# Wireless Communications Channels
# Lecture 10: Antennas and MIMO Systems

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# Antennas and Propagation for Wireless Systems

One important aspect is **how** the propagation channel and antenna(s) interact.

- The antenna **pattern** determines what the system sees!
- The delay and angular characteristics of the channel are **dependent** on the antenna pattern.

The user equipment (UE) will also naturally have a large influence on the behavior of the antenna, and therefore how it **sees** the channel.

- Change in the UE position will lead to change in the antenna pattern.
- Change in the antenna **pattern** leads to a change in the net **gain** and therefore, a change in the **efficiency** of the antenna!

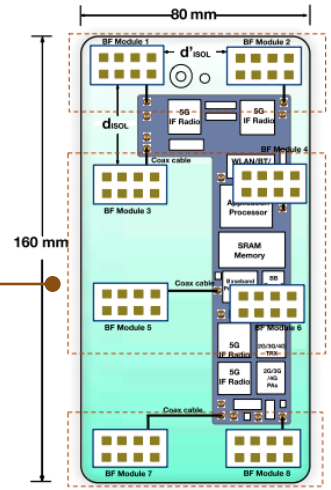
# Examples of Typical Antennas at TX and RX Link Ends

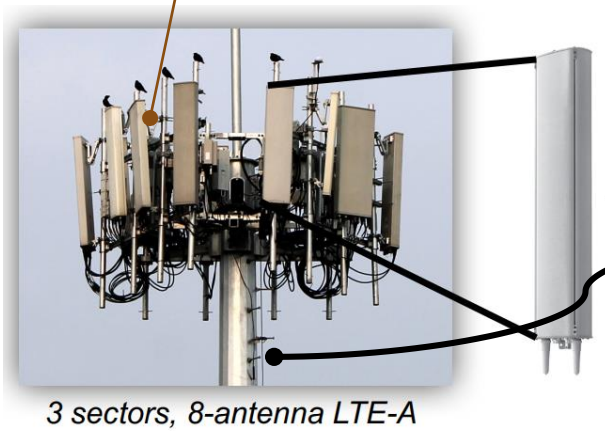
**Antennas and propagation interaction at the RX (UE):**

- Mock-up terminals (handsets, even laptops) with integrated antennas and casing
- Clearly influenced by the **local** scattering environments:
  - Mobility of the UE, mobility of the scatterers, surrounding environment (indoor vs. outdoor)

**At the TX side (consider a base station transmitting):**

- Type of installation – elevated on a tower, above the rooftop, or wall mounted.
- Obstacles or buildings near-by avoided but this gives rise to higher diffraction angles.




3 sectors, 8-antenna LTE-A

Courtesy: Ericsson AB, Sweden

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# Characterization of Antennas: Key Parameters

- **Directivity:** Total radiated power in a certain direction relative to the total transmitted power. Note that the gain and the directivity of an antenna are linked to each other.

- **Efficiency:** The efficiency of an antenna is a ratio of the power delivered to the antenna relative to the power radiated from the antenna.

- **Q-factor (a.k.a. quality factor):** Energy stored within the antenna compared to energy dissapated out of the antenna.

- **Mean effective gain:** Include influence of random channel. It is the average received power compared to average received power by isotropic antenna in real environment.

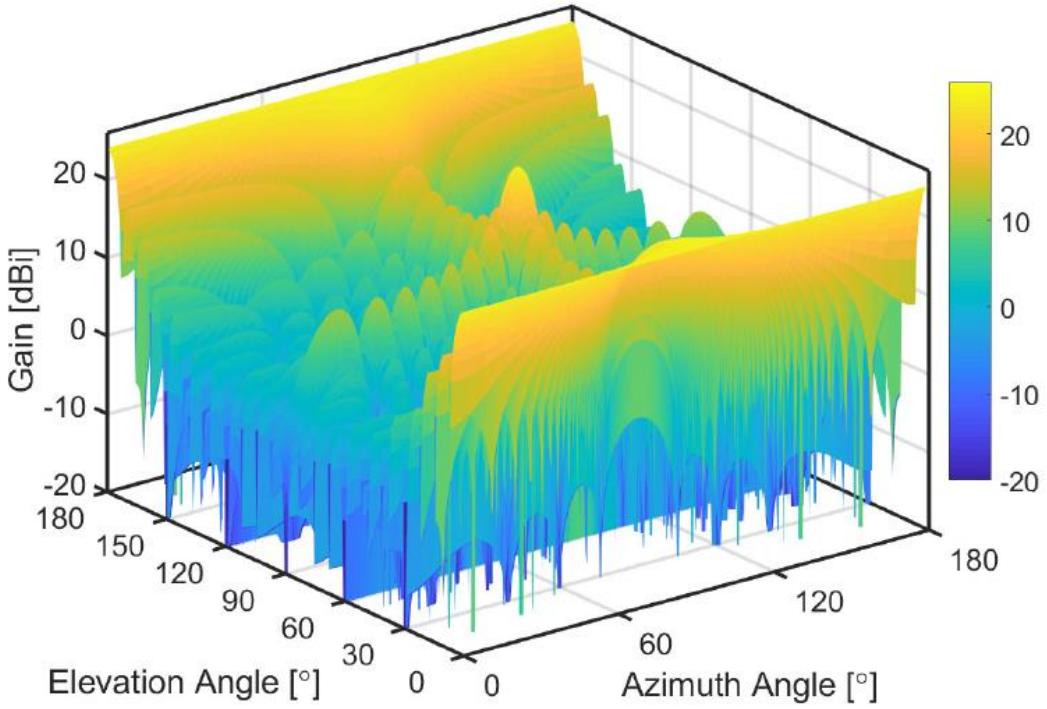
# 3D Antenna Radiation Patterns: A 5G Example

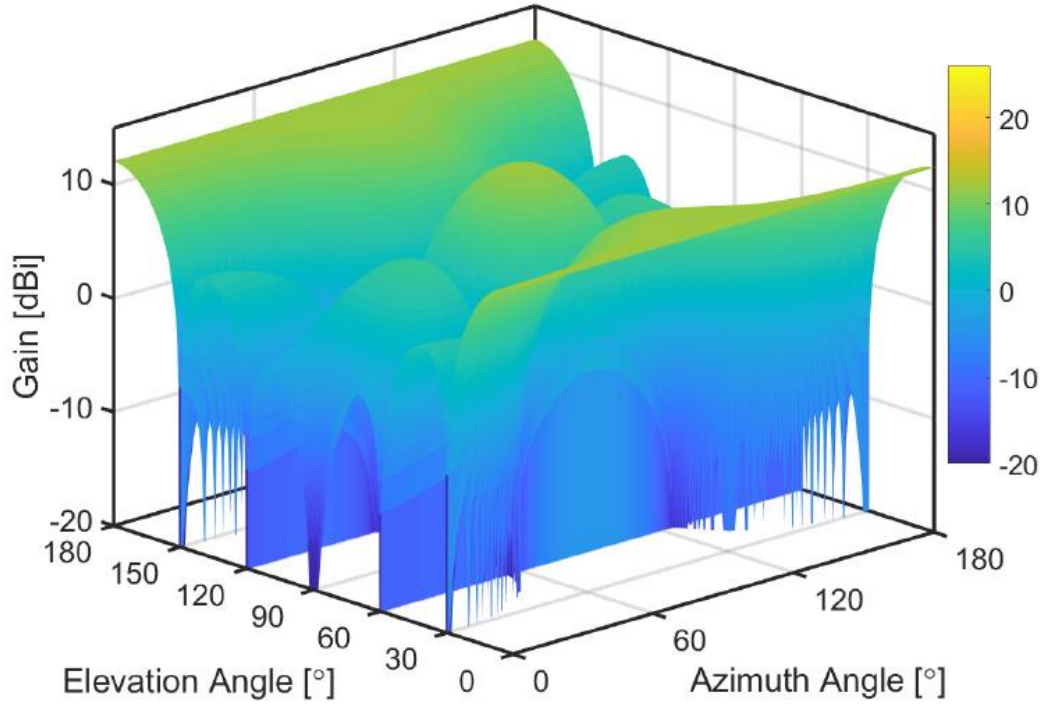
**BS: 16x16 cross-polarized UPA: 8(rows)x16(cols.)x2(pol.)**

- **Spacing:** λ/2 in azimuth, λ in elevation
- **Directional gain:** 8 dBi (per-element)
- **Half power beamwidth (HPBW):** 8° in azimuth and elevation.
- **Slant angle:** 45°

**UE: 4x4 cross-polarized UPA: 2x4x2**

- **Spacing:** λ/2 spacing in azimuth, λ in elevation
- **Directional gain:** 9 dBi (per-element)
- **HPBW:** 63° in azimuth and 32° in elevation.
- **Slant angle:** 45°

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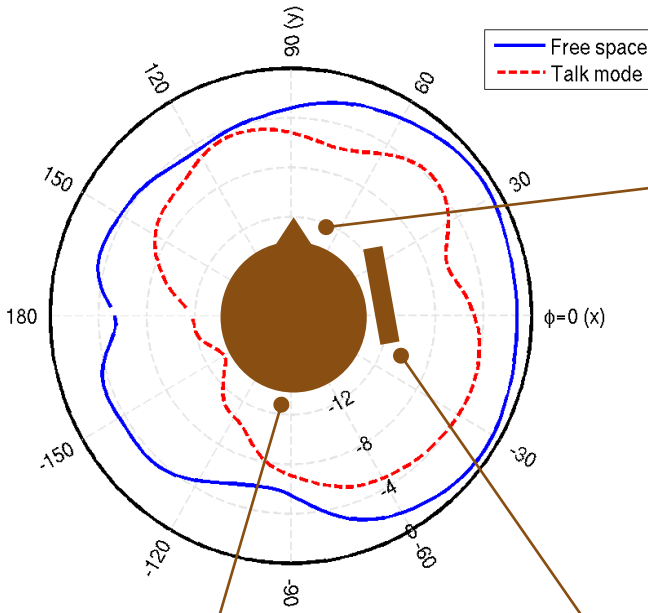
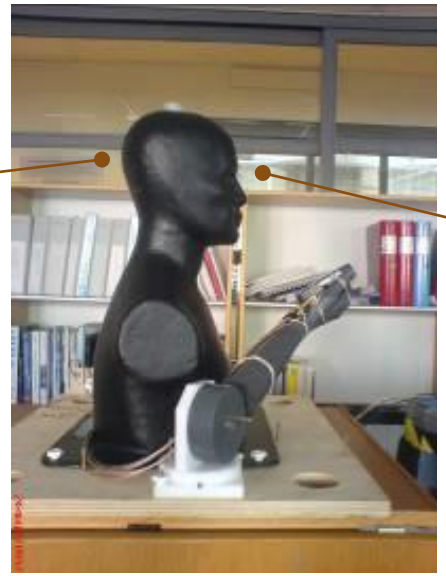
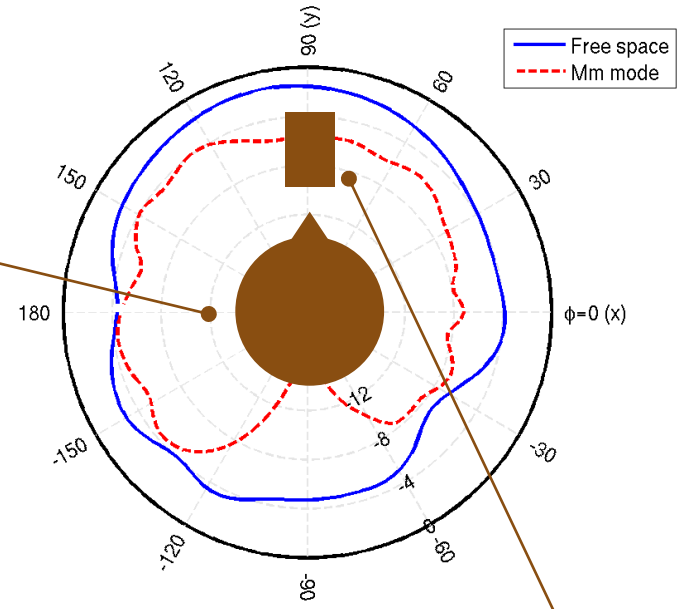
# Influence of User Equipment Position and Orientation

## Talk mode



## Data mode




User equipment

Head position

User equipment

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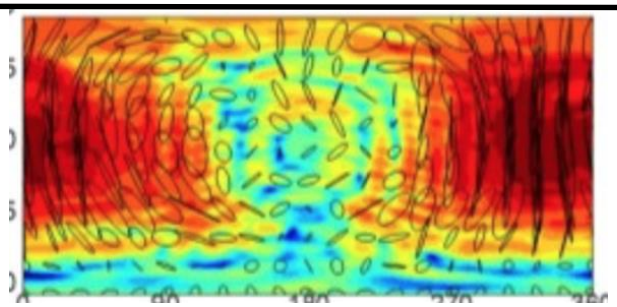
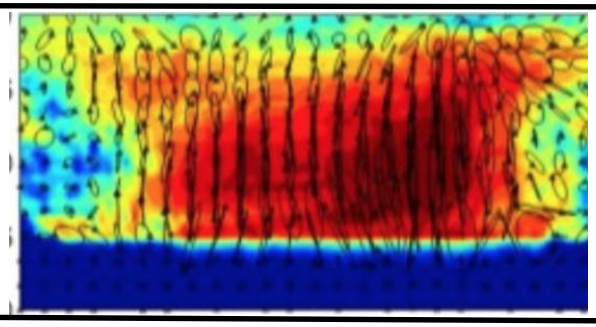
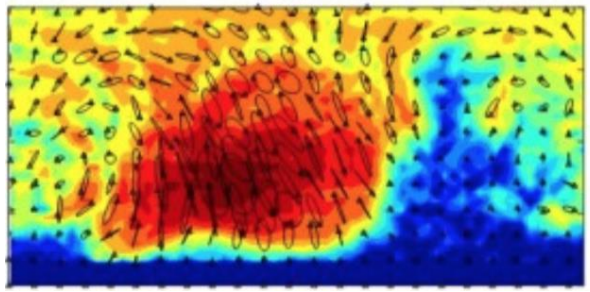
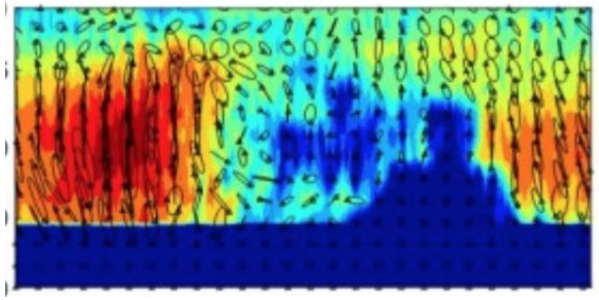
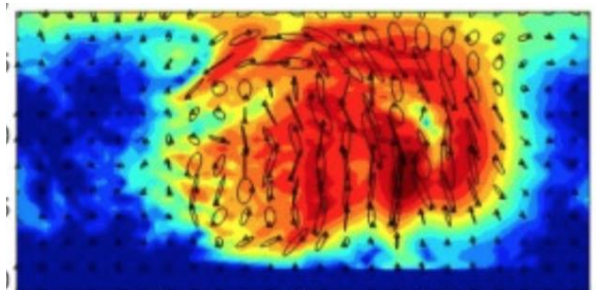
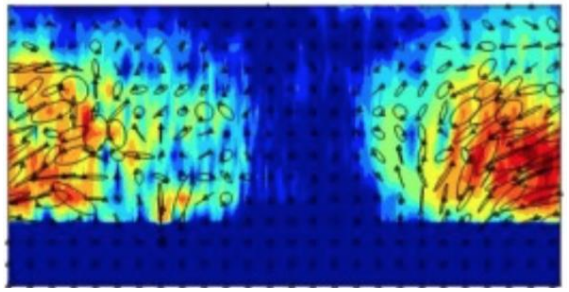
# Influence of a User: Continuation


Channel Characteristics and User Body Effects in an Outdoor Urban Scenario at 15 and 28 GHz

# Influence of a User: Continuation

| | 15 GHz | 28 GHz |
|---|---|---|
| Free space |  |  |
| Data mode  |  |  |
| Talk mode  |  |  |

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# Some Common Antenna Element Types

- Linear antennas (monopole, dipole,…)
- Helical antennas
- Microstrip antennas (patch elements,…)
- Planar inverted f antennas…

# Linear and Helical Antenna Characterization

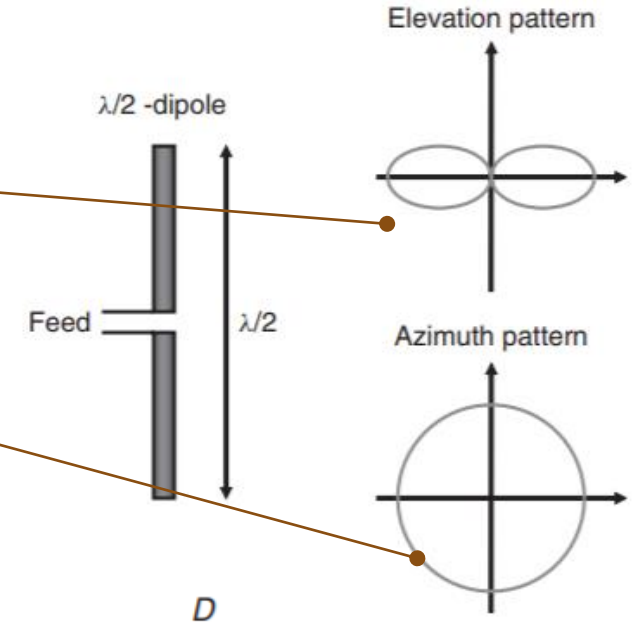
**Hertzian dipole (short dipole):**

Antenna pattern: $\widetilde{G}(\varphi,\theta) \propto \sin(\theta)$

Uniform across $\varphi$

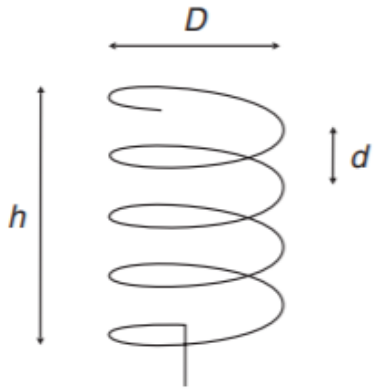
**Lambda/2 dipole:**

Antenna pattern: $\widetilde{G}(\varphi,\theta) \propto \frac{\cos\left(\frac{\pi}{2}\cos(\theta)\right)}{\sin(\theta)}$




**Helical antenna:** Combination of loop+linear antenna

- If dimensions much smaller than wavelength, behvaiour similar to a linear antenna.
- Bandwidth, and radiation efficiency increase with increasing *h*.

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# Microstrip Antennas

Dielectric substrate with ground plane on one side, and metallic patch on the other.

**Properties determined by:**

- ❑ Shape of the patch
- ❑ Dielectric (electrical) properties of the substrate used

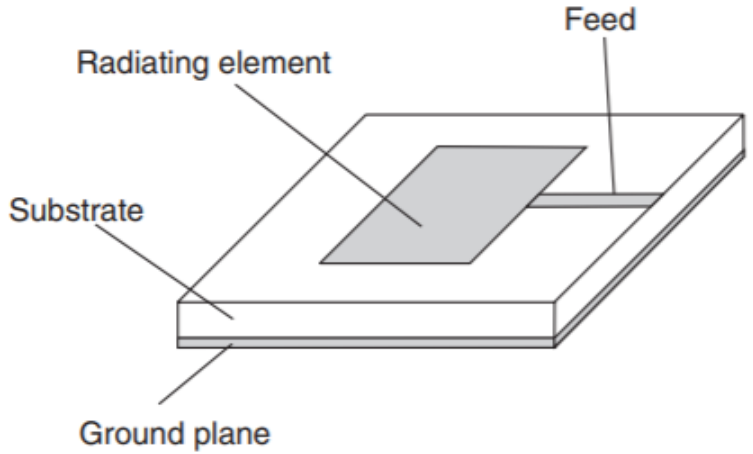
  Absolute permittivity: $\epsilon_r$, a measure of capacitance encountered when forming an electric field in a particular medium. Charge needed for unit flux generation.

**Advantages:**

- ❑ Small; can be manufactured cheaply
- ❑ Feedlines can be manufactured on same substrate as antenna can be integrated into the UE, without sticking out from the casing.

**Drawbacks:**

- ❑ Low bandwidth
- ❑ Low efficiency

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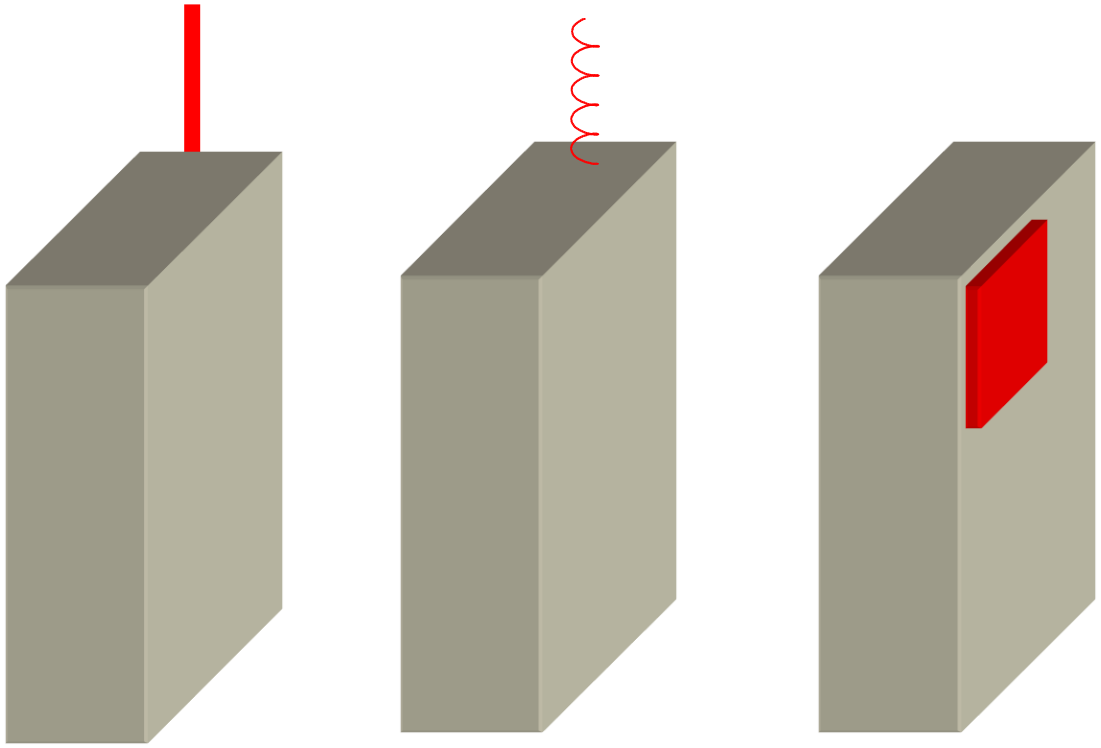
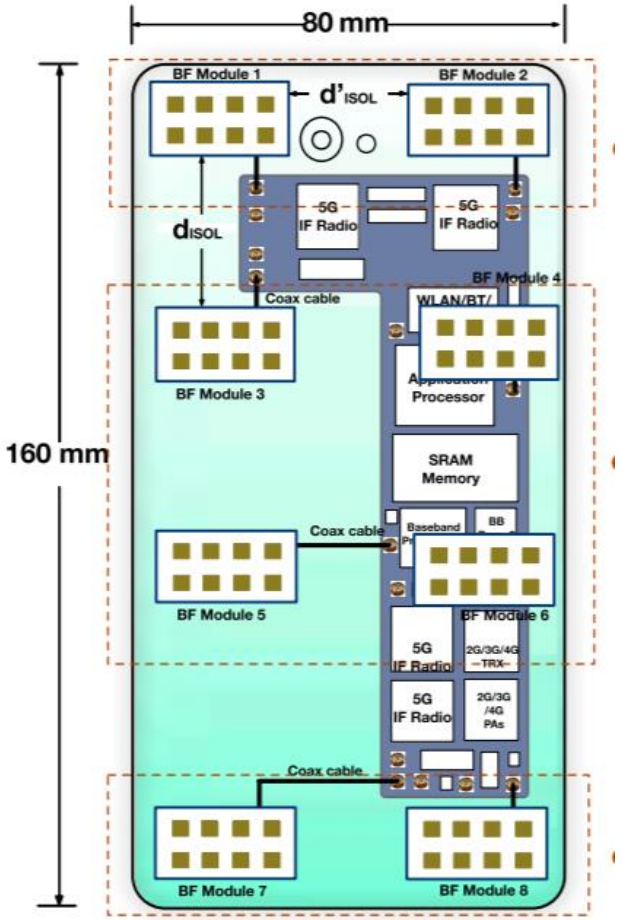
# UE Antenna Types: From 1G to 5G



Monopole Helix Patch

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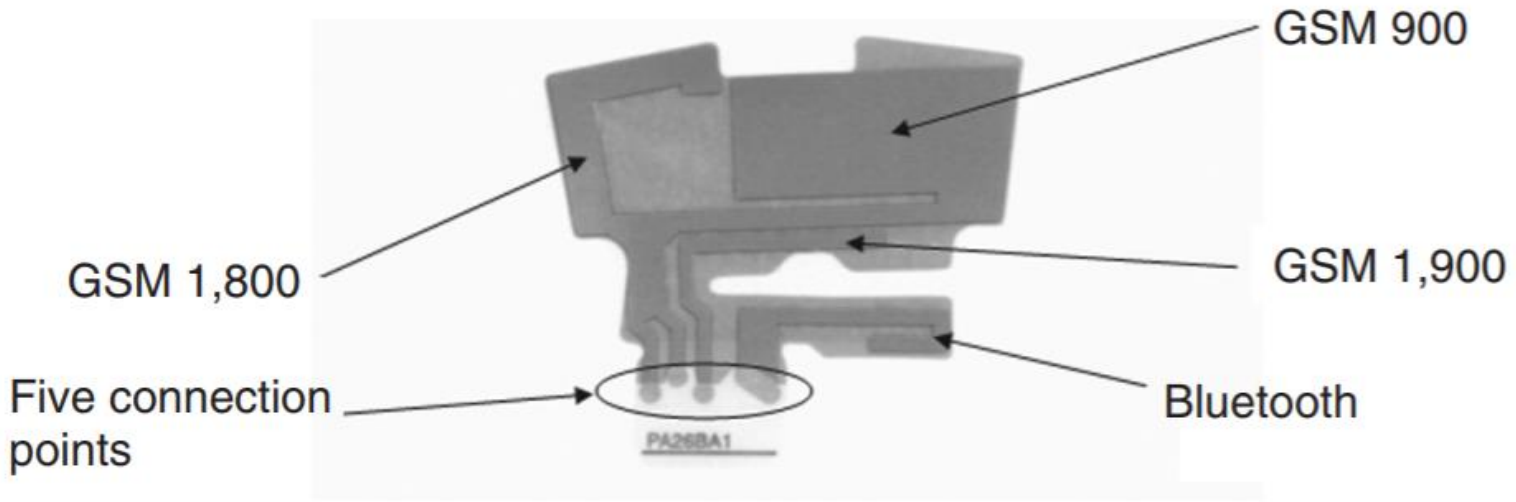
# Multiple Band Integrated Antennas

For many applications, different wireless services need to be covered

**Example: An old cellular handset needs:**

- ❑ GSM 900 MHz
- ❑ GSM 1800 MHz
- ❑ GSM 1900 MHz, and
- ❑ Bluetooth

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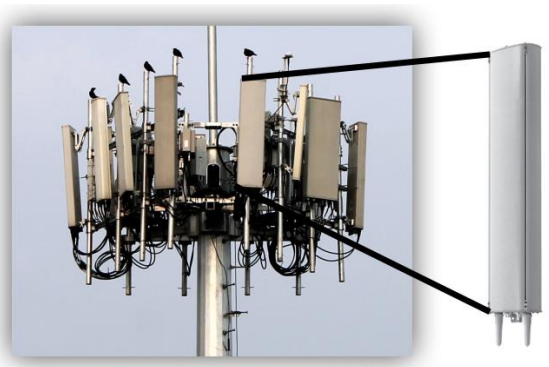
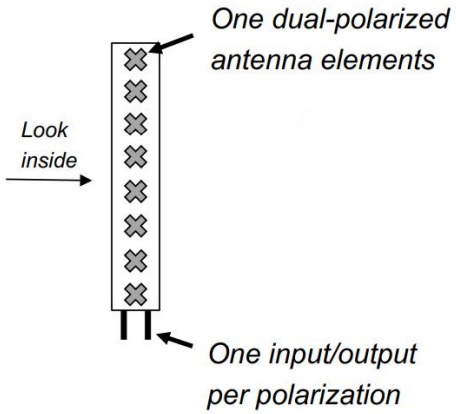
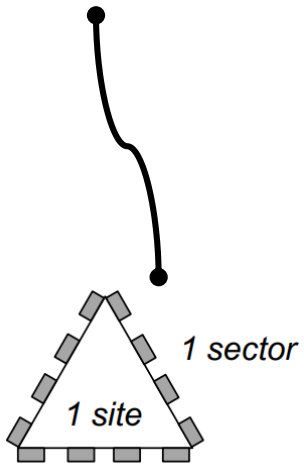
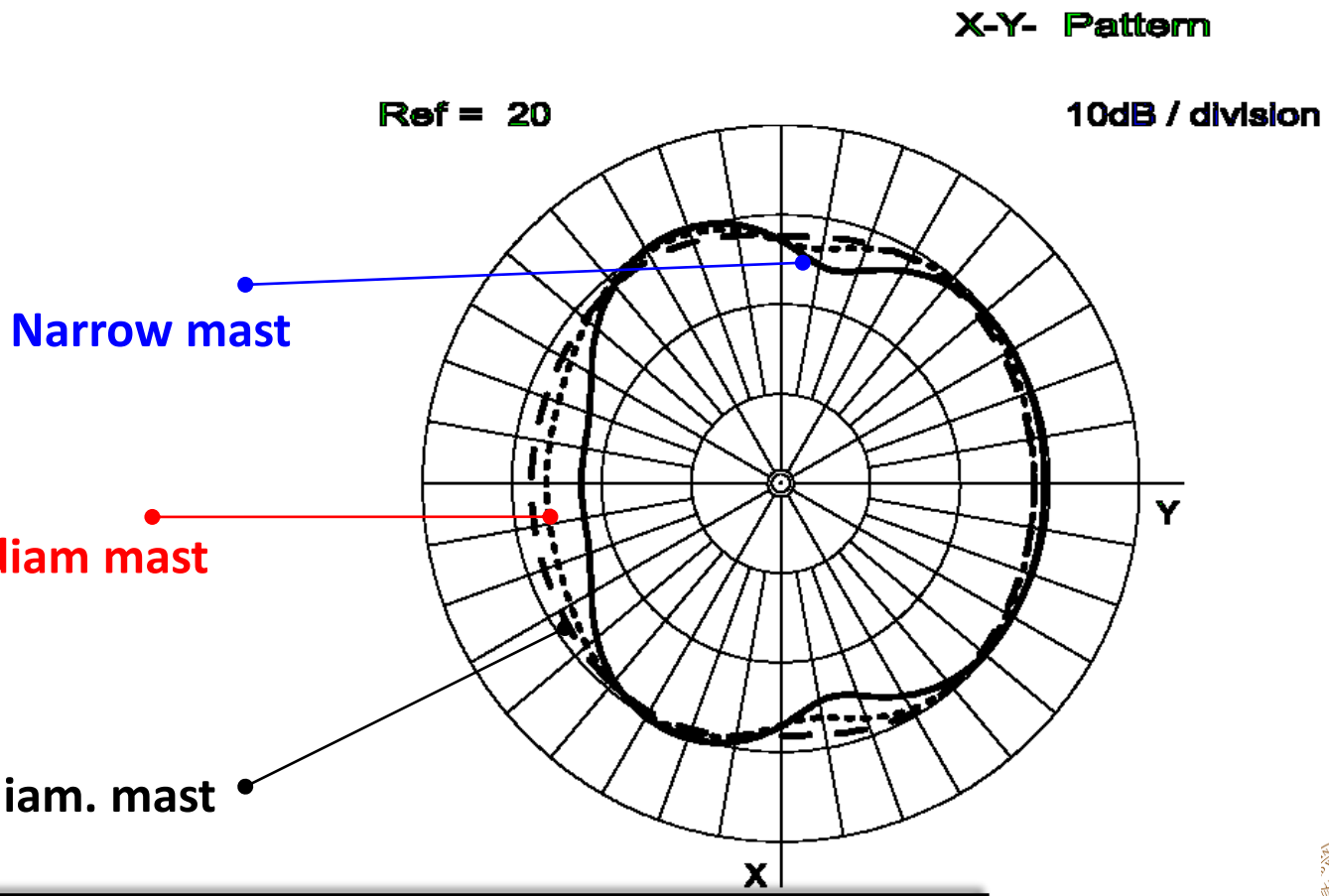
# Base Station Antennas (a.k.a. Panel Antennas) – I



3 sectors, 8-antenna LTE-A




**Base station antenna pattern affected by the mast (30 cm from antenna)**

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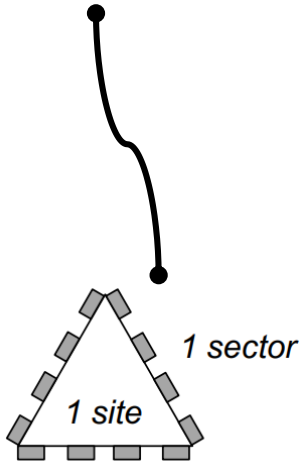
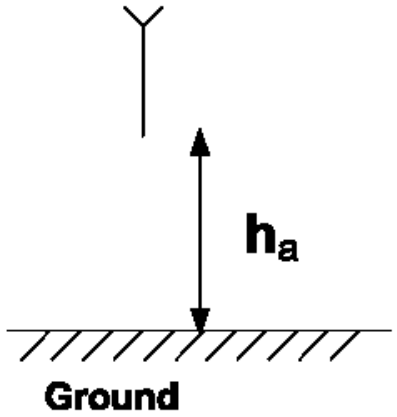
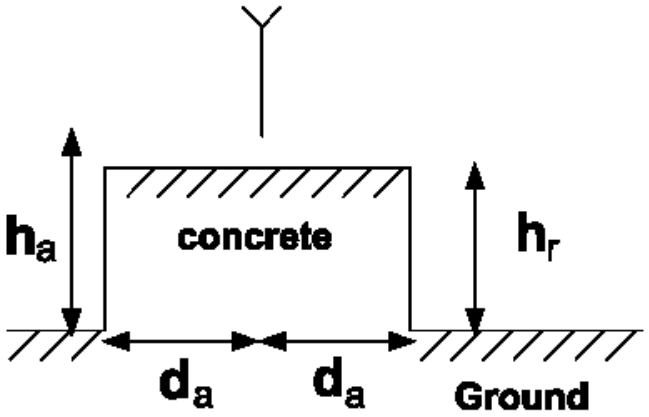
# Base Station Antennas (a.k.a. Panel Antennas) - II

3 sectors, 8-antenna LTE-A

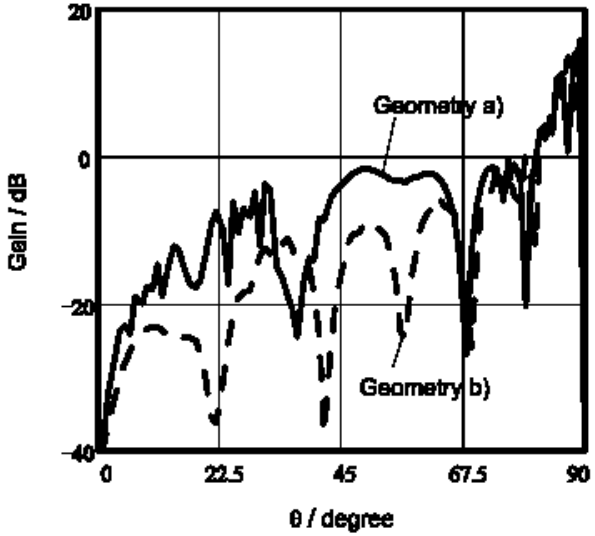



a)




b)




c)

**Base station antenna pattern affected by the concrete foundation too!**

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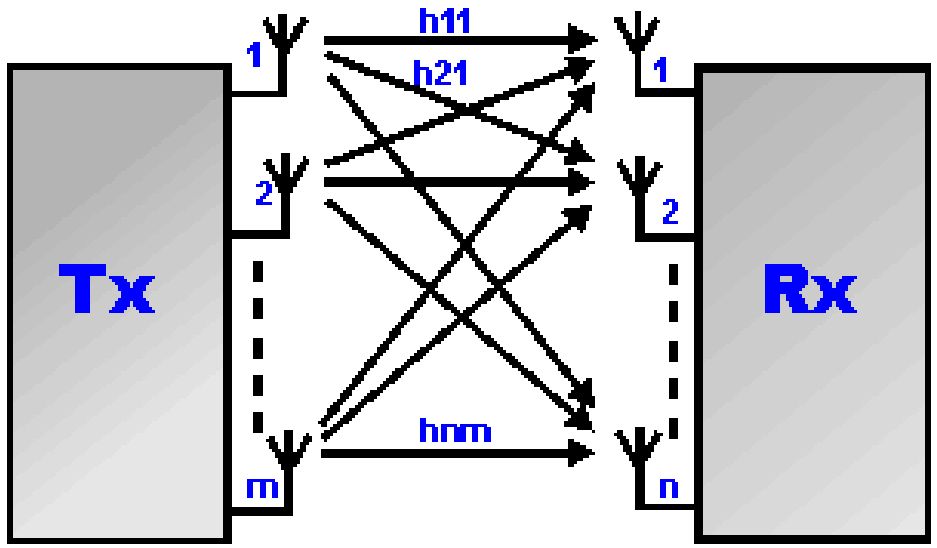
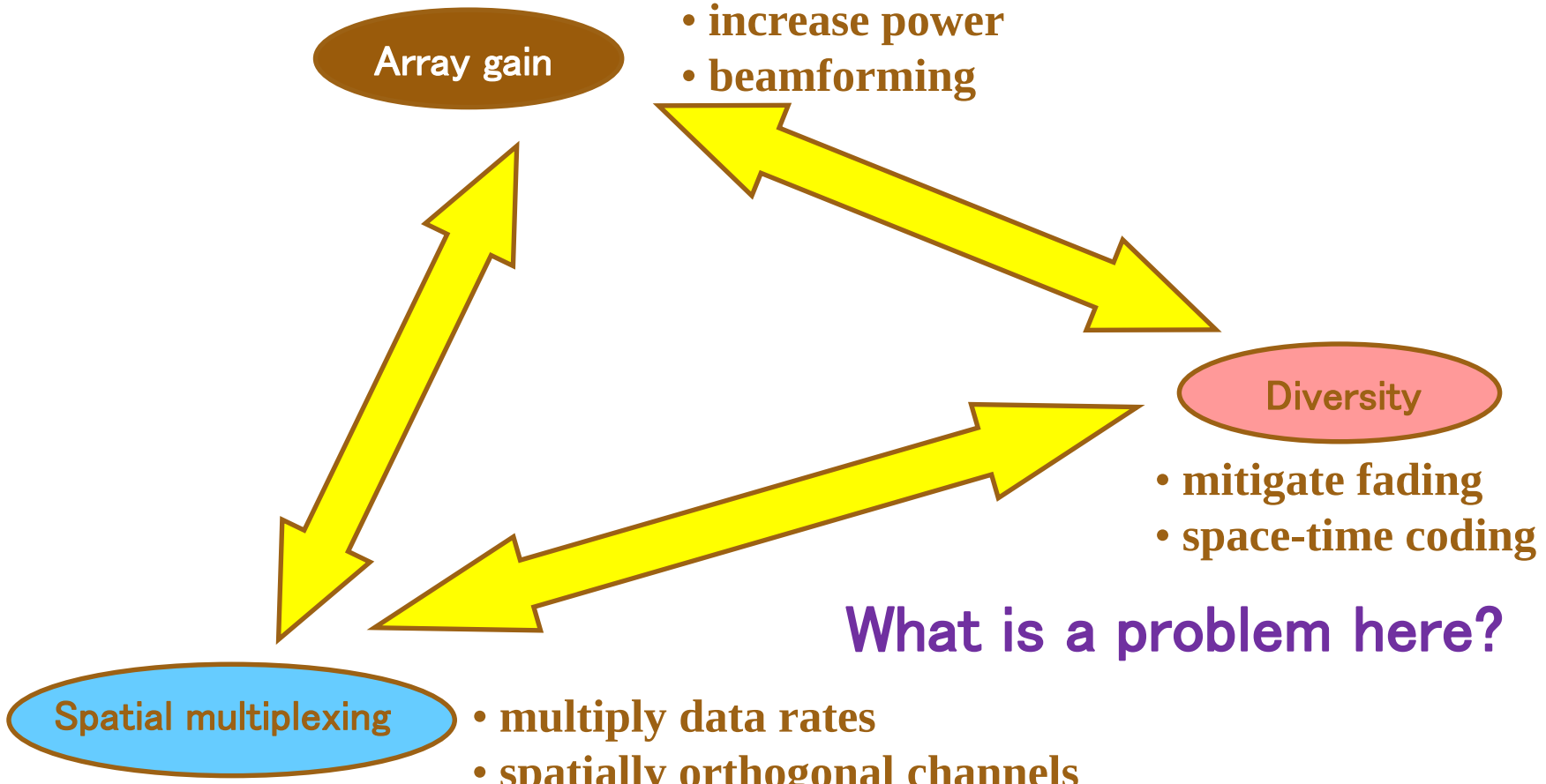
# Multiple Antenna (a.k.a. MIMO) Systems

A “MIMO” system consists of **several** antenna elements, plus **adaptive** signal processing, at both transmitter and receiver, the combination of which exploits the **spatial dimension** of the mobile radio channel.




Multiple antennas make transceivers spatially sensitive!

# Goals of MIMO

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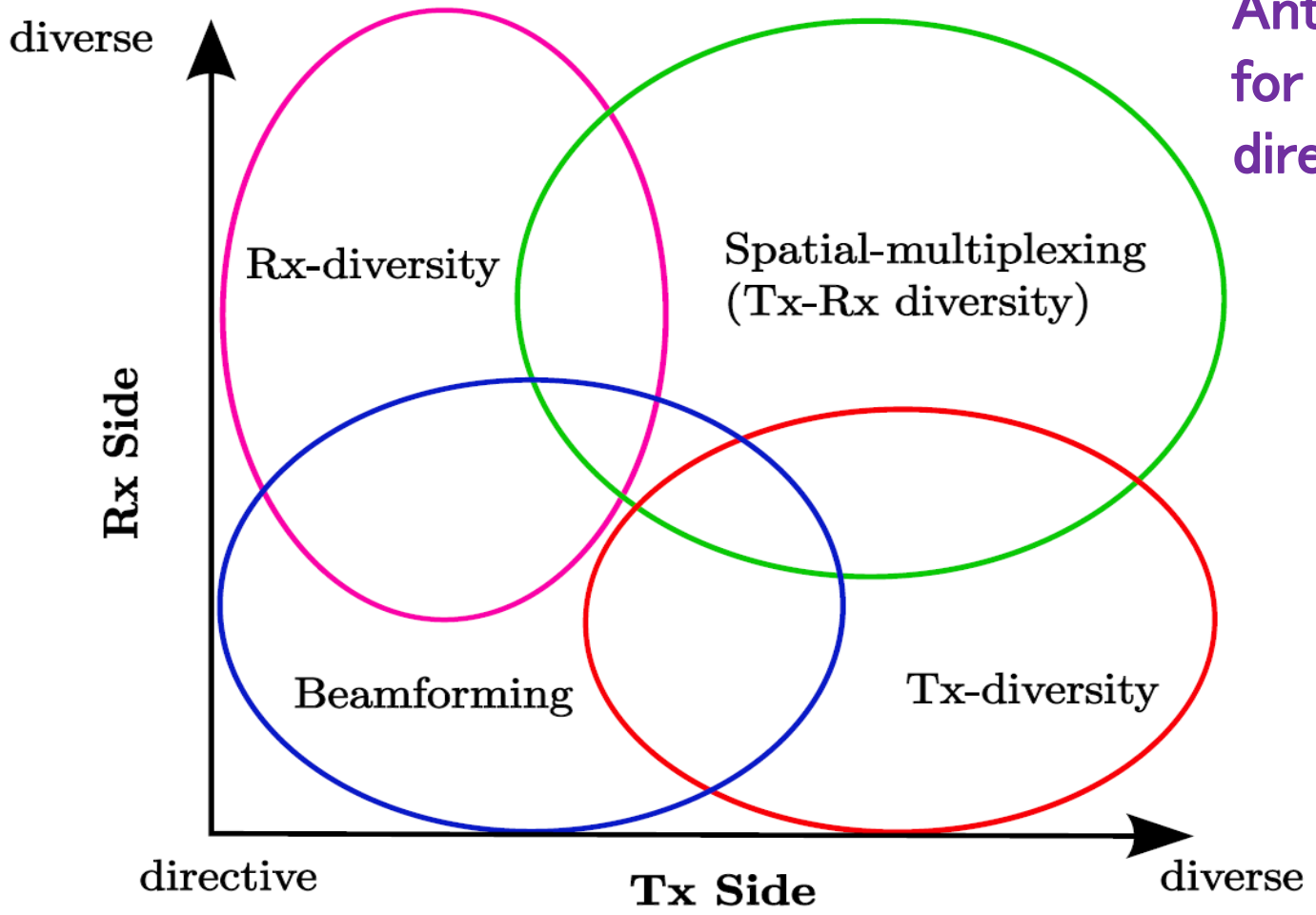
# Goals of MIMO




Antenna spacing for diverse vs. directive modes?

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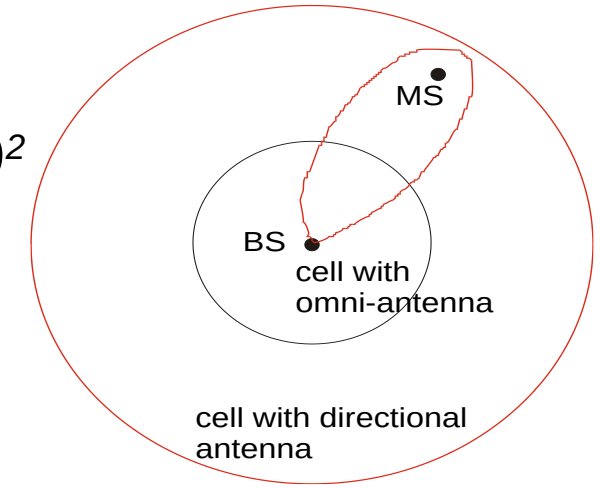
# Benifits of MIMO Systems

- **Higher spectral efficiency and capacity (higher bits/seconds/Hz)**
- **Better utilization of spectrum, which is expensive; but number of base stations limited (unless we talk of massive MIMO where we can use hundereds of elements)**
- **Better transmission quality**
- **Increased coverage due to higher array gain!**
  - Directional antennas have gain and received power: $P_R=G_T G_R P_T(\lambda/4\pi d)^2$
  - UE moves: follow UE with main beam of BS to steer the gain to UE
- **Improved user position estimation**

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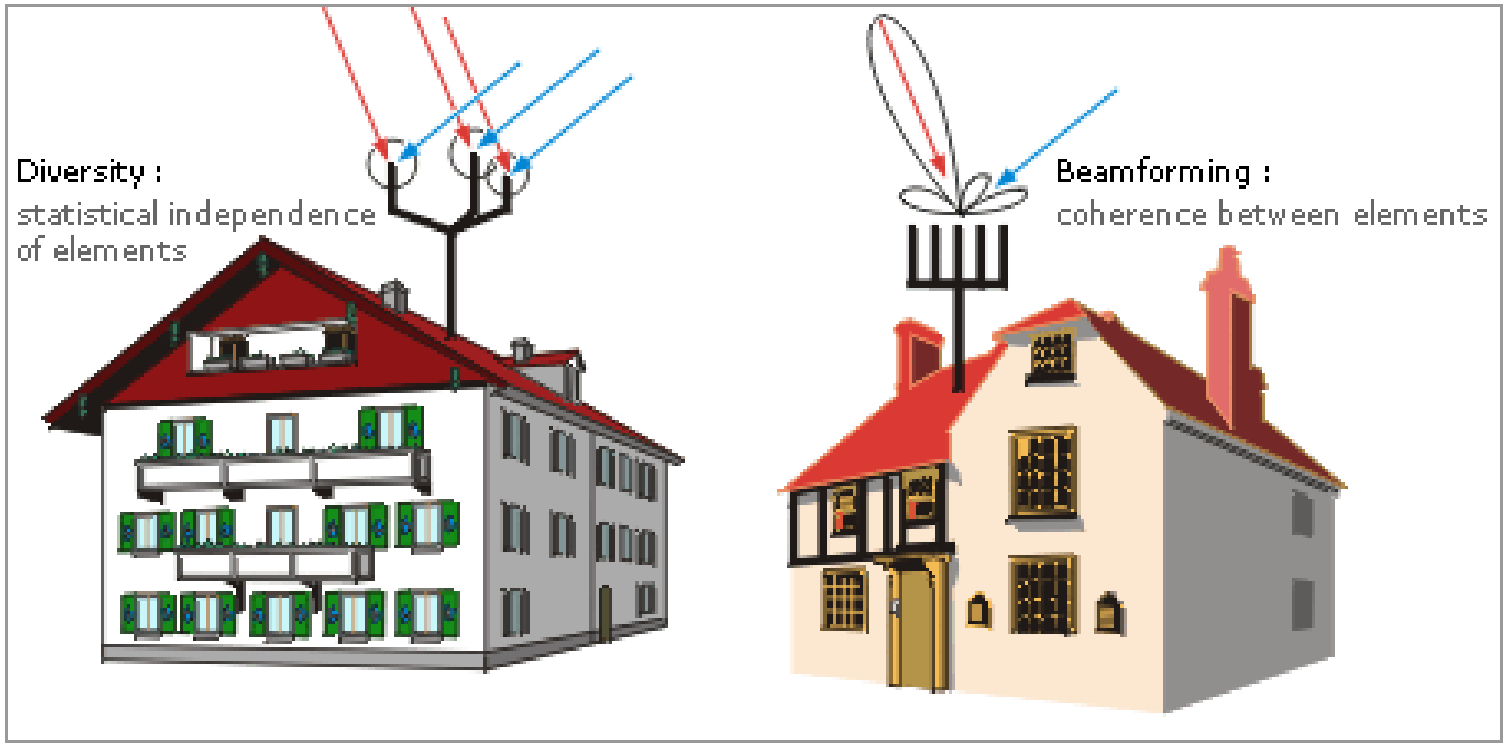
# Diversity vs. beamforming

Diversity: statistical independence of elements

Beamforming: coherence between elements

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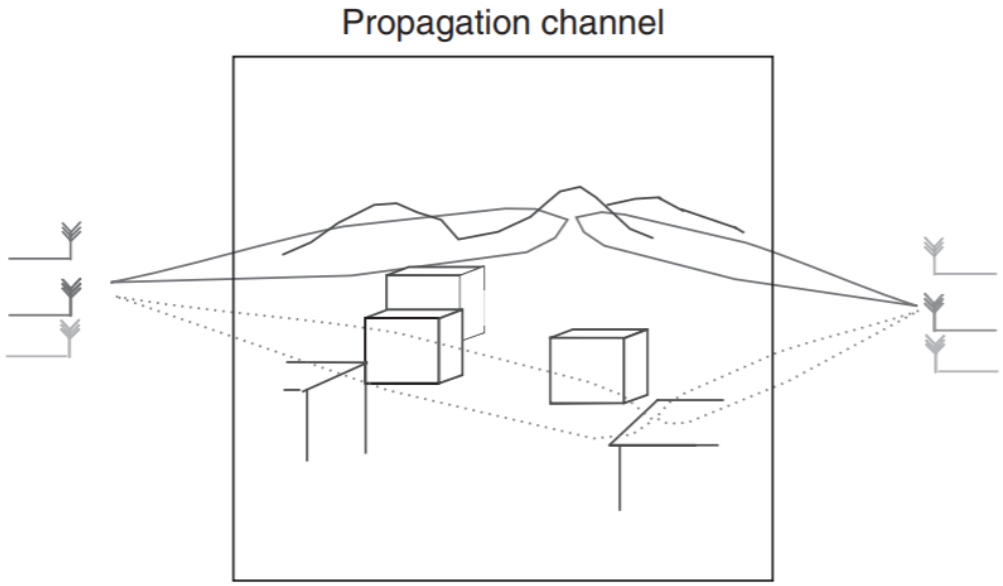
# Spatial multiplexing

Each MPC can carry independent data stream

Beamforming view:

- TX antenna “targets” energy onto one scatterer
- RX antenna receives only from that direction

Capacity goes linearly with number of antennas

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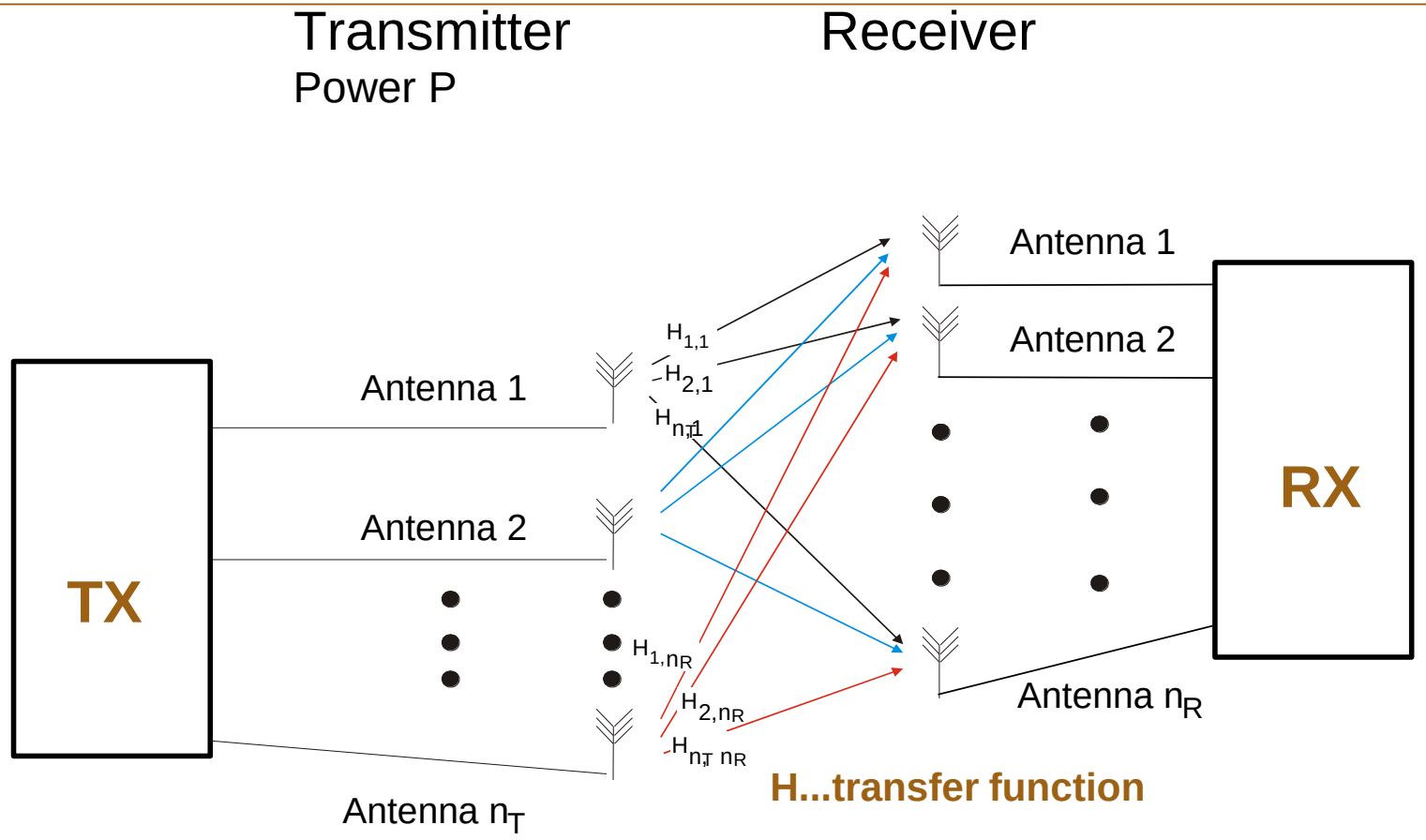
# History

- Diversity:
  - Receive diversity: since 1940s
  - Transmit diversity: early 1990s
    - Wittneben; Winters
  - Space-time codes in late 1990s
    - Tarokh et al.; Alamouti
- Spatial multiplexing:
  - Invented by Winters 1987
  - Theoretical treatment in mid-1990s
    - Winters Foschini&Gans; Telatar; Raleigh and Cioffi

**Examples of wireless systems with MIMO technology?**

# Signal model




$\gamma$...SNR at each receiver branch

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# Narrow-band vs broad-band models

For a narrow-band channel:

$\mathbf{H}$ is an $n_{\mathrm{Rx}} \times n_{\mathrm{Tx}}$ matrix.

$$\mathbf{y} = \mathbf{Hx} + \mathbf{n}, \text{ where}$$

$$\mathbf{y} = [y_1 \; y_2 \; \dots \; y_{n_{Rx}}]^{\mathrm{T}}, \leftarrow \text{receive signal vector}$$

$$\mathbf{x} = [x_1 \; x_2 \; \dots \; x_{n_{Tx}}]^{\mathrm{T}}, \leftarrow \text{transmit signal vector}$$

$\mathbf{n}$ is a noise vector where :

$$\mathbb{E}\left[\mathbf{n}\mathbf{n}^{\mathrm{H}}\right] = \sigma^2 \mathbb{I}_{n_{Rx} \times n_{Rx}}$$

Ideally, $\mathbf{H}$ is assumed to be i.i.d. ← Often not true!

Wideband channel matrix entries are frequency dependent

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# Capacity formula

Instantaneous channel characterized by matrix ***H***

- Shannon's formula (for two-dimensional symbols):

$$C = \log_2(1+\gamma \mid H \mid^2) bits/s/Hz$$

- Foschini's formula:

$$C = \log_2\left(\det\left[\boldsymbol{I}_{n_R} + \frac{\gamma}{n_T}\boldsymbol{H}\boldsymbol{H}^H\right]\right) bits/s/Hz$$

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# Capacity in realistic channels

Influence of various effects:

- Correlation: line-of-sight component, small angular spread
- Frequency selectivity: gives additional diversity
- Limited number of effective scatterers

# Channel knowledge is important for the system

- Channel knowledge  at RX
  - unknown
  - known (estimated or perfect)
- Channel knowledge  at TX
  - unknown (no channel state information, CSI)
  - average CSI known
  - instantaneous CSI known (estimated or perfect)

Different strategies for different combinations!

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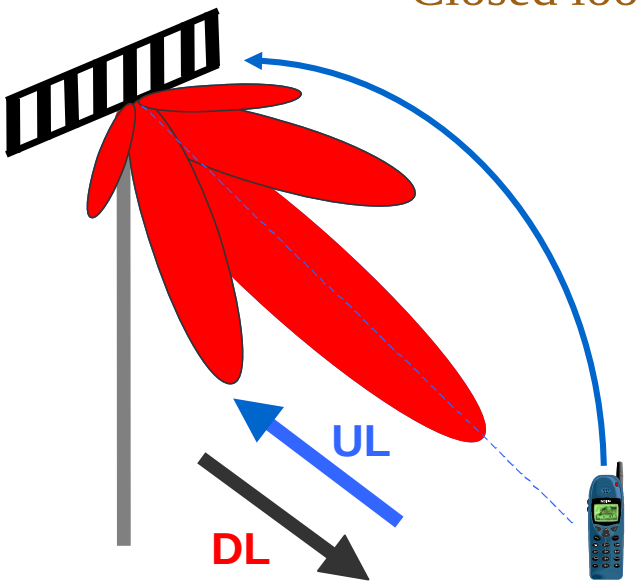
# Mobile Feedback based CSI

Closed loop control:




Estimate:
$h_{DL}$

- MS estimates $h_{DL}$
- Feedback of DL channel parameters

Drawbacks:

- Reduces spectral efficiency
- Feedback errors (noise, quantization)
- Sensitivity to
  - high mobile speed
  - terminal implementation

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