Drahtlose Breitbandkommunikation - MIMO

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Vorlesung Drahtlose Breitbandkommunikationssysteme

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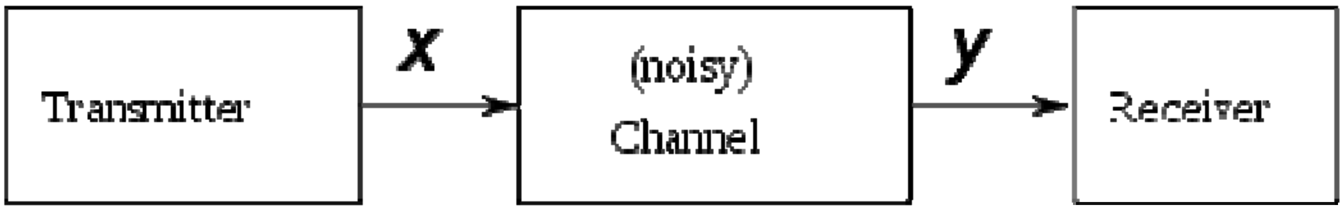
Channel Capacity: Shannon Theorem [Wikipedia]

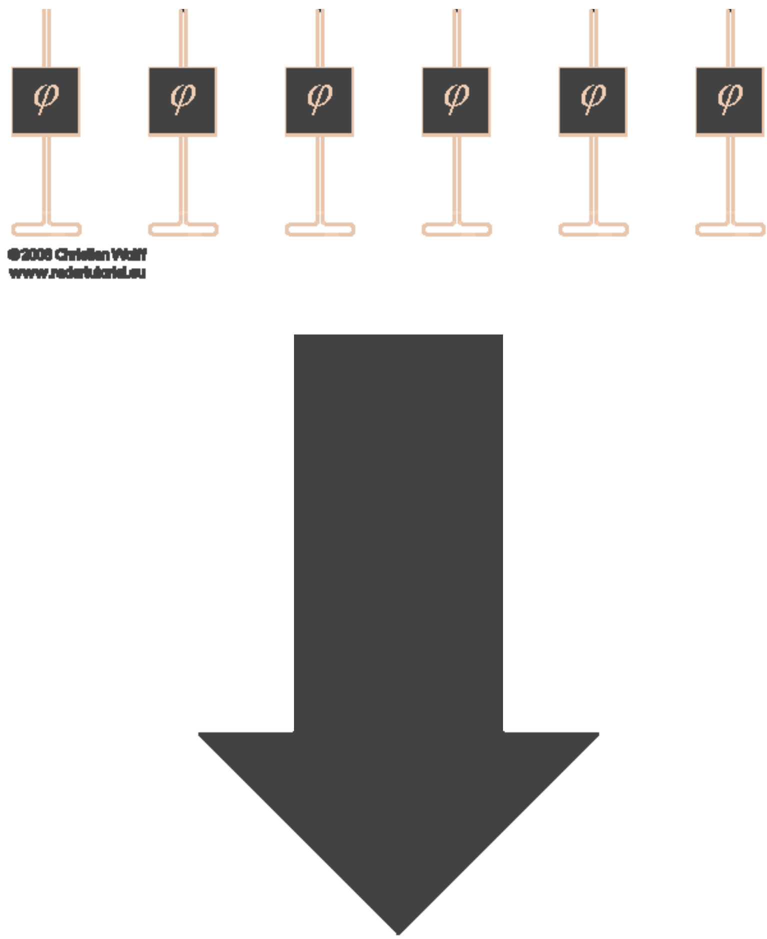


- The **Shannon limit** or **Shannon capacity** of a communications channel is the theoretical maximum information transfer rate of the channel, for a particular noise level.
- Stated by Claude Shannon in 1948 (with sketchy proof)
- The first rigorous proof by Amiel Feinstein in 1954.
- The Shannon theorem states that given a noisy channel with channel capacity *C* and information transmitted at a rate *R*, then if $R<C$ there exist codes that allow the probability of error at the receiver to be made arbitrarily small.
  - This means that, theoretically, it is possible to transmit information nearly without error at any rate below a limiting rate, *C*.

Beamforming

- Beamforming is a signal processing technique used in sensor arrays for directional signal transmission or reception.
- This is achieved by combining elements in a phased (timed) array in such a way that signals at particular angles experience constructive interference while others experience destructive interference.
- Beamforming can be used at both the transmitting and receiving ends.
- The improvement compared with omnidirectional reception/transmission is known as the receive/transmit gain (or loss).
- Beamforming can be used for radio or sound waves.
- It is used in radar, sonar, seismology, wireless communications, radio astronomy, acoustics, and biomedicine.
- Adaptive beamforming is used to detect and estimate the signal-of-interest at the output of a sensor array by means of optimal (e.g., least-squares) spatial filtering and interference rejection.

Source: Wikipedia (http://en.wikipedia.org/wiki/Beamforming)



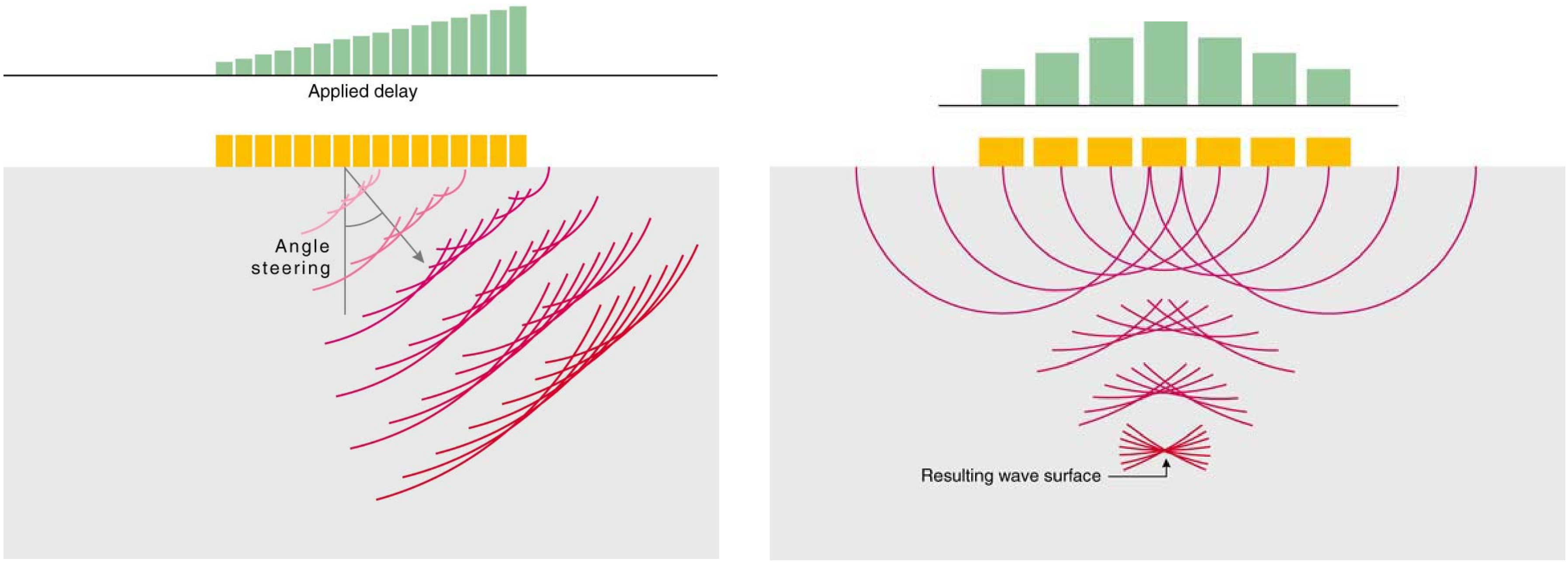
Delay <-> Phaseshift

- In principle, delay elements are needed for beamforming, which are difficult to implement
- Phase shifters can be used to generate a delay for a single specific frequency
- For broadband signals, phase shifters are sub-optimal since the delay is frequency dependent

  -> Beam widening

Beamforming -prinziple

- Beamsteering and Beamfocussing



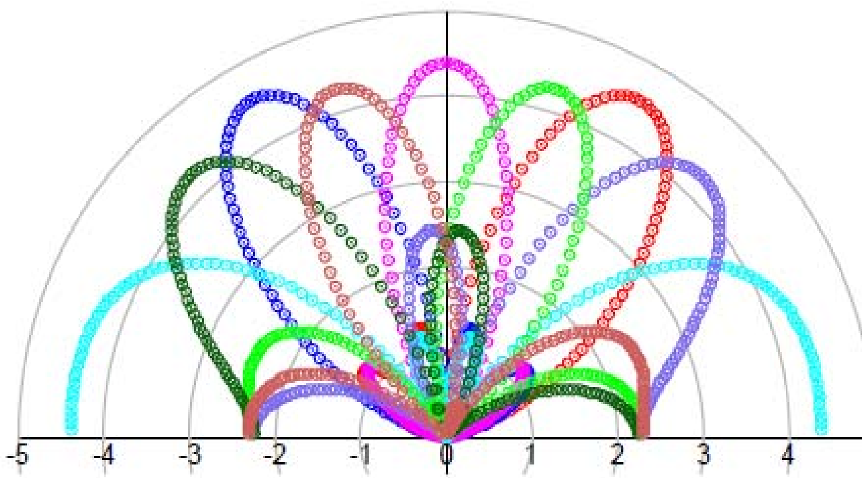
Source: *http://www.detectunit.co.za/phased_arry.pdf*

Beamforming-animation

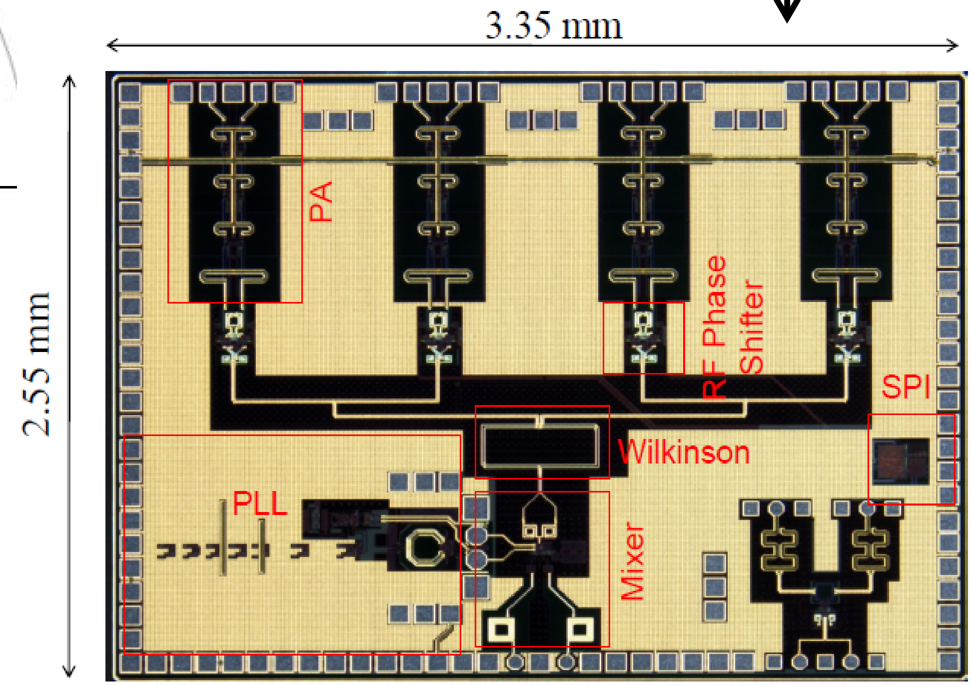
http://www.radartutorial.eu/06.antennas/pic/if3.big.gif

https://en.wikipedia.org/wiki/Phased_array

https://www.geogebra.org/m/ArF3sKpW



Simulated 8 beams of the
← beam-steering TX chip
fabricated at IHP



Beamforming using 60-GHz Technology

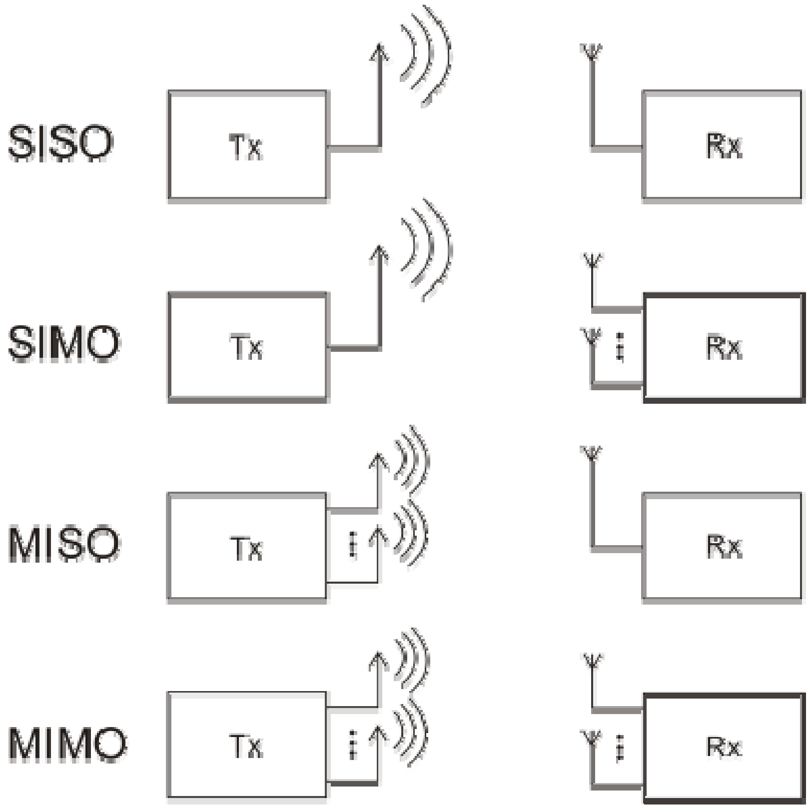
Source: http://wirelessgigabitalliance.org/specifications/

MIMO-Techniken

- MIMO = Multiple Input Multiple Output (das heisst, es werden Mehrantennensysteme eingesetzt)
- Erhöhung der spektralen Effizienz möglich (je nach Anzahl der verwendeten Antennen)
- Zum Teil hoher Rechenaufwand in Empfänger und/oder Sender notwendig
- Kanaleigenschaften für jede Antenne (Kanalmatrix) müssen bekannt sein
- Vor allem interessant, für hohe Trägerfrequenzen (kleine Antennen), da sonst große Antennenarrays notwendig sind.

SISO -> MIMO (Wikipedia)

Depending on the number of antennae, wireless communication systems can be classified into:



= Single Input Single Output

= Single Input Multiple Output

= Multiple Input Single Output

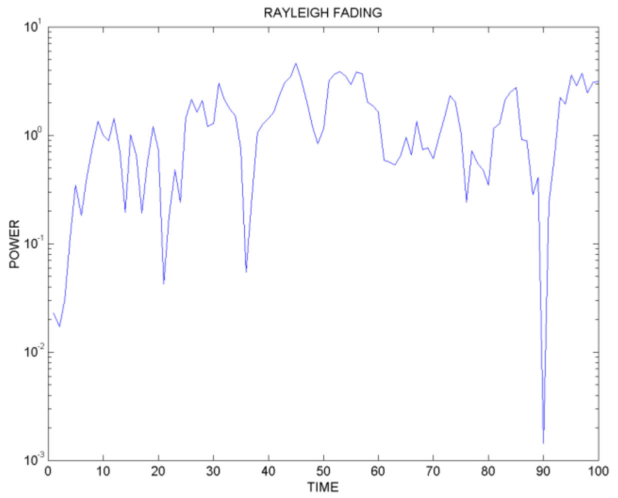
= Multiple Input Multiple Output

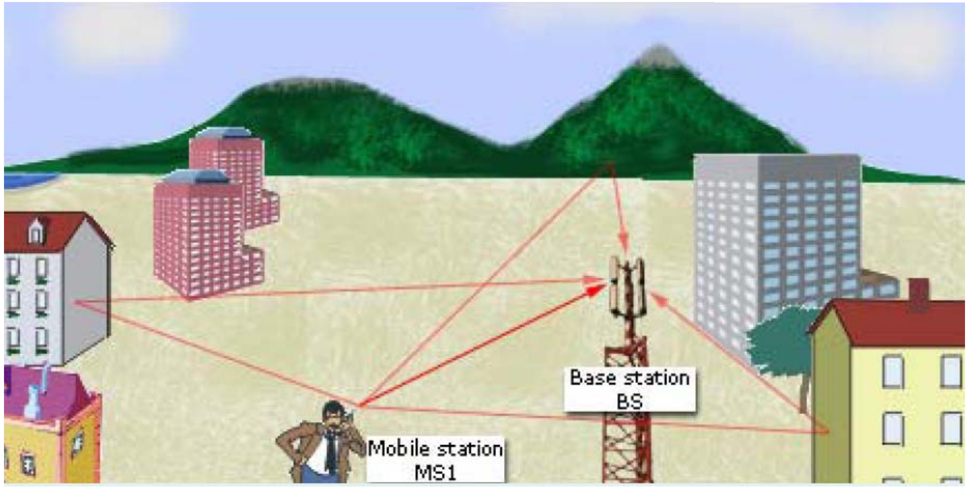
Source: Benjamin Baumgärtner (Wikipedia)

Multiple-input Multiple-Output (MIMO) systems

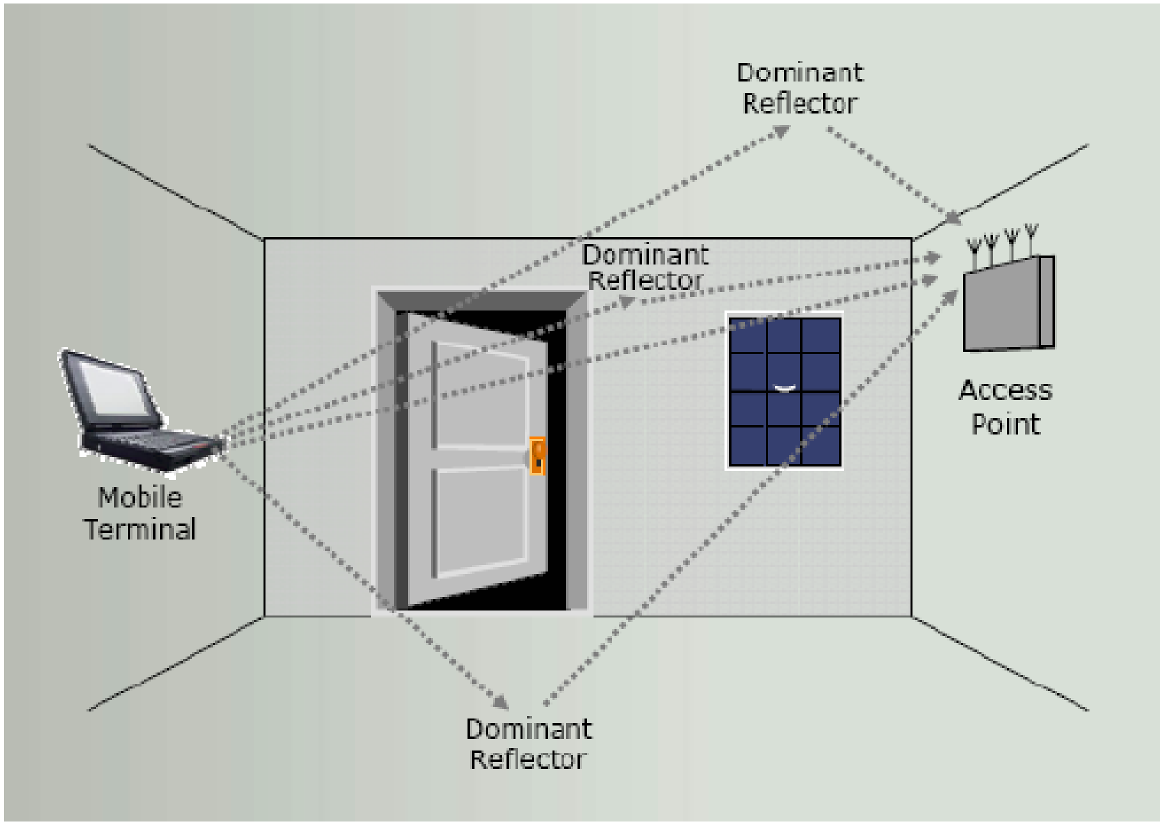
Context: single-antenna communication systems (SISO)
The wireless channel is very **hostile**

- Fading: fluctuations in received signal strength
  - Amplitude
  - Phase
- Other issues:
  - Signal power falls off with distance (Path loss)
  - Scarce available bandwidth
  - Reflections, diffractions, scattering
- Line of Sight (LOS) and NLOS situations





- Idea: MIMO (Multiple-In Multiple-Out):
  - Exploit in rich scattering environments, the spacial component as well as the frequency component
  - Special variants: SIMO; MISO (S=„Single“)



What are the aims of MIMO?

- High data rate wireless communications links
- Wide coverage
- Offering good Quality of Service (QoS) → high reliability of the communication channel

High data rate → Achieve "Channel Capacity (C)"

Quality → Minimize Probability of Error (P_e)

Other Issues →
- Minimize complexity/cost of implementation of proposed system
- Minimize transmission power required (translates into SNR)
- Minimize Bandwidth (frequency spectrum) used

Standards use MIMO

- Wireless Local Area Networks (WLAN) : 802.11n
- Cellular networks: HSDPA+, 3GPP-LTE
- WiMAX (802.16e)

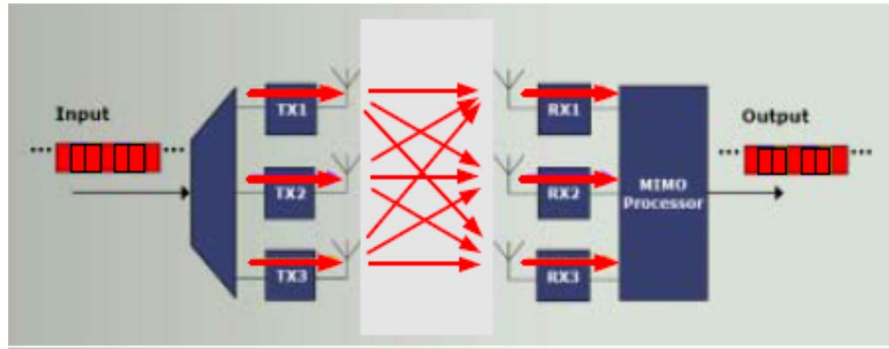
MIMO: Modes

(Diversity)

- **Spatial Expansion:**

  Transmission of the same data over each antenna

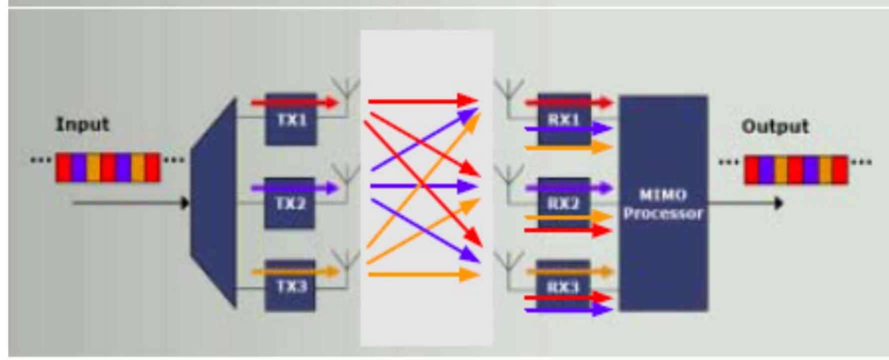
  Increased Range/Robustness



- **Spatial Multiplexing:**

  Transmission of different data over each antenna

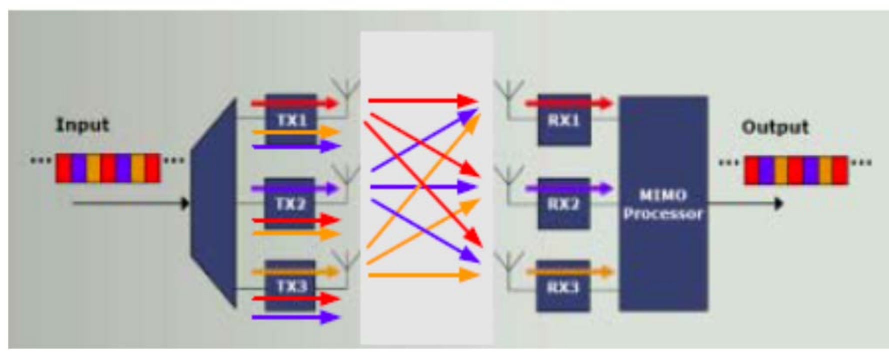
  Increased Datarate



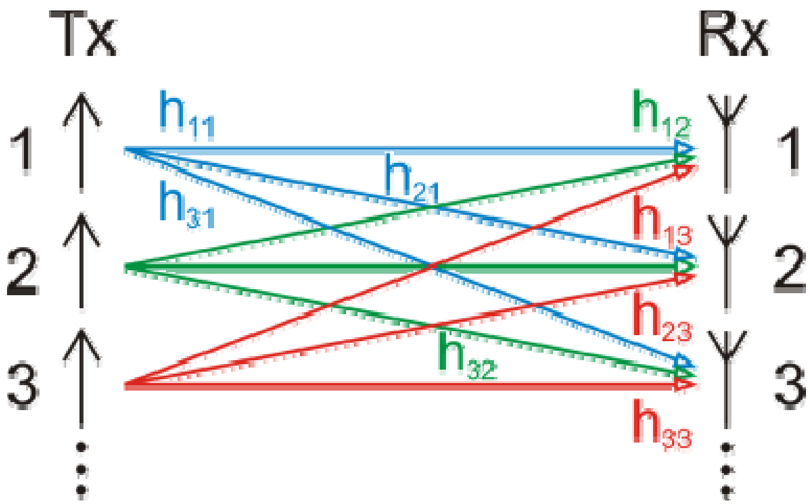
- **Beamforming:**

  Precoding of the transmitted data such that the main paths are used for the transmission

  Increased Datarate/Range/Robustness



MIMO Kanalmatrix (Wikipedia)

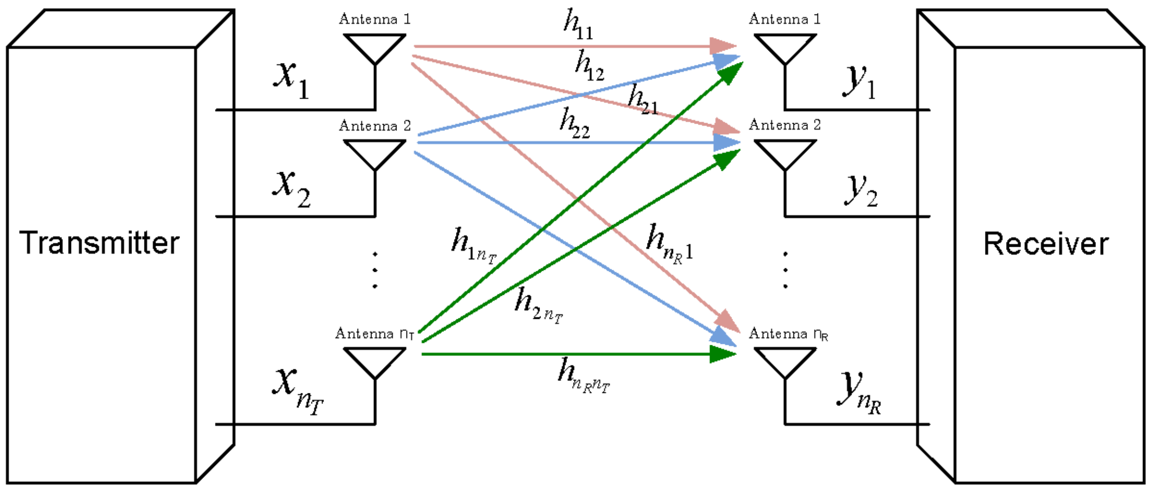


Graphical Representation

$$\underline{H} = \begin{bmatrix} h_{11} & \cdots & h_{1n_T} \\ h_{21} & \cdots & h_{2n_T} \\ \vdots & \ddots & \vdots \\ h_{n_R1} & \cdots & h_{n_Rn_T} \end{bmatrix} \text{ mit } h_{ij} = \alpha + j\beta$$

Matrix Notation

Source: Wikipedia (http://de.wikipedia.org/wiki/MIMO_(Nachrichtentechnik)



MIMO channel matrix

$$\mathbf{H}(t,f) = \begin{bmatrix} h_{11}(t,f) & \cdots & h_{1n_T}(t,f) \\ h_{21}(t,f) & \ddots & h_{2n_T}(t,f) \\ \vdots & \ddots & \vdots \\ h_{n_R1}(t,f) & \cdots & h_{n_Rn_T}(t,f) \end{bmatrix}$$

h_{ij} is a Complex Gaussian random variable that models fading gain between the i^{th} transmit and j^{th} receive antenna

Time-invariant channel : $\mathbf{H}(f)$
Flat-fading channel : $\mathbf{H}(t)$
Invariant channel : $\mathbf{H}$

Input/output relationship:

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}$$

MIMO potentials

- If scattering is rich enough and inter-element spacing sufficient, the subchannels are uncorrelated → independent fading
- One is able to transmit independent information streams on different antennas

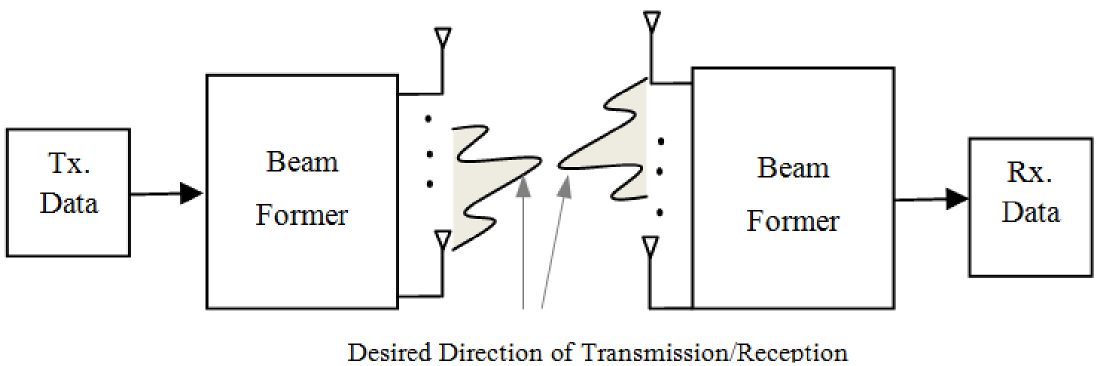
MIMO design criterion

MIMO offers numerous features that current communications systems can take advantage of

- **Diversity**
  - Send the same information through different paths (single-stream)
  - No channel knowledge (CSI) required
  - Mitigates fading, more reliable reception
  - Essential in fading channels, slope of the bit error rate (BER) curve with SNR (for high SNRs), maximum diversity is $n_{\mathrm{T}} \times n_{\mathrm{R}}$
- **Spatial multiplexing**
  - Transmit independent data signals from individual antennas
  - different SISO channels
  - lineal increase of capacity with $r = \min(n_{\mathrm{T}}, n_{\mathrm{R}})$

Coding gain (array gain): Precoding/beamforming

- Increase in average SNR due to coherent combining, increase coverage
- Usually single-stream beamforming
- Requirement of CSI at the transmitter (CSIT) or/and receiver (CSIR)

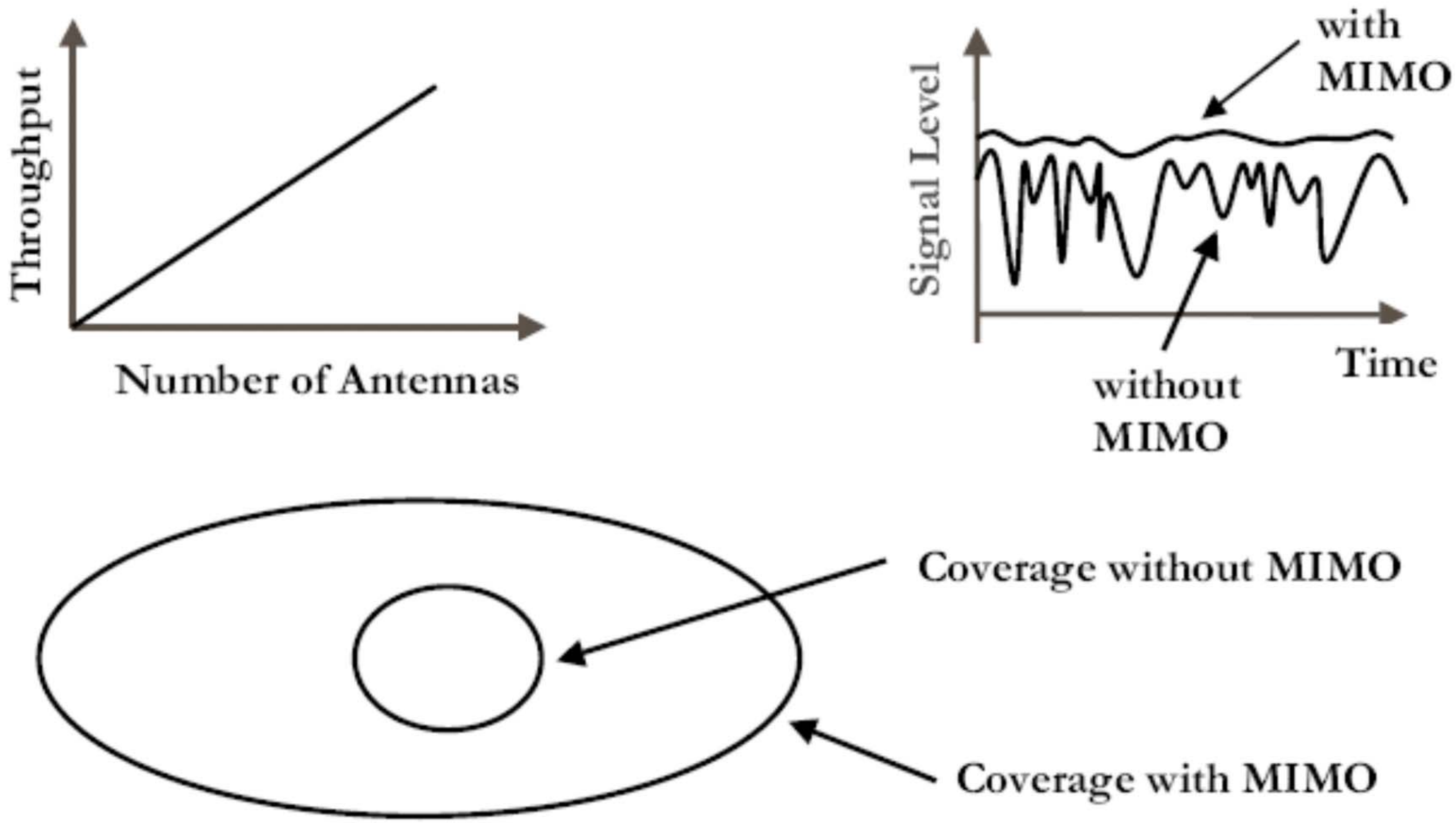


Transmission over MIMO channels

We can use the advantages provided by MIMO channels to:

- Maximize diversity to combat channel fading and decrease the BER → **space-time codes** (STC)
- Maximize the throughput → **spatial multiplexing**
- Try to do both at the same time → trade-off between increasing the throughput and increasing diversity [Zheng and Tse, IEEE Trans. IT, 2003]

Combined advantages of MIMO



Coordinated Multi Point Transmission (CoMP)

- Reduce Interference
- Increase SNR
- CoMP is a distributed MIMO

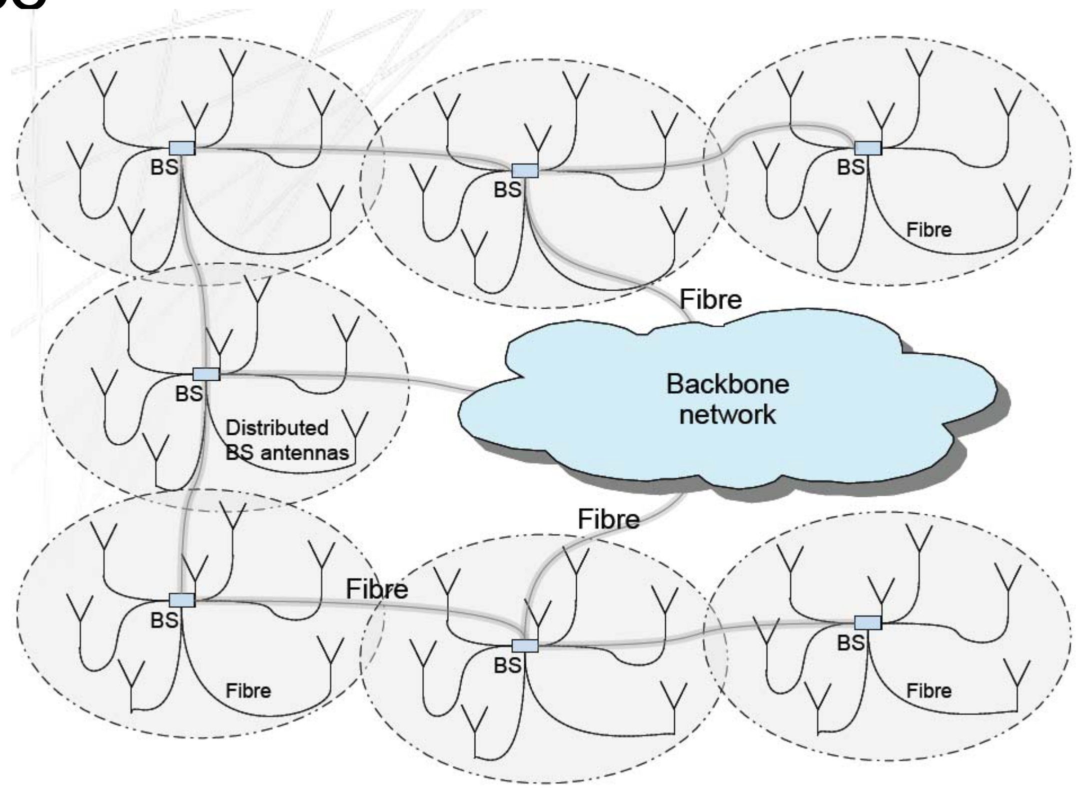


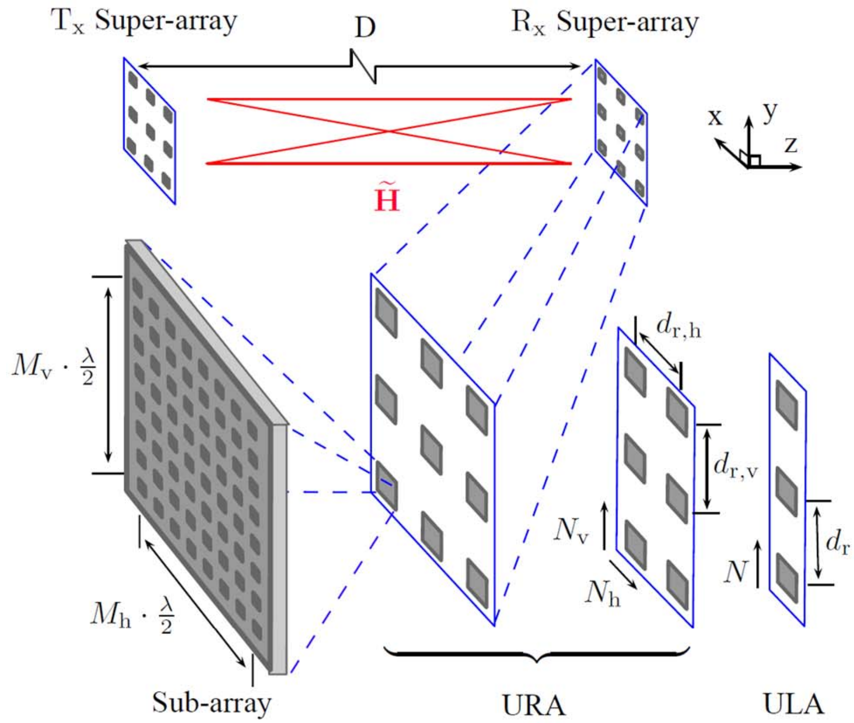
Fig: [Tölli et al.]

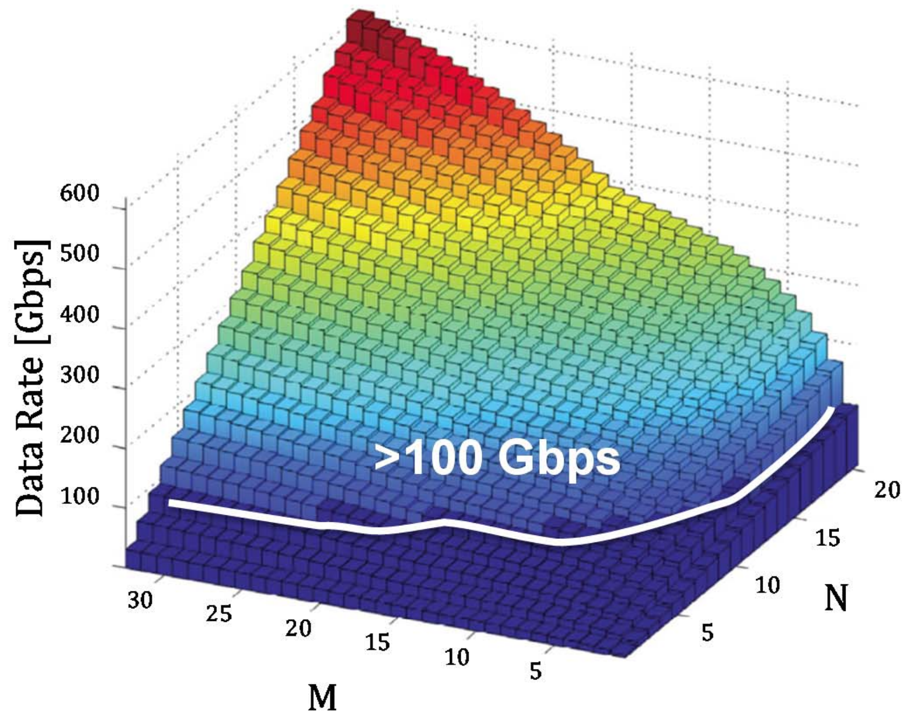
- Synchronisation of BS needed
- Channel State Information (CSI) must be known by all BS
- Very complex technique; Used for LTE-advanced

→Perhaps applicable for WLANs

Antenna Topology for LOS-MIMO

$$d_{\mathrm{OPT}} = \sqrt{D \cdot \lambda / N_{\mathrm{A}}}$$

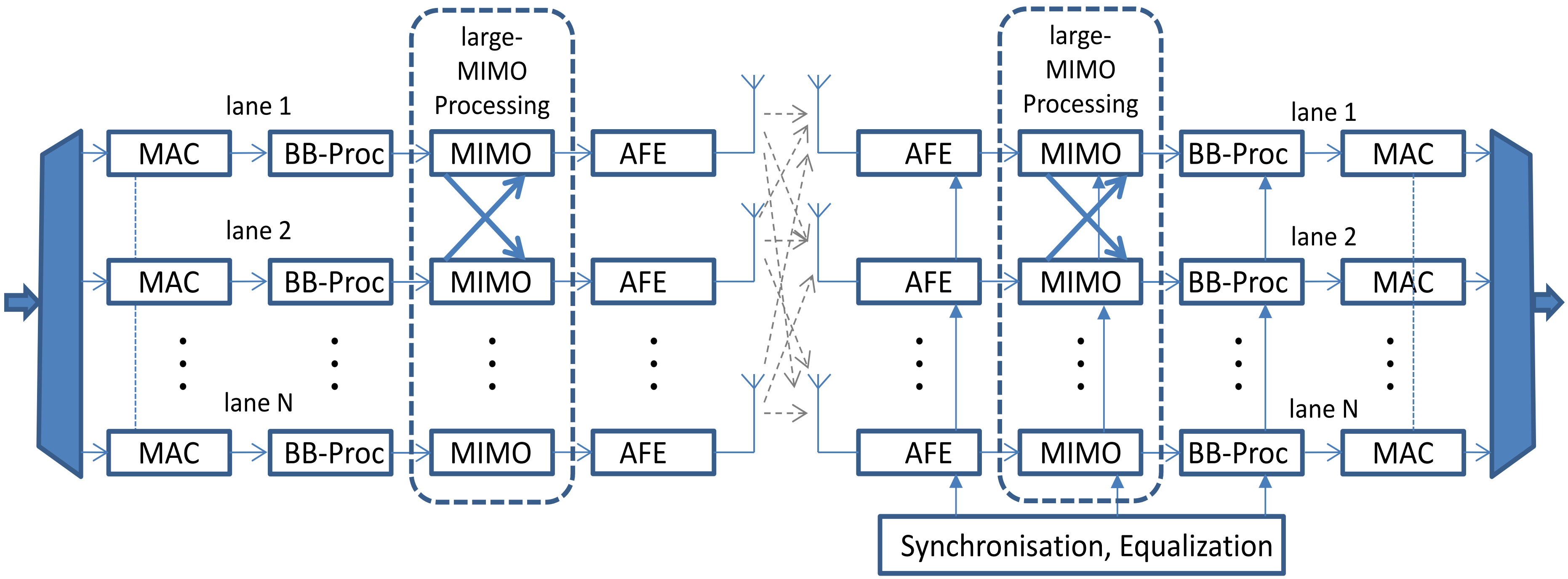




Index	$N=N_{\mathrm{v}}\times N_{\mathrm{h}}$	M^2	R(Gbps)	$\bar{\gamma}$[dB]	P_{T}[dBm]	Height×Width
1	$4=2\times 2$	23^2	101.7	40.8	15.2	0.50m×0.50m
2	$6=3\times 2$	10^2	101.4	27.1	16.0	0.82m×0.50m
3	$8=4\times 2$	5^2	105.4	21.1	22.0	1.06m×0.50m
4	$9=3\times 3$	4^2	107.8	19.1	24.0	0.82m×0.82m

Source: Darko Cvetkovski

Architecture of the massive MIMO System



Challenges:
- Antenna design and optimisation (partitioning)
- Channel characterisation (for LOS-MIMO + 3D Antennas)
- massive MIMO processing (algorithms + implementation)
- Scalable parallel implementation of BB-processor and MAC, …

Trends: Transmission Schemes

- Frequency selectivity
- Beam-widening

High-resolution multi-carrier transmission ???

- Rank of channel
- Antenna size

LOS-MIMO + 3D Antennas

- 3D Antennas

- Backhaul application
- Outdoor channel

LOS-MIMO

- MIMO under LOS conditions with large linear or planar antennas

- Data rate,
- # of spatial streams

NLOS-MIMO

- Use of fading and interference characteristics
- Usually linear or array antenna

- Distance
- Fading, interference

Beamforming

- Patch array antenna with adjustable gain and directivity

SISO

- Patch array antenna with fixed gain and directivity