Wireless Communications Channels
Lecture 9: 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!
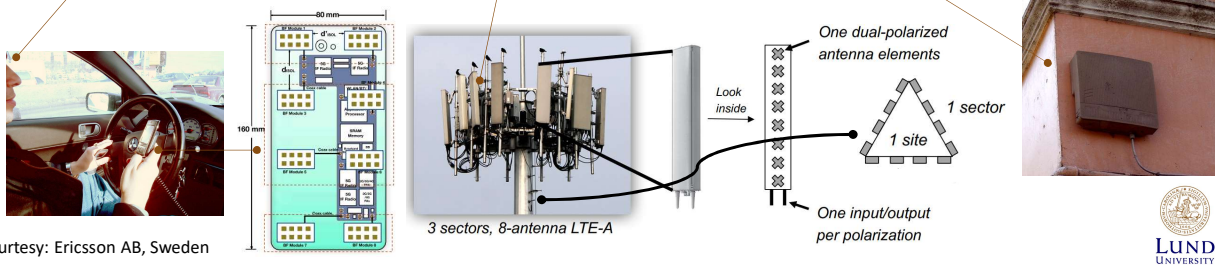
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Examples of Typical Antennas at TX and RX Link Ends

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.

80 mm

160 mm

Courtesy: Ericsson AB, Sweden

3 sectors, 8-antenna LTE-A

Look inside

One dual-polarized antenna elements

1 sector

1 site

One input/output per polarization

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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.

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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.
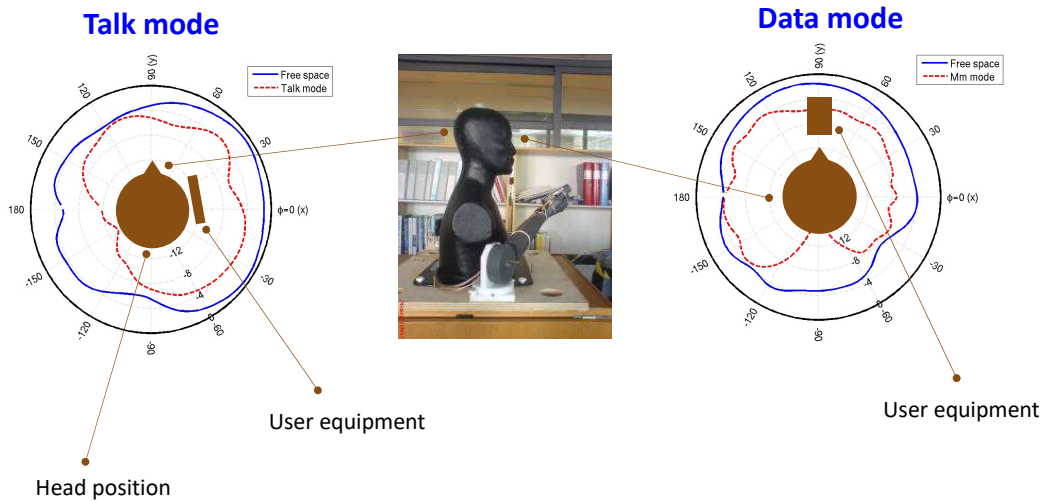- ❑ **Slant angle:** 45°

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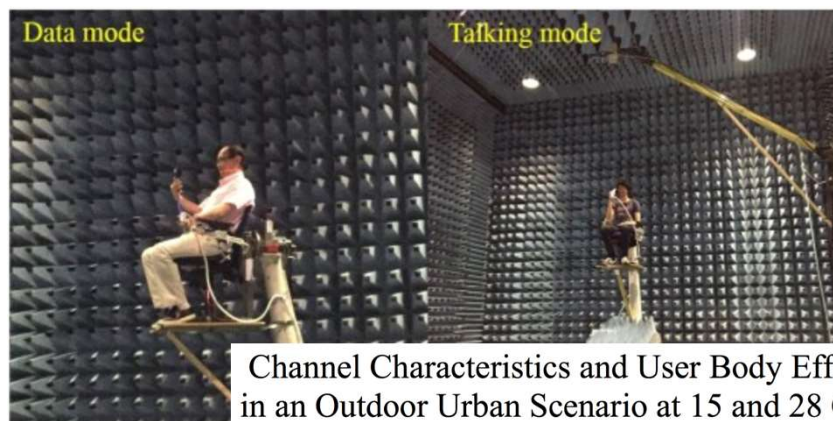- ❑ **HPBW:** 63° in azimuth and 32° in elevation.
- ❑ **Slant angle:** 45°
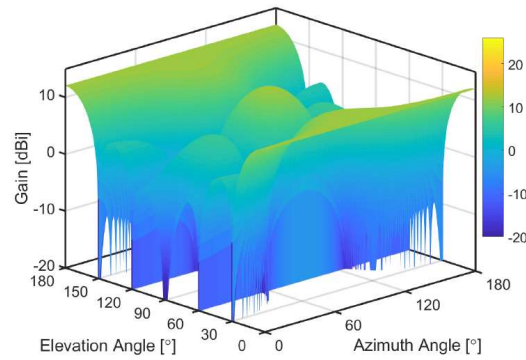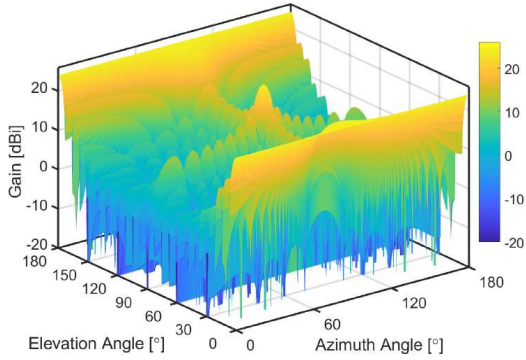
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Influence of User Equipment Position and Orientation

Talk mode

Data mode

User equipment

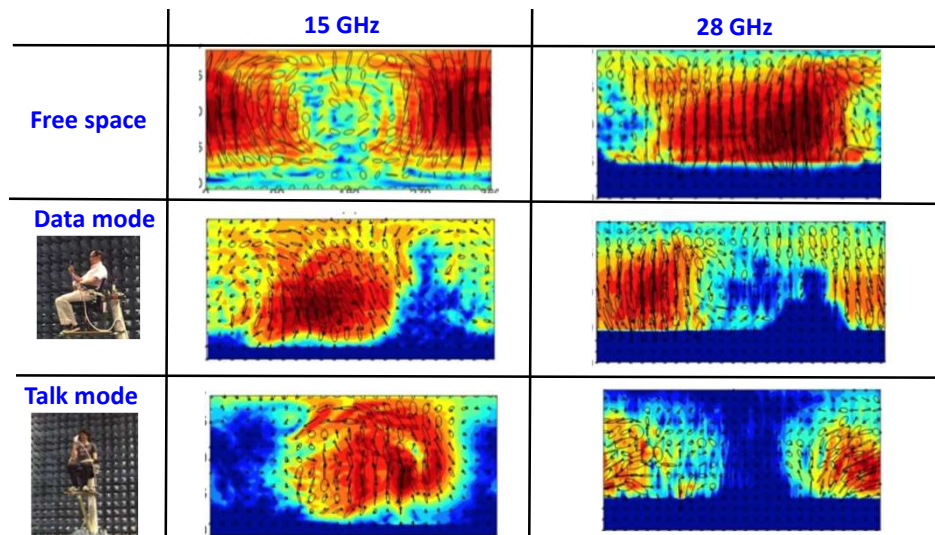User equipment

Head position

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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

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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…

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Linear and Helical Antenna Characterization

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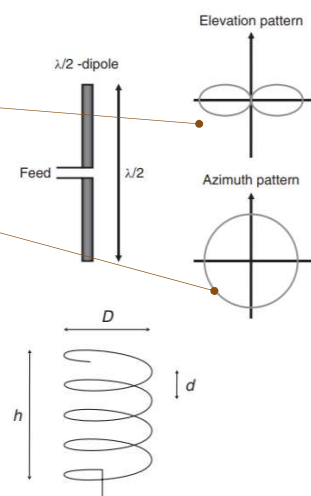Antenna pattern: $\widetilde{G}(\varphi, \theta) \propto \sin(\theta)$

Uniform across φ

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

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: 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.
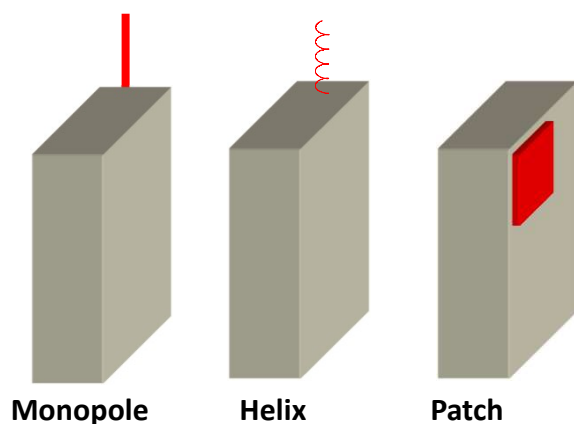
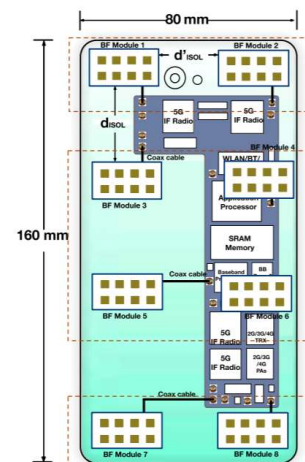**Drawbacks:**
- ❑ Low bandwidth
- ❑ Low efficiency
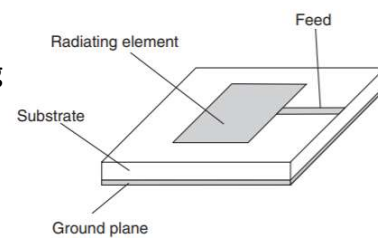
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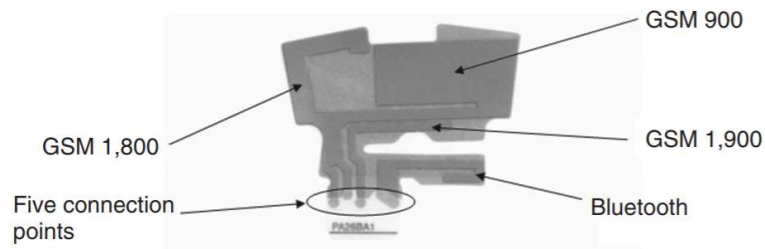# UE Antenna Types: From 1G to 5G

Monopole　　**Helix**　　**Patch**

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Multiple Band Integrated Antennas

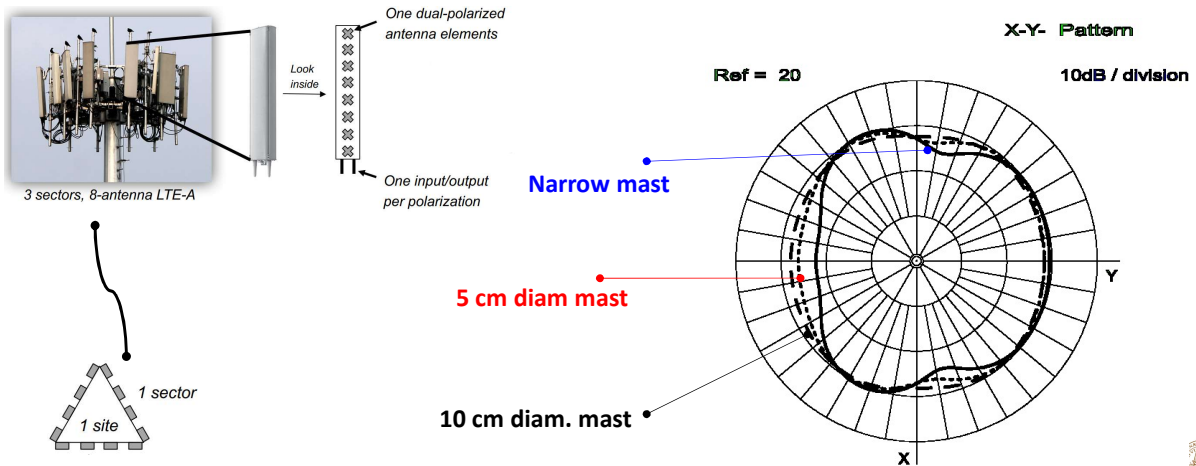For many applications, different wireless services need to be covered
Example: An old cellular handset needs:
- ❑ GSM 900 MHz
- ❑ GSM 1800 MHz
- ❑ GSM 1900 MHz, and
- ❑ Bluetooth

GSM 900

GSM 1,800

GSM 1,900

Five connection points

Bluetooth

PA26BA1

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

One dual-polarized antenna elements

Look inside

One input/output per polarization

3 sectors, 8-antenna LTE-A

1 sector

1 site

X-Y- Pattern

Ref = 20

10dB / division

Narrow mast

5 cm diam mast

10 cm diam. mast

Y

X

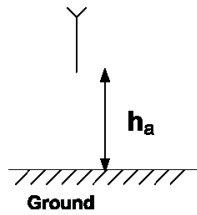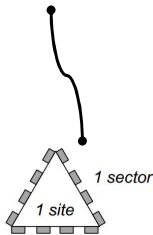**Base station antenna pattern affected by the mast (30 cm from antenna)**
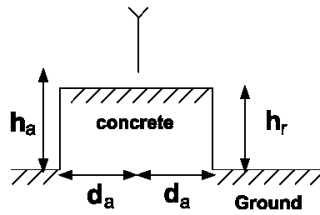
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Base Station Antennas (a.k.a. Panel Antennas) - II

3 sectors, 8-antenna LTE-A

1 sector

1 site

a)

b)

c)

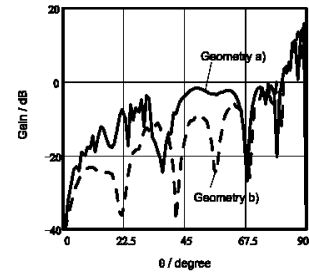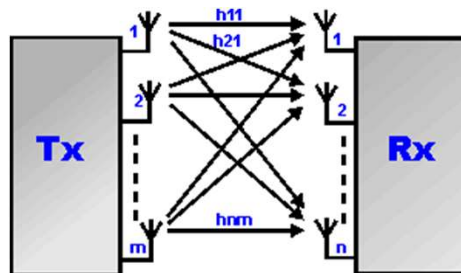Base station antenna pattern affected by the concrete foundation too!

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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!

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Goals of MIMO

Array gain
- increase power
- beamforming

Diversity
- mitigate fading
- space-time coding

What is a problem here?

Spatial multiplexing
- multiply data rates
- spatially orthogonal channels

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Goals of MIMO

diverse

Rx Side

Rx-diversity

Spatial-multiplexing
(Tx-Rx diversity)

Beamforming

Tx-diversity

directive   Tx Side   diverse

Antenna spacing for diverse vs. directive modes?

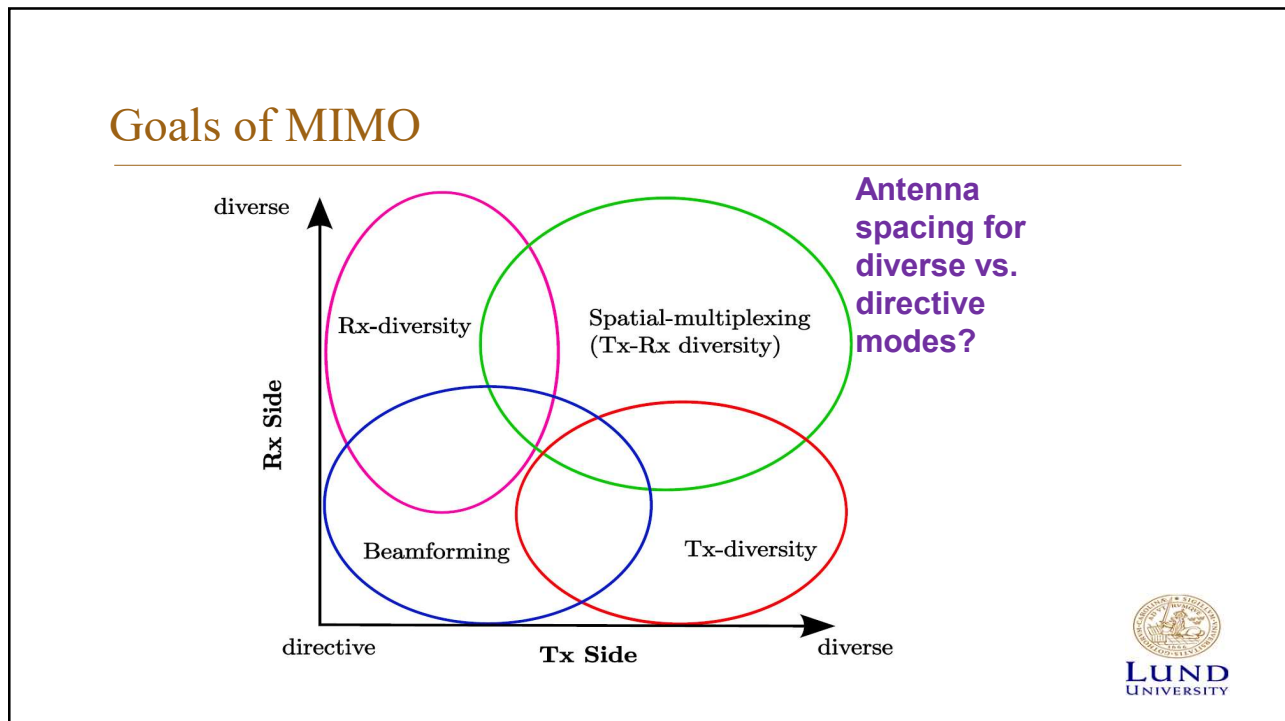LUND
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Benifits of MIMO Systems

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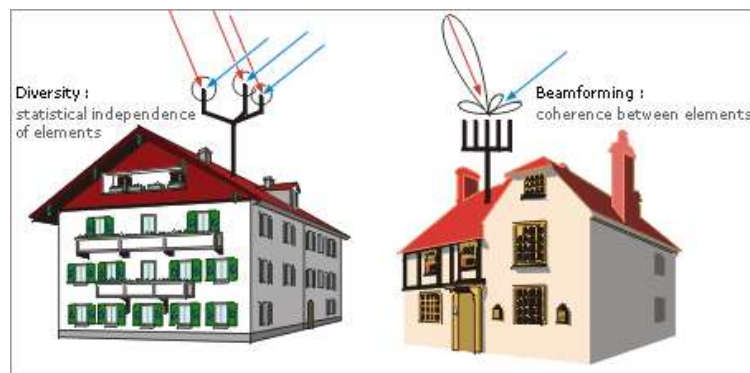
MS

BS
cell with
omni-antenna

cell with directional
antenna

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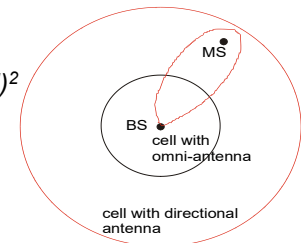
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Diversity vs. beamforming

Diversity: statistical independence of elements
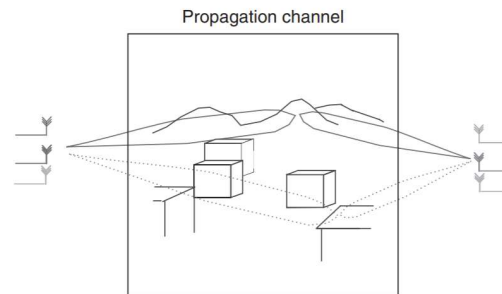Beamforming: coherence between elements

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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

Propagation channel

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History

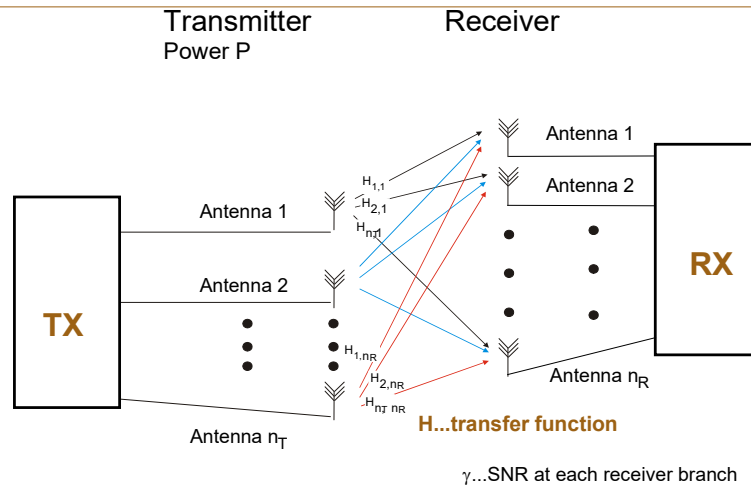- Diversity:
  – Receive diversity: since 1940s
  – Transmit diversity: early 1990s
    » Wittneben; Winters
  – Space-time codes in late 1990s
    » Tarokh et al.; Alamouti
- Spatial multiplexing:
  – Invented by Winters 1987
  – Theoretical treatment in mid-1990s
    » Winters Foschini&Gans; Telatar;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

Examples of wireless systems with MIMO technology?

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Signal model

Transmitter
Power P

Receiver

Antenna 1

Antenna 2

$H_{1,1}$
$H_{2,1}$
H_{n_T1}

Antenna 1

Antenna 2

RX

TX

Antenna 2

H_{1,n_R}
H_{2,n_R}
$H_{n_T n_R}$

Antenna n_R

H...transfer function

Antenna n_T

γ...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.

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

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

$\mathbf{x} = [x_1 \ x_2 \ \ldots \ x_{n_{Tx}}]^{\mathrm{T}}$, ←transmit signal vector

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

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

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):

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

- Foschini's formula:

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

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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

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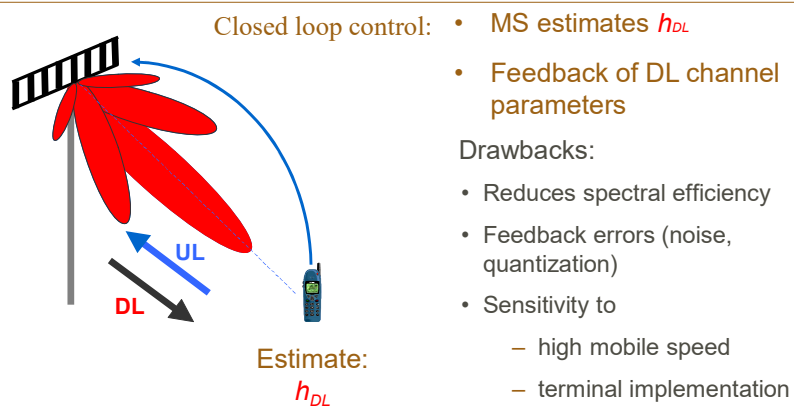## Channel knowledge is important for the system

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

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

UL

DL

Estimate:
h_{DL}

Wireless Communication Channels

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