Helsinki University of Technology
S.72.333 Postgraduate Course in Radio Communications

Overview of MIMO Radio Channels

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Outline

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II. Characteristics of MIMO channels

- MIMO channel capacity
- Environments and simulation methods
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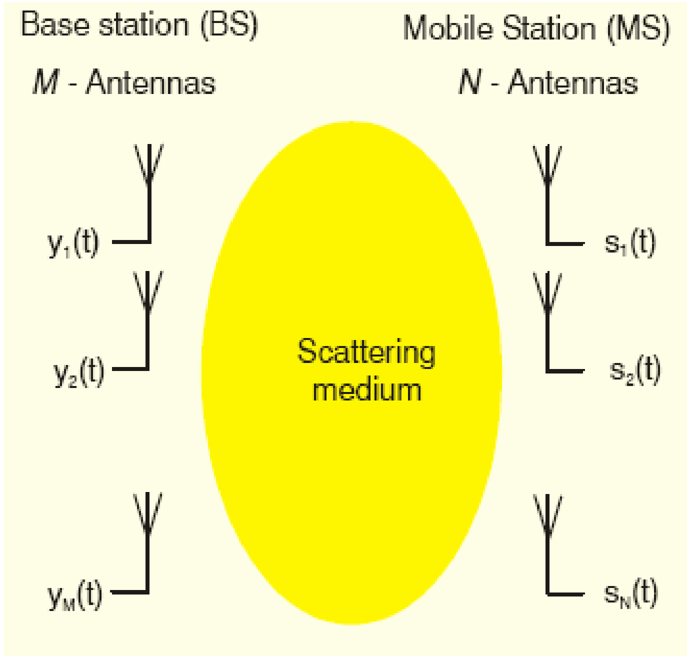
I. Introduction (1/3)

- Multiple-Input Multiple-Output (MIMO) System:

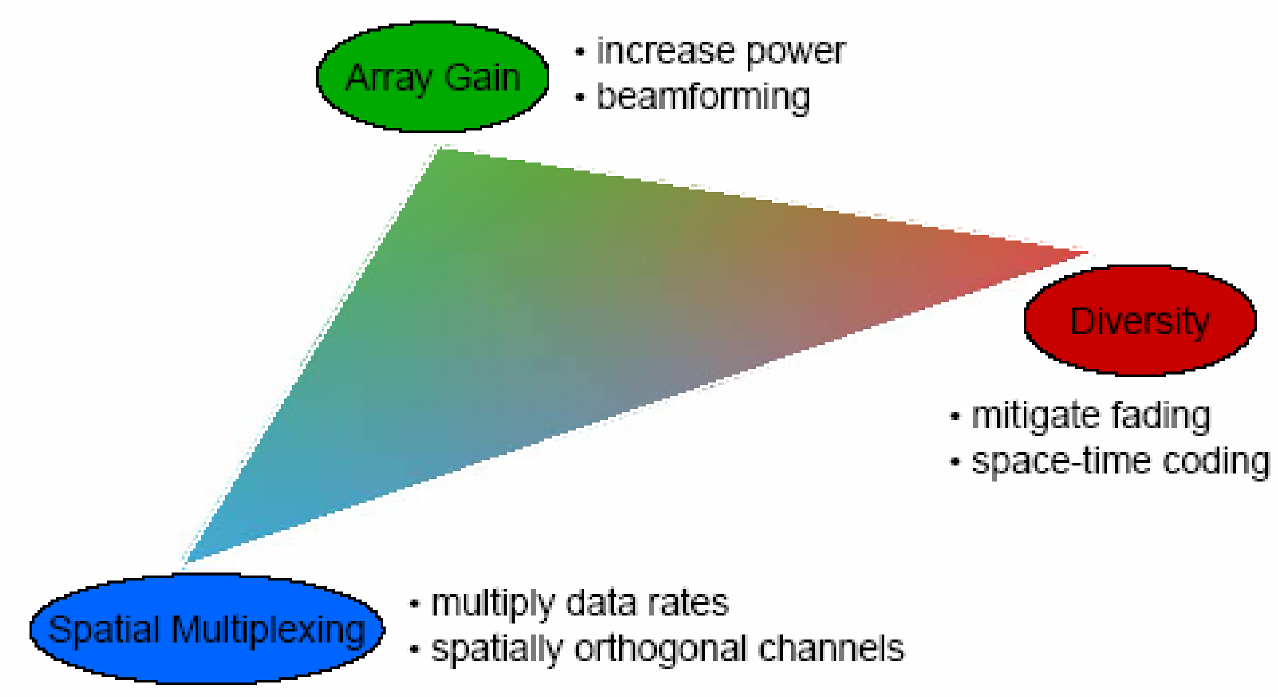
Transmitting (TX) and receiving (RX) ends equipped with multiple antenna elements.



- Radio channel: propagation medium between the TX and RX antennas.

I. Introduction (2/3)

- MIMO is critical technology for current and forthcoming cellular systems. Due to the potentials:



I. Introduction (3/3)

- MIMO channel is two-dimensional (spatial and temporal), they are often described independently.

- Development of MIMO channel models are based on propagation environment, i.e., macro-, micro- or pico cell. The simulation methods include statistical, measurement-based and ray-tracing.

- MIMO channel is various and complex, we'll concentrate mainly on:
  - Introduce the basic MIMO channel concepts, try to compare them with conventional (SISO) channels as possible.
  - Investigate some empirical channel models and their applications.

II. MIMO channel transfer function

- MIMO channel transfer function ***H*** is a complex matrix. For narrowband of ***M*** and ***N*** antenna elements at TX and RX expressed as

$$H = \begin{vmatrix} h_{11} & h_{12} & \cdots & h_{1N} \\ h_{21} & h_{22} & & \cdots \\ \vdots & \vdots & \vdots & \vdots \\ h_{M1} & \cdots & \cdots & h_{MN} \end{vmatrix}$$

- Where h_{ij} is complex coefficient between i^{th} / j^{th} TX/RX antennas
- Channel amplitude gains $\left|h_{ij}\right|$ are usually Rayleigh distributed variables.

II. Capacity of the radio channel

- The capacity of a communication system (Shannon's formula) as

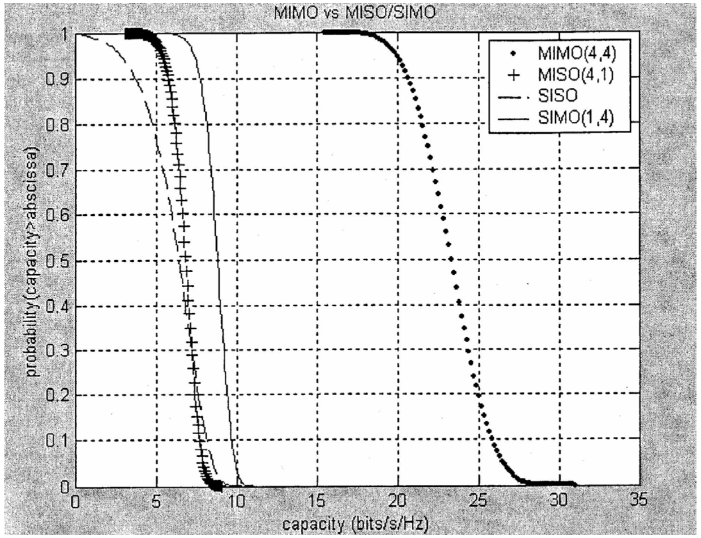
$$C = W \cdot \log_2(1 + SNR)$$

- In the high capacity links (e.g. WLANs), limited by two problems
  - High pathloss (include in SNR)
  - Interference of multipaths (include in W)
- The use of MIMO systems could resolve both above-mentioned problems
  - Provides greater gain.
  - Cancel interference with use of array processing techniques.

II. MIMO channel capacity

- Several channel parameters influence on MIMO capacity.
  - ➢ Capacity is lower with increasing Ricean factor
  - ➢ Lower capacity can be caused by higher channel fading correlation
  - ➢ High XPD enhances the capacity

- Increased MIMO channel capacity



II. MIMO channel capacity

- Two capacity forms are often used to describe different properties of MIMO channel.

  Ergodic (mean) capacity:

  1. Maximal average information rate over the distribution of the channel matrix elements, so it is significant when every channel used.
  2. Used as a measure for the spectral efficiency, more representative for average throughput achievable on the channel.

  Outage capacity:

  1. Quantifies level of performance that is guaranteed with a certain level of reliability, e.g., define the probability that capacity is less than outage capacity as q, information rate guaranteed for 1-q channel realizations.
  2. Describe diversity advantage of the channel.

II. MIMO channel characteristics

- Recall the conventional (SISO) channel impulse response (IR)

$$h(t,\tau) = \sum_{i=1}^{N} a_i(t) e^{j\phi_i(t)} \delta(\tau - \tau_i)$$

where $a_i(t) e^{j\phi_i(t)}$ is complex amplitude of the multipath components.

- Channel is described as time-variant. WSSUS assumption is often made for deriving the channel parameters.
- No information about the angle-of-arrival (AOA) of each multipath component.

II. Characteristics of MIMO channel

- MIMO channel IR can be expressed as

$$h(t,\tau)=\sum_{i=1}^{N}a_i(t)e^{j\phi_i(t)}\vec{a}(\theta_i)\delta(\tau-\tau_i)$$

where $\vec{a}(\theta_i)$ is the spatial response vector. Usually, it is a function of array geometry and AOA of the received signal.

  - MIMO channel IR is a summation of several multipath components, each has its own amplitude, phase and AOA.
  - In the model, information on space and time are described independently.

II. MIMO channel classification

- MIMO channel is classified as

Low-rank: $S_t < \dfrac{1}{B_r}$ and $S_\varphi < \varphi_{3dB}$ (narrow-band)

High-rank: $S_t \geq \dfrac{1}{B_r}$ or $S_\varphi \geq \varphi_{3dB}$ (wide-band)

  - S_t and S_φ are delay spread and angle spread, B_r is receiver bandwidth, φ_{3dB} denotes 3dB-beamwidth of the antenna array in azimuth.
  - For simplicity, directional dispersion is restricted only on azimuth direction.

II. Channel estimation methods

- Statistical method

  Temporal and spatial properties are often generated independently, and AOA in the mobile station is uniformly distributed on $[-\pi, \pi]$

- Measurement-based

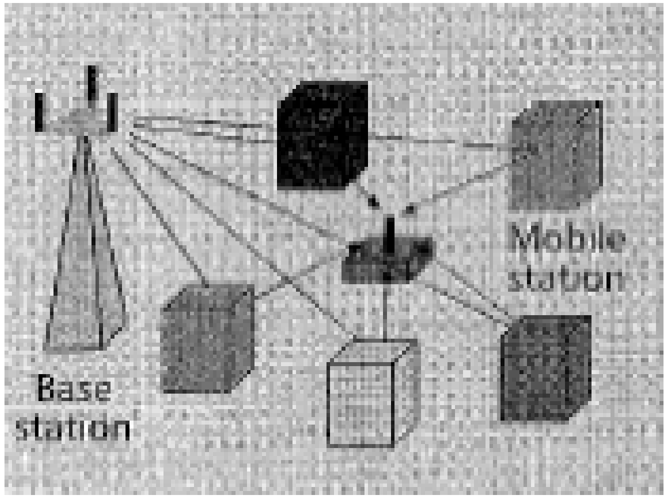
  Measurement is used to generate the time-variant directional distribution of channel IRs $h(\tau, t, \theta)$.

- Ray tracing method

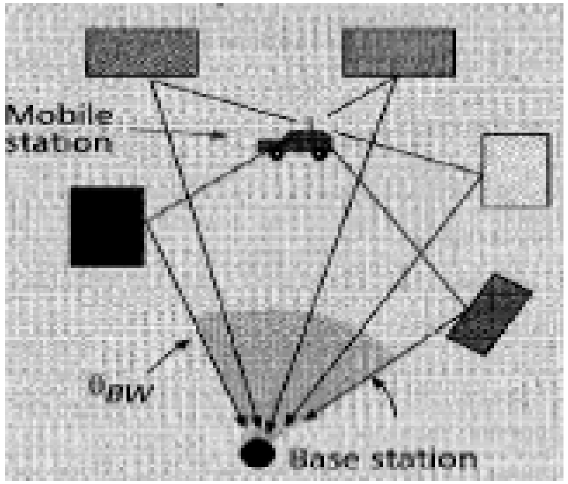
  Based on the geometric theory and reflection, diffraction and scattering models, however, high computational burden makes it difficult to use.

II. Channel environments

Macrocell



Mobile station perspective



Base station perspective

- **Scatterers surrounding MS are about the same/higher height, implies arriving signal from all directions, i.e., AOA is uniformly distributed $[-\pi, \pi]$.**
- **BS is deployed higher than the surrounding scatterings, multipath components are restricted to a smaller angular region θ_{BW} .**

II. Channel environments

Microcell

- BS antenna is mounted at same height as surrounding objects, scattering process also happens in vicinity of BS. Implies AOA is larger than in Macrocell environments.
- Large angle spreads and antenna element spacings result in lower signal correlation, provide an increased diversity gain.

Picocell

- A property of many indoor channels. The most complicated environments.
- Experimental measurements show that the scaterers appear in cluster, which means the multipath components arriving in group.

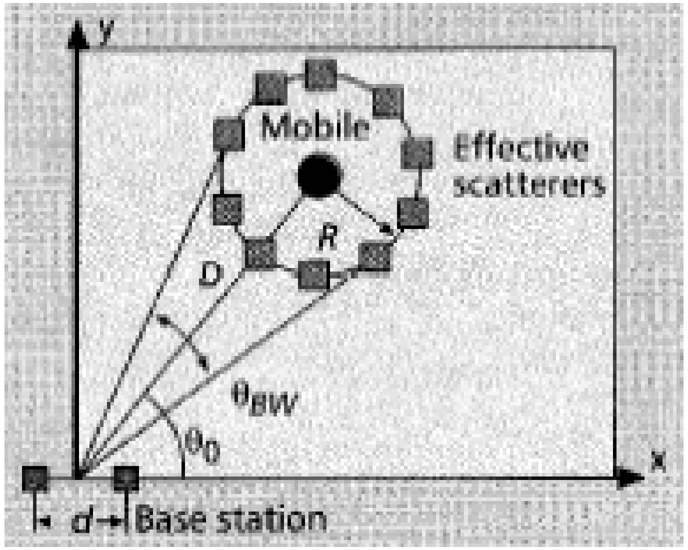
II. Statistical models

Lee's model (Macrocell)

- The discrete AOAs at mobile

$$\theta_i \approx \frac{R}{D}\sin\left(\frac{2\pi}{N}i\right)$$

- The correlation of the signals between any two elements of the array



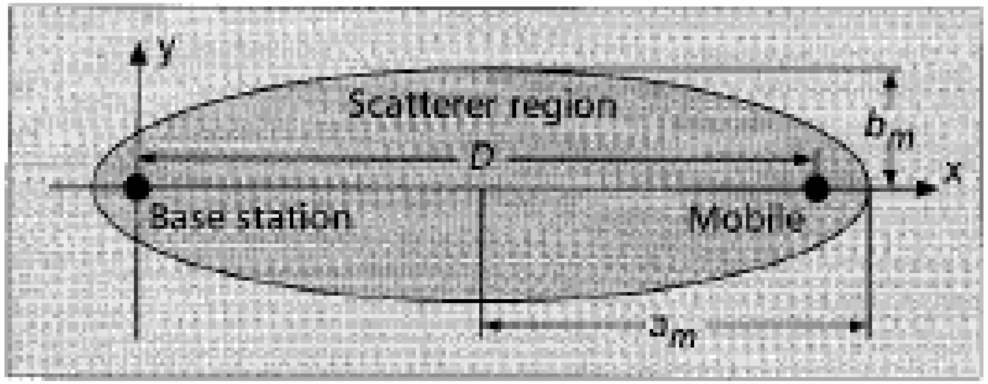
(scatterers evenly spaced on a circular ring)

$$\rho(d,\theta_0,R,D) = \frac{1}{N}\sum_{i=0}^{N-1}\exp\left[-j2\pi d\cos(\theta_0+\theta_i)\right]$$

➢ Level of correlation will determine performance of spatial diversity methods.

II. Statistical models

Geometrically based elliptical model (Microcell)



- Scaterers are uniformly elliptically distributed, BS and mobile are the foci.
- A nice attribute is multipath signals arrive within an absolute delay $\leq \tau_m$, ignoring the larger delays (experience greater pathloss).
- Choice of τ_m will determine both the delay spread and angle spread.

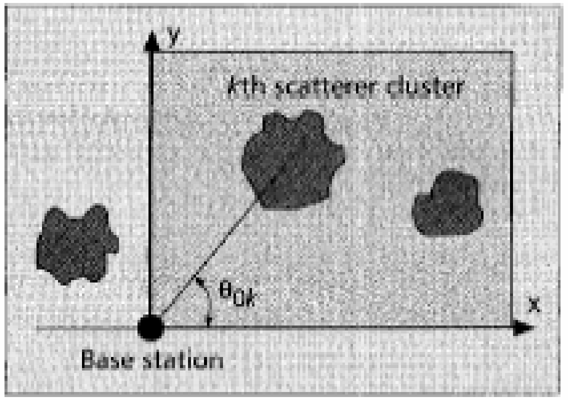
II. Statistical models

Saleh-Valenzuela's mode (Indoor)

- **Time and angle are statistically independent.**

$$h(t) = \sum_{i=0}^{\infty}\sum_{j=0}^{\infty} \alpha_{ij}\delta\left(t - T_i - \tau_{ij}\right)$$

$$h(t) = \sum_{i=0}^{\infty}\sum_{j=0}^{\infty} \alpha_{ij}\delta\left(\theta - \Theta_i - \omega_{ij}\right)$$



➡ ***i, j*** **correspond clusters and rays within a cluster.** α_{ij} **are Rayleigh distributed with mean square value described by a double-exponential decay**

$$\overline{\alpha_{ij}^2} = \overline{\alpha_{00}^2}\exp\left(-T_i/\Gamma\right)\exp\left(\tau_{ij}/\gamma\right)$$

➡ Θ_i **is the mean angle, uniformly distributed** $[-\pi,\pi]$ **.** ω_{ij} **is ray angle within a cluster modeled as a Laplacian distributed with zero mean and standard deviation** σ **.**

$$f(\omega) = \frac{1}{\sqrt{2}\sigma}\exp\left(-\left|\frac{\sqrt{2}\omega}{\sigma}\right|\right)$$

II. Measurement-based models

Extended Tapped- Delay- Line Model

- A wideband extension of traditional statistical tapped-delay-line model and includes AOA information

$$h(\tau,t,\theta)=\sum_{w=1}^{W}a_w(t)\delta(\tau-\tau_w)\delta(\theta-\theta_w)$$

W taps, each with time delay, complex amplitude and AOA.

- The joint density functions of the model parameters should be determined from measurements.

II. Measurement-based models

Ricean *K*-factor

- Model expression: $K \propto (antenna\_h)^{0.46} (distance\_d)^{-0.5}$

➢ In SISO, a high ***K***- factor (power ratio of LOS/ mean NLOS components) is desirable because the smaller fade margin needs to be allocated.

➢ In MIMO, high-*K* channel show a lower MIMO capacity. Because higher ***K***, more dominant H_{LOS} , its effect is to drive up antenna correlation and overall effective rank down therefore show low useable spatial degree of freedom. E.g., a (4,4) MIMO capacity with $K=0$ is almost always higher than with $K=10$.

➢ From a network deployment perspective, use of MIMO does not/does substantially improve link throughput near BS/ far away from BS.

III. Summary

- Physical layer is the bottleneck of wireless communication systems.

  MIMO system is being more and more interesting due to the potentials in which.

- The performance of radio systems highly depend on the accurate channel information, which provides the reliable estimates for the system design.

  It is important to know the knowledge of MIMO channel.

- Basic MIMO channel concepts, the empirical channel models and their applications are introduced and analysed.

IV. References

[1] J. Fuhl et al., "Unified channel model for mobile radio systems with smart antennas", IEE Proc. Vol. 145, No. 1 February 1998.

[2] Richard B. Ertel and Psulo Cardieri, "Overview of spatial channel models for antenna array communication systems", IEEE Personal Communications, Feb., 1998.

[3] David Gesbert et al., "From theory to practice: an overview of MIMO Space-Time coded wireless systems", IEEE Jounal on delected areas in communications, Vol. 21, No. 3, April 2003.

[4] Arogyaswami Paulraj, Rohit Nabar and Dhananjay Gore, *Introduction to Space-Time wireless communications, Cameridge University Press.*

Homework

1. In high capacity environments (e.g, WLANs), what factors limit the capacity of communication system? Why? what channel parameters influence on MIMO channel capacity? Try to explain (more detailed explanation is preferred).