Wireless Communications Channels
Lecture 9: Antennas and MIMO Systems

EITN85: Dr. Harsh Tataria (harsh.tataria@eit.lth.se)

Department of Electrical and Information Technology, LTH
Lund University

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!

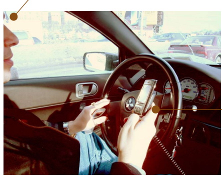
Examples of Typical Antennas at TX and RX Link Ends

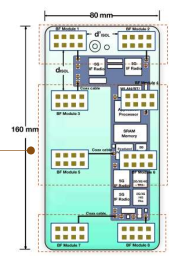
Antennas and propagation interaction at the RX (UE):

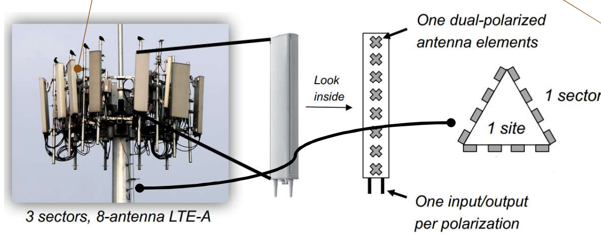
- ❑ Mock-up terminals (handsets, even laptops) with integrated antennas and casing
- ❑ Clearly influenced by the **local** scattering environments:
  - ❑ Mobility of the UE, mobility of the scatterers, surrounding environment (indoor vs. outdoor)

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

LUND UNIVERSITY

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.

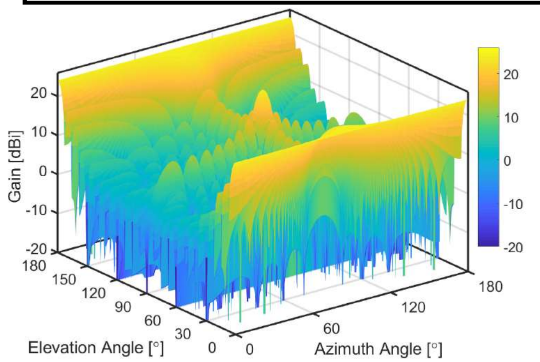
- ❑ **Mean effective gain:** Include influence of random channel. It is the average received power compared to average received power by isotropic antenna in real environment.

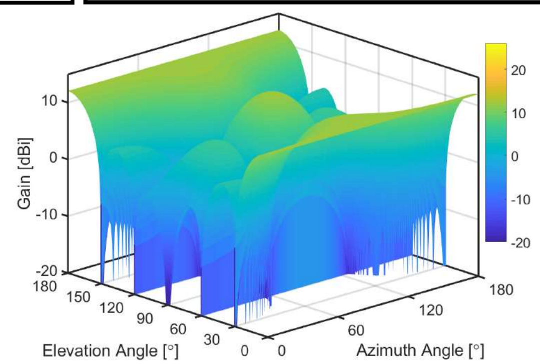
LUND UNIVERSITY

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°

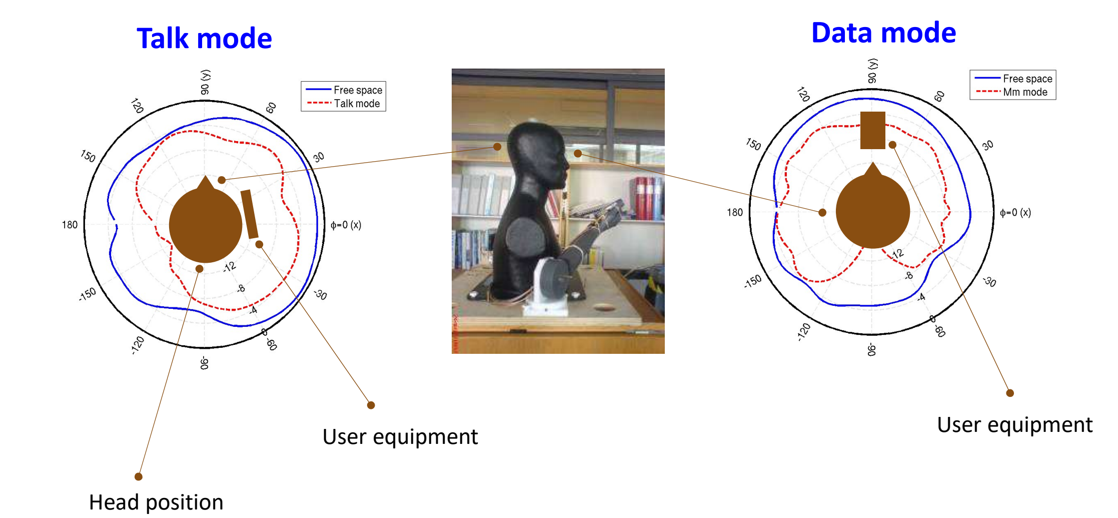
UE: 4x4 cross-polarized UPA: 2x4x2
- **Spacing:** λ/2 spacing in azimuth, λ in elevation
- **Directional gain:** 9 dBi (per-element)
- **HPBW:** 63° in azimuth and 32° in elevation.
- **Slant angle:** 45°





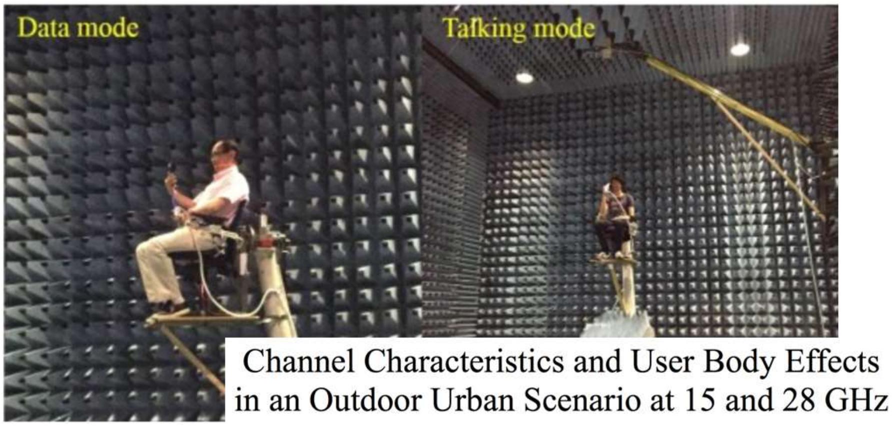
LUND UNIVERSITY

Influence of User Equipment Position and Orientation

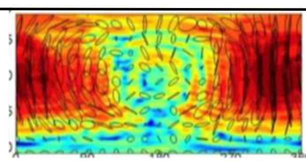
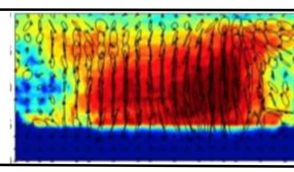
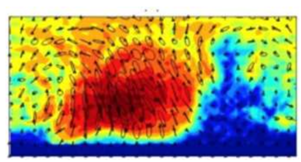
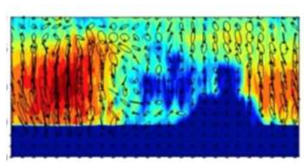
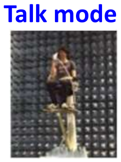
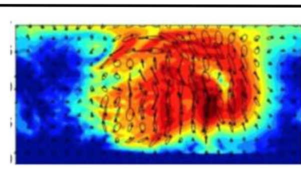
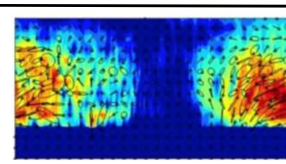


LUND UNIVERSITY

Influence of a User: Continuation



Influence of a User: Continuation

	15 GHz	28 GHz
Free space		
Data mode 		
Talk mode 		

Some Common Antenna Element Types

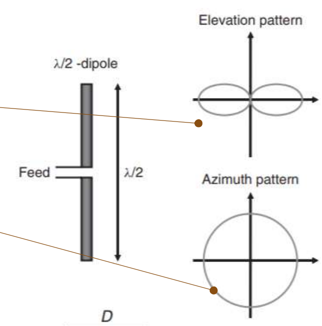
- ❑ Linear antennas (monopole, dipole,…)
- ❑ Helical antennas
- ❑ Microstrip antennas (patch elements,…)
- ❑ Planar inverted f antennas…

Linear and Helical Antenna Characterization

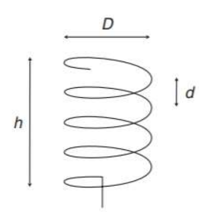
Hertzian dipole (short dipole):
Antenna pattern: $\widetilde{G}(\varphi,\theta) \propto \sin(\theta)$

Uniform across φ

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.*



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

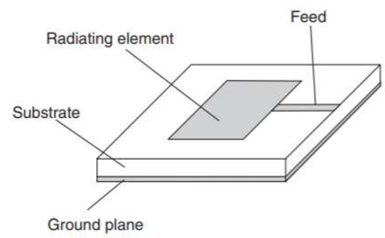
Absolute permittivity: ϵ_r, a measure of capacitance encountered when forming an electric field in a particular medium. Charge needed for unit flux generation.

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.

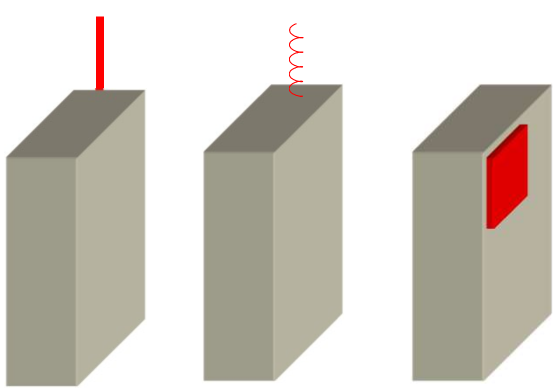
Drawbacks:

- ❑ Low bandwidth
- ❑ Low efficiency

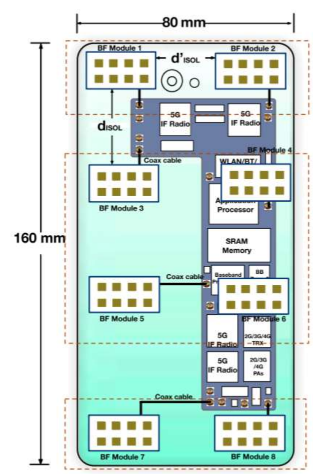


LUND UNIVERSITY

UE Antenna Types: From 1G to 5G



Monopole Helix Patch



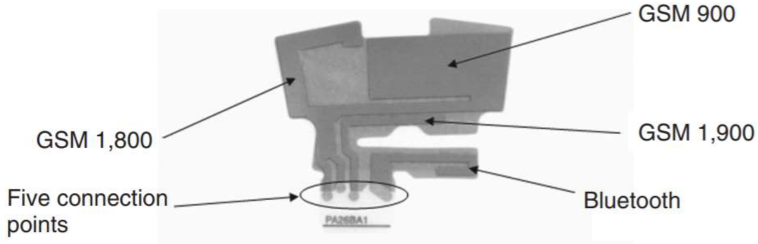
LUND UNIVERSITY

Multiple Band Integrated Antennas

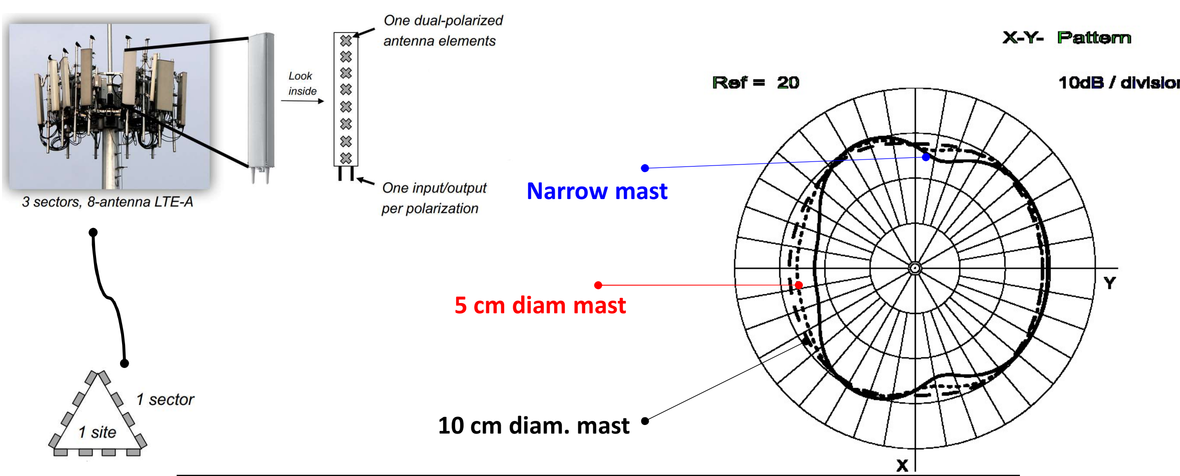
For many applications, different wireless services need to be covered

Example: An old cellular handset needs:

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

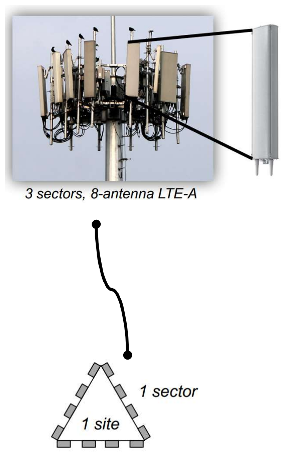


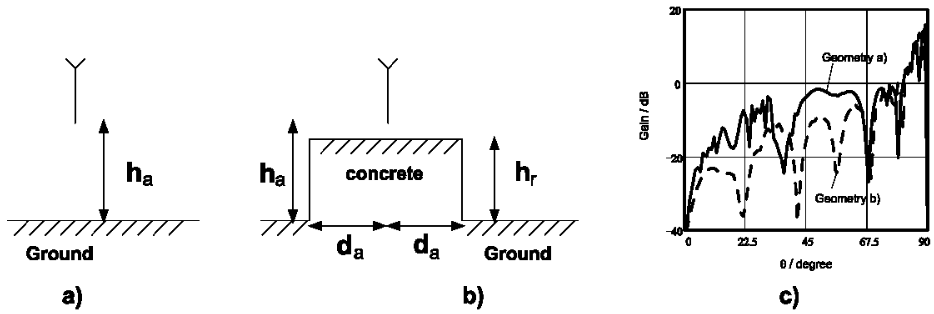
Base Station Antennas (a.k.a. Panel Antennas) – I



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

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

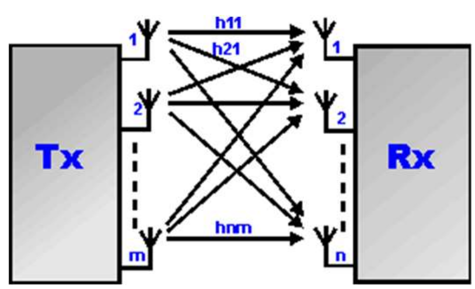




Base station antenna pattern affected by the concrete foundation too!

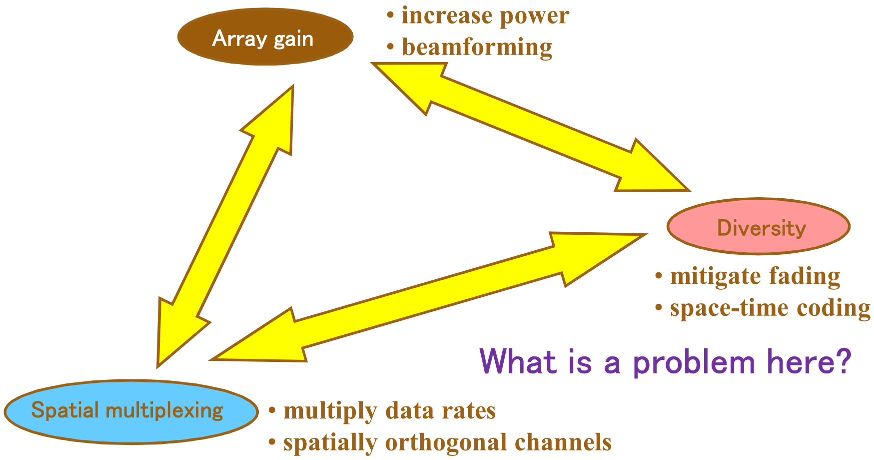
Multiple Antenna (a.k.a. MIMO) Systems

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.



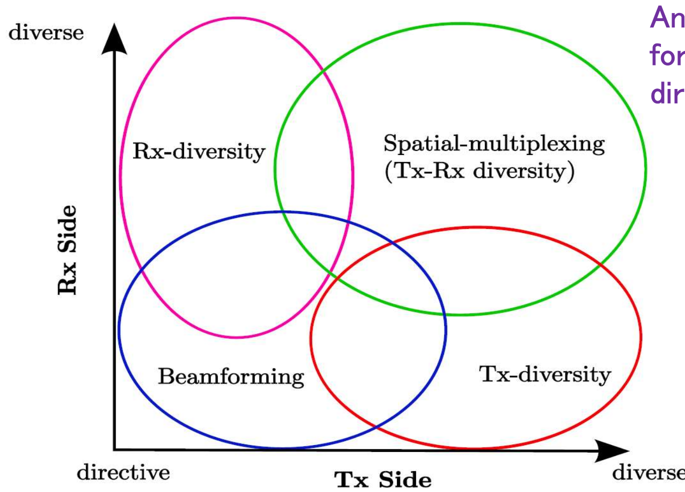
Multiple antennas make transceivers spatially sensitive!

Goals of MIMO



What is a problem here?

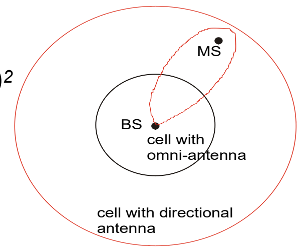
Goals of MIMO



Antenna spacing
for diverse vs.
directive modes?

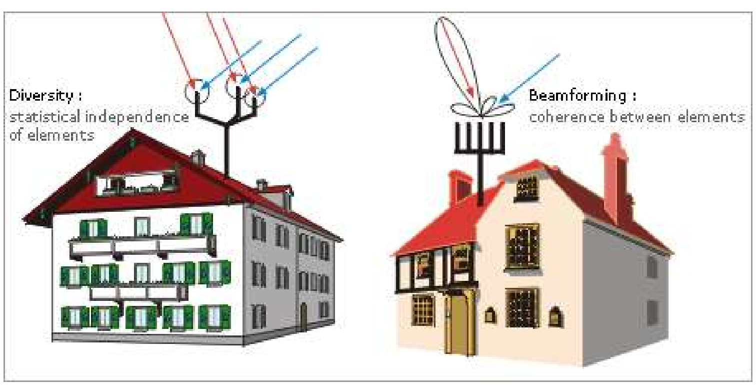
Benifits of MIMO Systems

- 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: $P_R=G_TG_RP_T(\lambda/4\pi d)^2$
  - UE moves: follow UE with main beam of BS to steer the gain to UE
- Improved user position estimation



Diversity vs. beamforming

Diversity: statistical independence of elements
Beamforming: coherence between elements



Spatial multiplexing

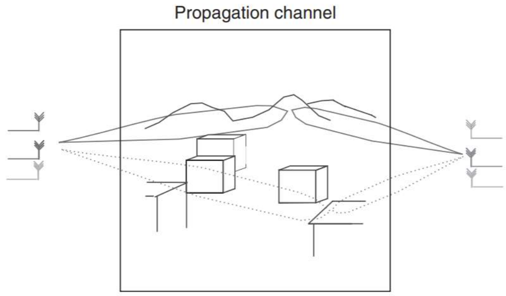
Each MPC can carry independent data stream

Beamforming view:

– TX antenna "targets" energy onto one scatterer

– RX antenna receives only from that direction

Capacity goes linearly with number of antennas



LUND UNIVERSITY

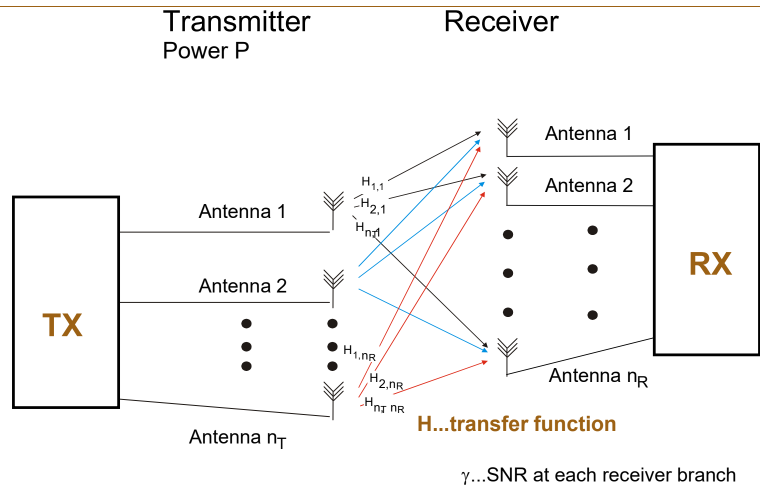
History

- 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?

LUND UNIVERSITY

Signal model



Narrow-band vs broad-band models

For a narrow-band channel:

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

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

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

$$\mathbf{x} = [x_1 \; x_2 \; \dots \; x_{n_{Tx}}]^{\mathrm{T}},$$ ← 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

Capacity formula

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

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

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

- Foschini's formula:

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

LUND UNIVERSITY

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

LUND UNIVERSITY

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)

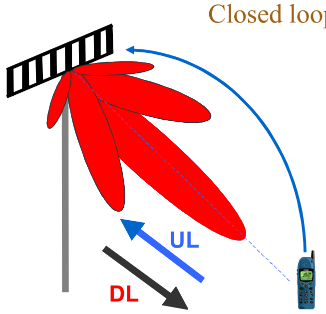
Different strategies for different combinations!

LUND UNIVERSITY

Mobile Feedback based CSI

Closed loop control:

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



Estimate: h_{DL}

Drawbacks:

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

Wireless Communication Channels

LUND UNIVERSITY

LUND
UNIVERSITY