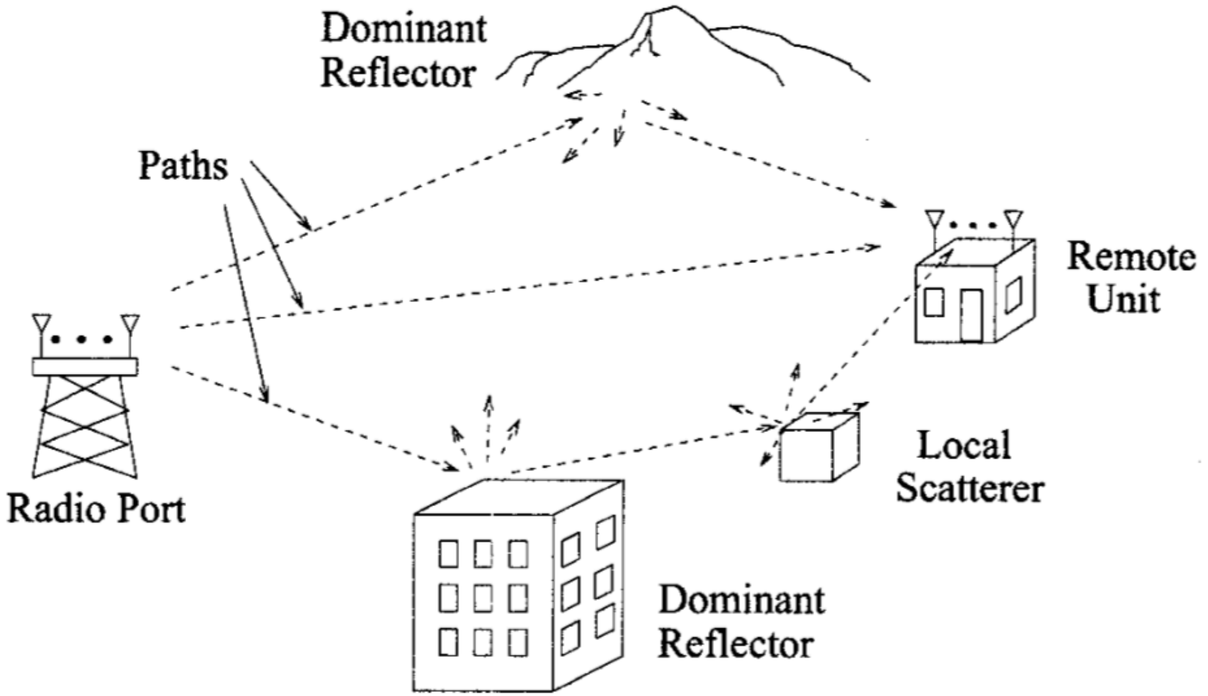


Figure 1: Illustration of the physical wireless channel.

Also called *multiplexing gain*

Outline of this course

- Lecture 1:
  - Motivation for multiple antennas
  - History of multiple antenna communications
- Basic multi–antenna channels (Lecture 2)
- Diversity and ergodic capacity (Lecture 3)
- Point-to-point MIMO (Lecture 4)

- Multi-user MIMO (Lectures 5-12)
  - Capacity bounds, Channel estimation, Power control, etc.

Based on the manuscript: “Introduction to Multiple Antenna Communications”

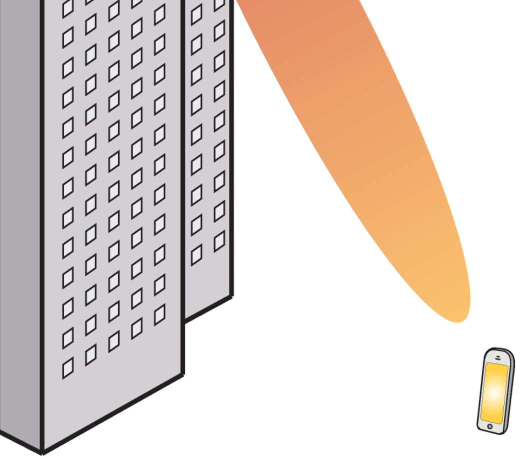
Based on the book “Fundamentals of Massive MIMO”

Summary

- Mobile communications require multiple antennas
  - Adaptive directive transmission (beamforming gain)
  - Mitigate channel fading (diversity gain)
  - Increase data rates (multiplexing gain)

- Useful in low-band, mid-band,
  and high-band spectrum

Multiple Antenna Communications



Lecture 1:

Motivation for Multiple Antenna Communications

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