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MIMO antennas, propagation channels, and their impact on system design

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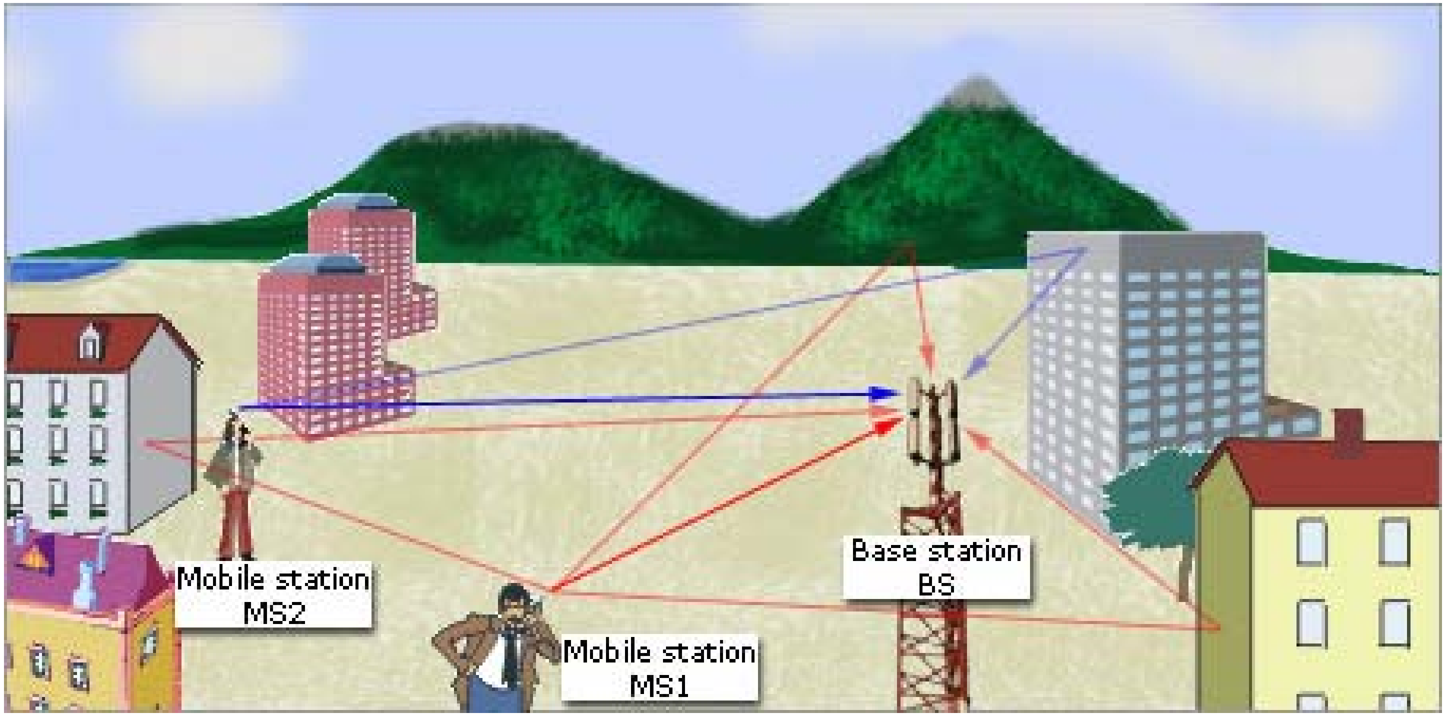
Wireless propagation channels describe how electromagnetic signals get from transmitter to receiver

- *It is the propagation channel that distinguishes wireless communications from wired communications:*
  - Multipath propagation (-> Fading, Time variations)
  - Interference



Antennas describe how electromagnetic waves are launched from TX and received at RX

- Antennas are interface between RF electronics and channel
  - TX antennas determine how waves are sent off into space
  - RX antennas receive the waves
- Complex antenna patterns determines how multipath components interact with antennas

- Channels and antennas determine the possibilities of signal transmission schemes and signal processing

Understanding channels is vital **for theory**

Any breakthrough in communications theory is based on simplified channel model! But at some point we must ask

"Which effects are real, and which are artifacts of the channel model?"

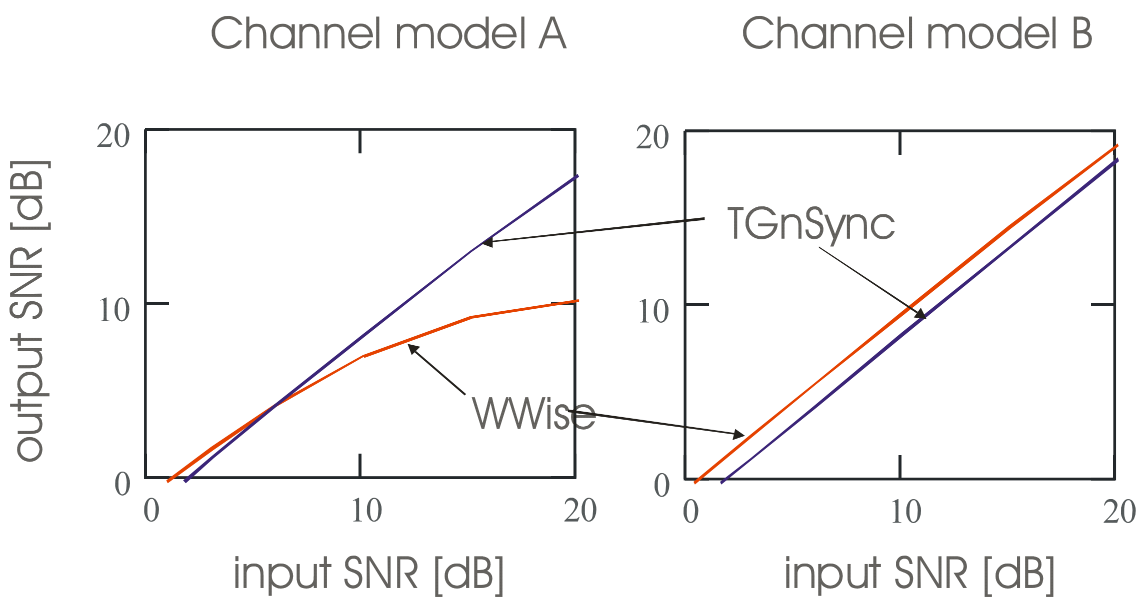
(A. Lapidoth)

Example: Rayleigh fading results in finite probability that receive power is larger than transmit power

- Too unlikely to matter in most cases
- Multiuser diversity always selects user with instantaneously best SNR
- What if number of users becomes very large ?

Understanding channels is vital for system testing

- Comparison of different systems:
  Different systems may “win” in different channels
  Channel model for standards need to be chosen carefully



Comparison of MIMO-OFDM-based proposals for 802.11n

Understanding channels is vital for system design

- System parameters have to be chosen according to propagation channel
- System cannot cover all thinkable “worst cases” (too inefficient); has to be designed *just right* for the channels in which it should operate
- Example:
  - Repetition frequency for training sequence of MIMO channel estimator

Understanding channels is an inspiration for theory and system design

- The channel creates the problems for effective data transmission
- Understanding where the problems are coming from gives ideas for how to circumvent them
- Example:
  - RF preprocessing for antenna selection

So……

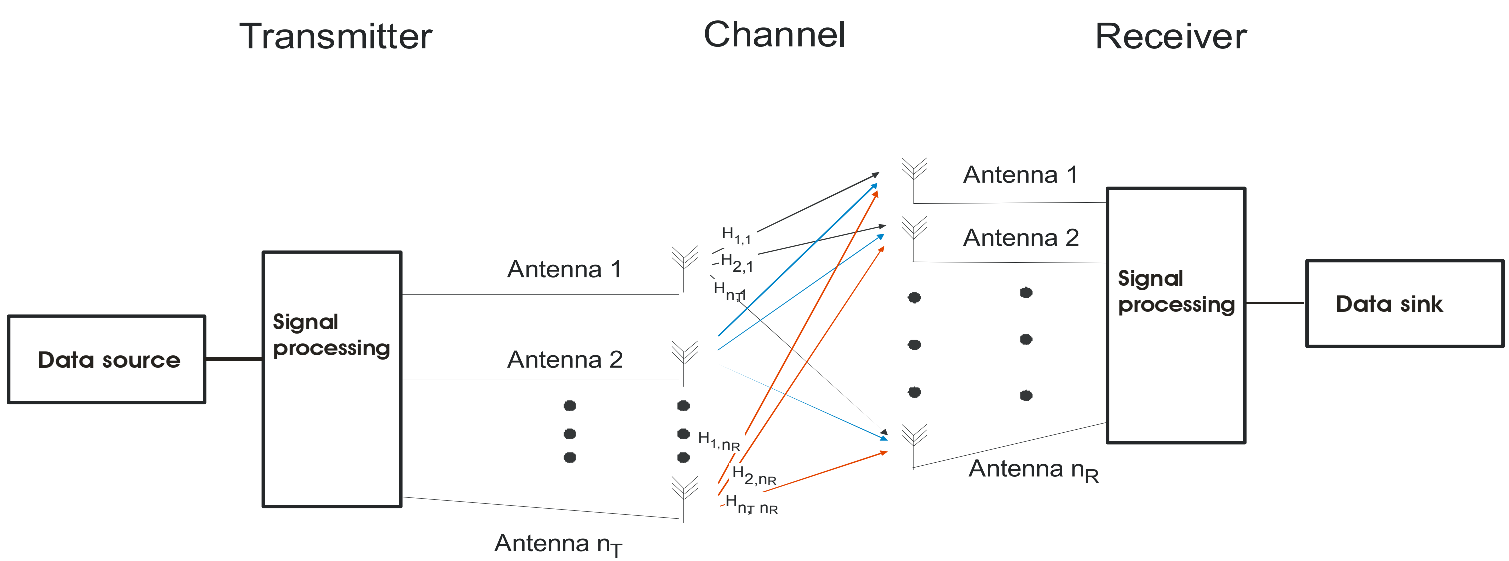
“Know thy channel”

(Solomon Golomb)

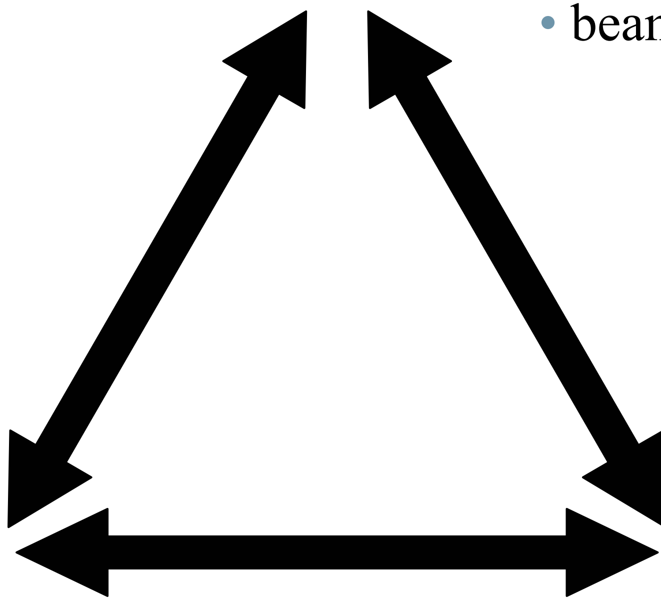
Definition of MIMO

- What is a MIMO system?

  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.



Goals of MIMO



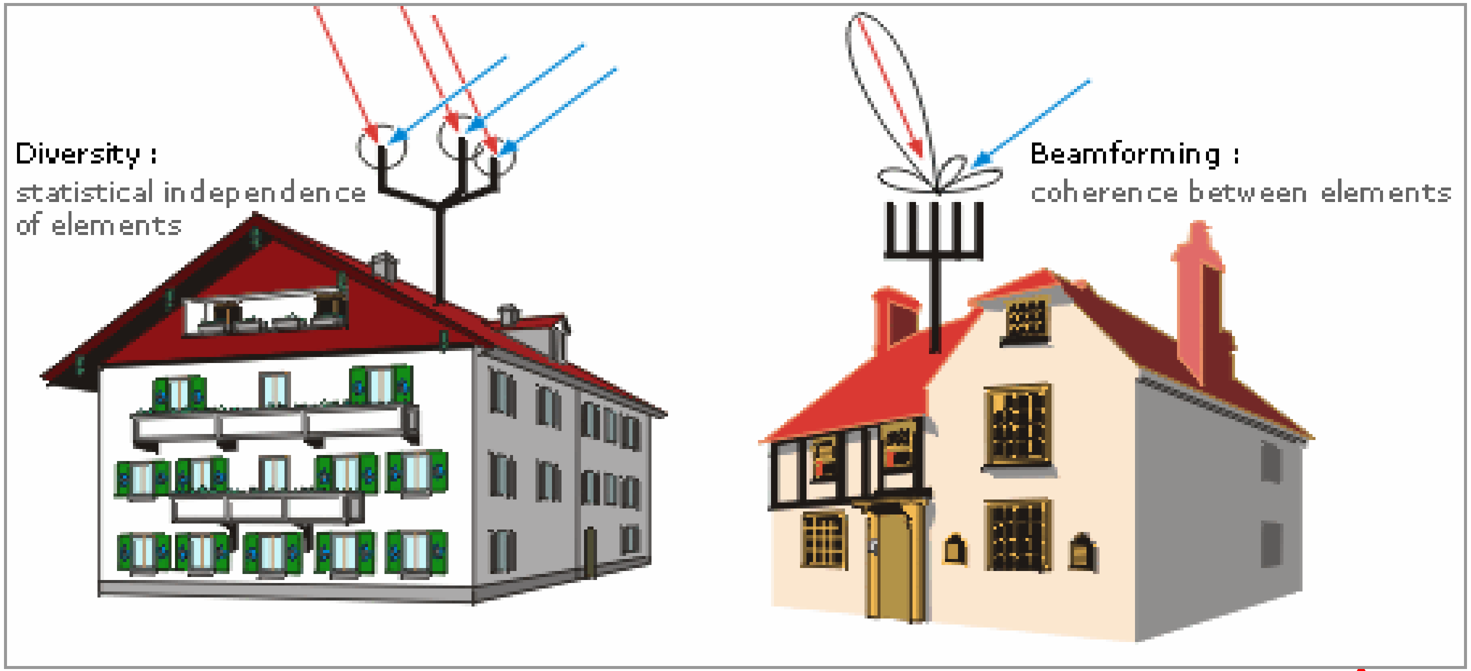
Array Gain
- increase power
- beamforming

Spatial Multiplexing
- multiply data rates
- spatially orthogonal channels

Diversity
- mitigate fading
- space-time coding

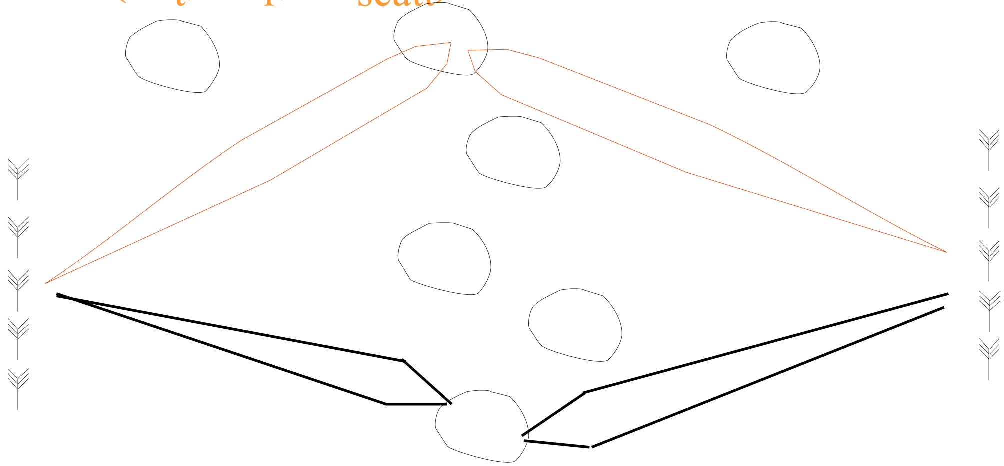
Diversity vs. array gain

- Diversity: reduce probability that signals at all antenna elements are in fading dip simultaneously
- Beamforming: increase mean SINR when receiving signals from certain direction



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
- Channel capacity grows linearly with number of antenna
  - $C \sim \min(N_t, N_r, N_{scatt})$



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

    Paulraj; Telatar; Foschini&Gans; Raleigh and Cioffi, Tarokh et al.
  - Prototypes in early 2000s
  - Standardized systems for large-scale deployment: after 2005
    - IEEE 802.11n, 3GPP Release 7, Wimax, 3GPP-LTE

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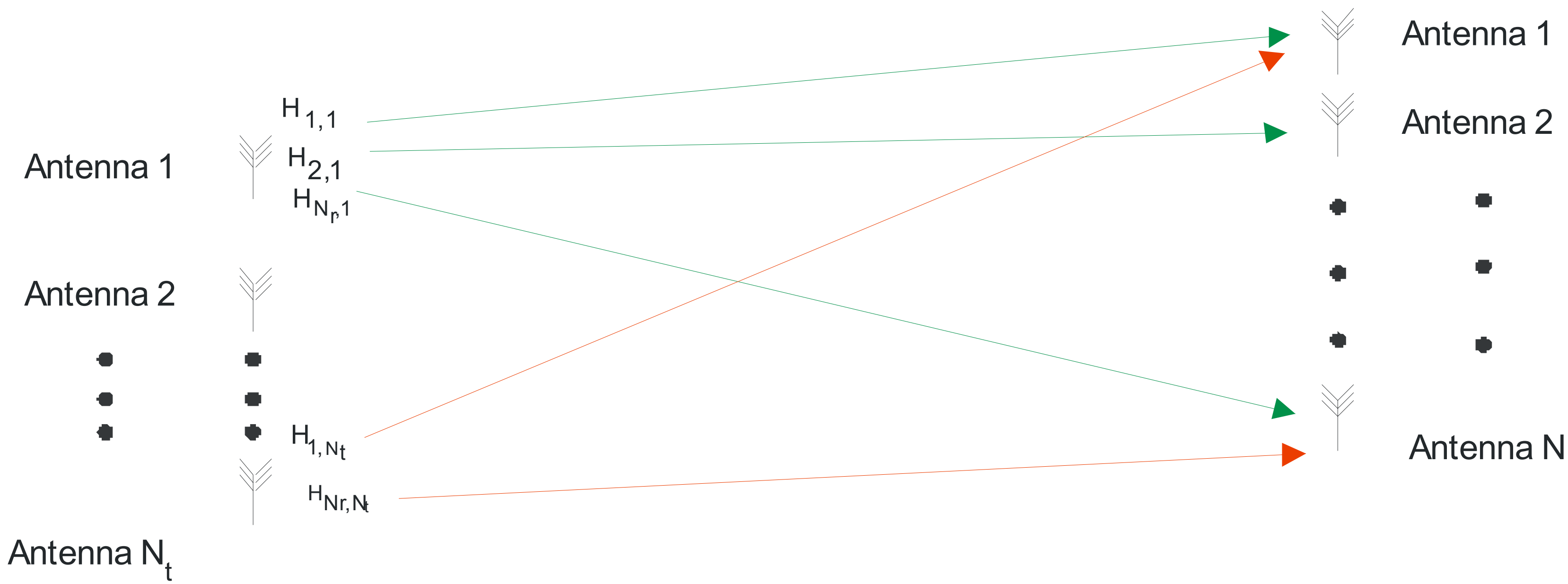
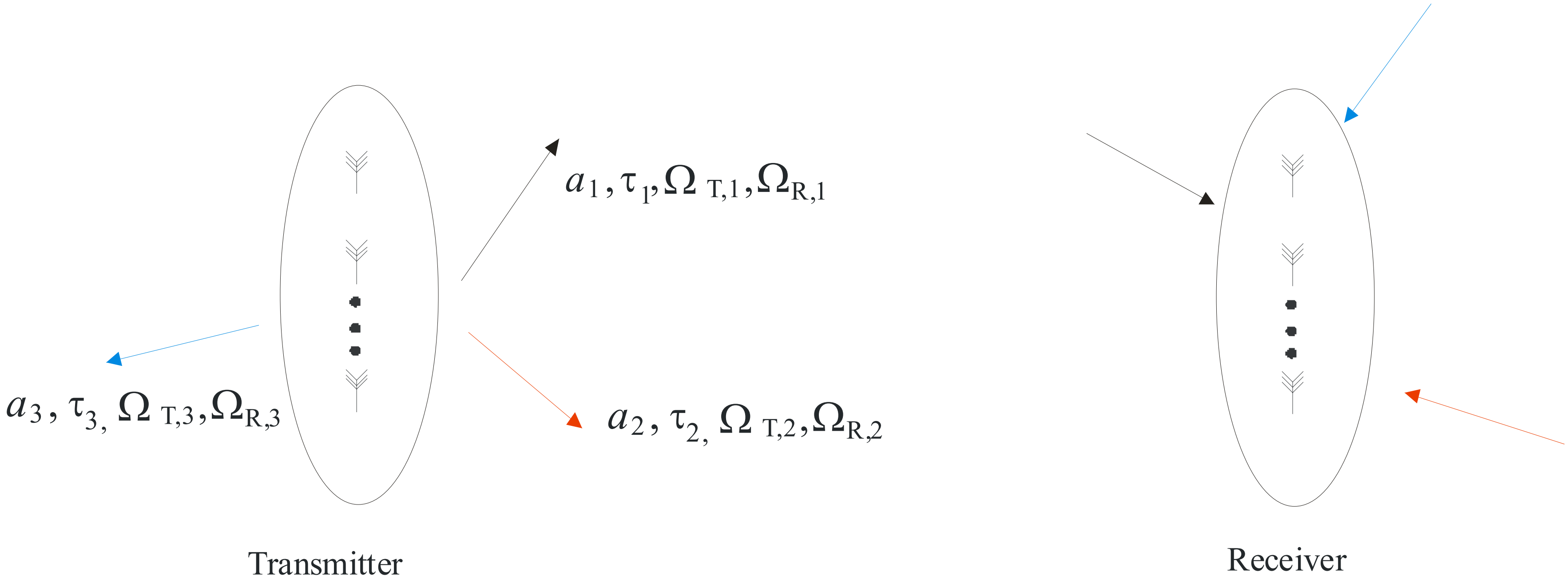
Types of MIMO channel models: transfer function matrix



- Transfer function from each transmit- to each receive antenna
- System-oriented description: signals at antenna connectors
- Easy to measure
- No connection to physics of propagation
- Assumes specific antenna array configuration

Types of MIMO channel models: double-directional model

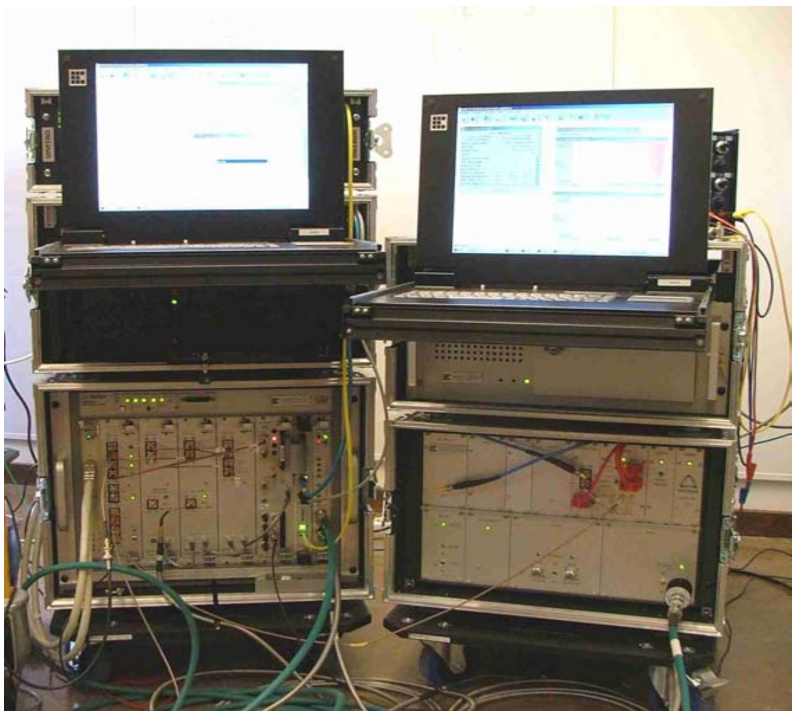


- Parameters of the multipath components
- Channel-oriented description
- Independent of antenna properties

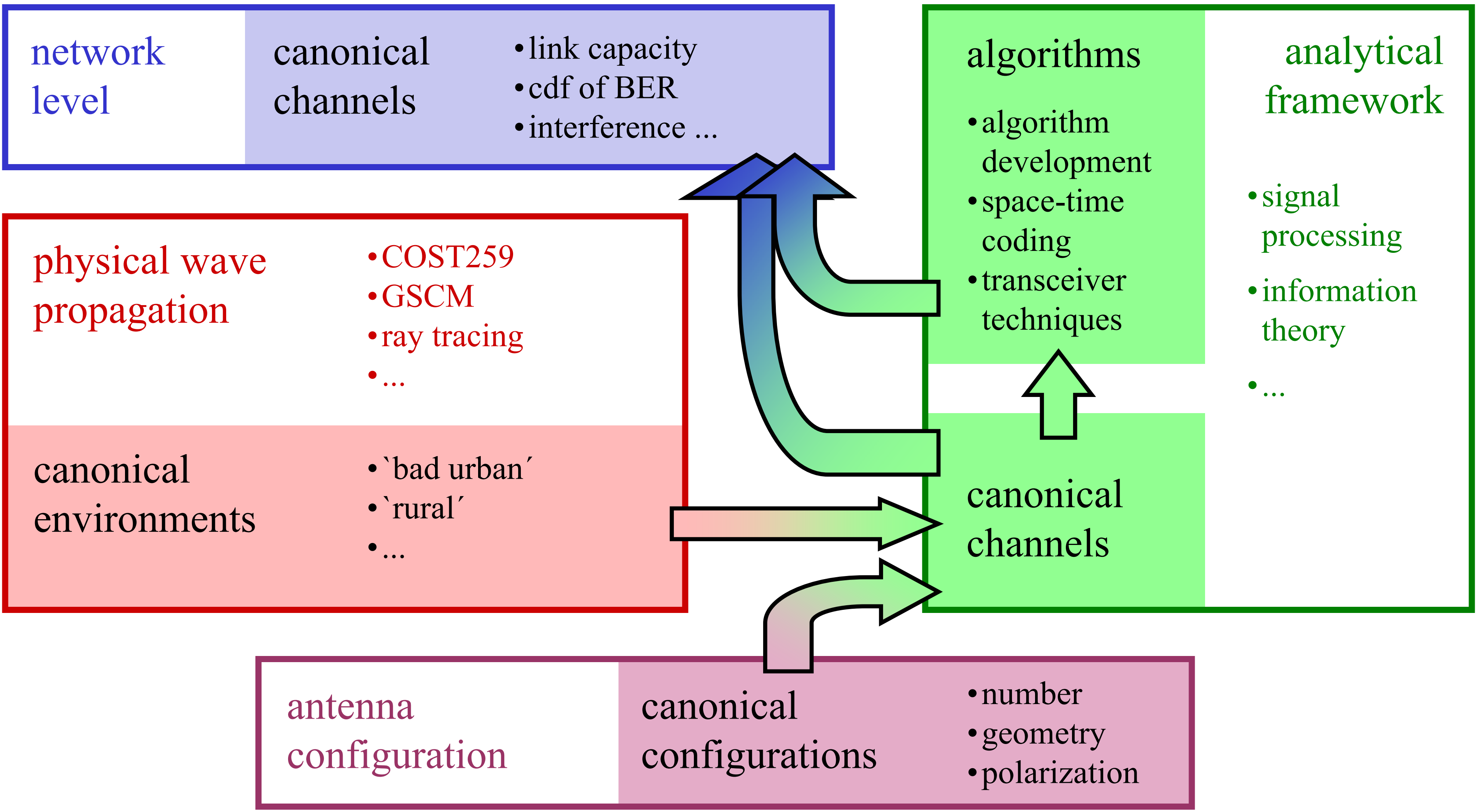
M. Steinbauer, A. F. Molisch, and E. Bonek, "The double-directional mobile radio channel", *IEEE Antennas Prop. Mag.*, 43, No. 4, 51-63 (2001).

The RUSK Lund Channel sounder for measuring

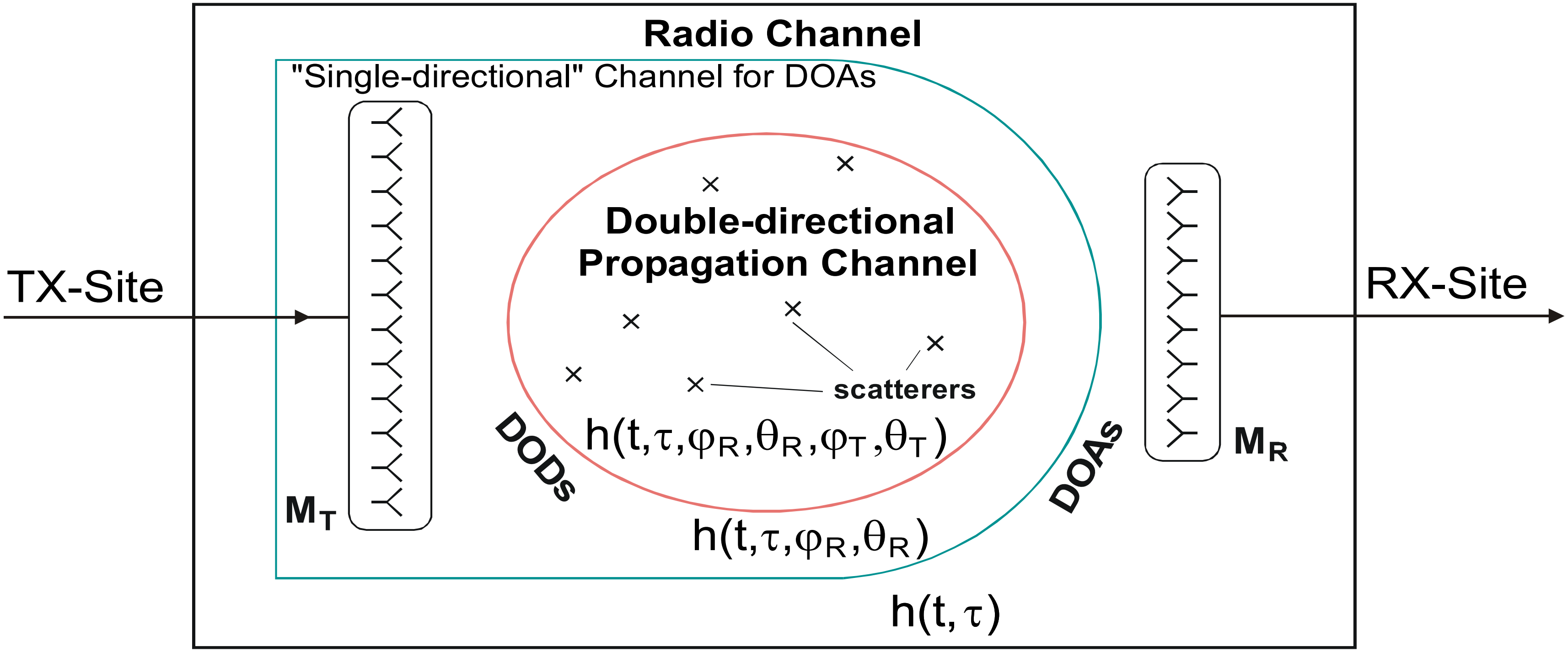
- A fast switched measurement system for radio propagation investigations at 300 MHz, 2 GHz and 5 GHz.
- Up to 240 MHz bandwidth
- MIMO capacity determined by the switches, currently 32 elements at each side.
- Multipath parameter extraction by SAGE/RIMAX algorithm



Spatial channel models – an overview



The Double-directional Propagation Channel



transfer function

double-dir. Impulse response

antenna pattern

element location factor

$$h(\tau, x_R, x_T) = \sum_{i=1}^{N} h(\tau_i, \Omega_{R,i}, \Omega_{T,i}) \cdot g_R(\Omega_R) g_T(\Omega_T) \cdot e^{j\left\langle \vec{k}(\varphi_{R,i})\vec{x}_R \right\rangle} e^{j\left\langle \vec{k}(\varphi_{T,i})\vec{x}_T \right\rangle}$$

…used now in almost all standardized MIMO models

- COST 259: macro-micro- and picocells

  M. Steinbauer and A. F. Molisch (eds.), "Directional channel models", Chapter 3.2 (pp. 132-193) of "Flexible Personalized Wireless Communications", L. Correia (ed.), Wiley, 2001

- 3GPP: cellular systems in urban and suburban area

  Spatial Channel Modeling Ad-hoc group (A. Kogiantis, et al.: SCM text version 6.0, SCM AHG Doc. 134, Jan. 2003.

  G. Calcev, D. Chizhik, B. Goeransson, S. Howard, H. Huang, A. Kogiantis, A. F. Molisch, A. L. Moustakas, D. Reed and H. Xu, "A Wideband Spatial Channel Model for System-Wide Simulations", IEEE Trans. Vehicular Techn., 56, 389-403,2007.

- 802.11n: indoor WiFi systems

  V. Erceg, et al., "TGn channel models", IEEE document 802.11-03/940r4, May 2004.

- COST 273: macro-, micro-, picocells, peer-to-peer, fixed wireless

  A. F. Molisch and H. Hofstetter, "The COST 273 MIMO channel model", in L. Correia (ed.), "Mobile Broadband Multimedia Networks", Academic Press, (2006).

P. Almers, et al.. Survey of Channel and Radio Propagation Models for Wireless MIMO Systems. EURASIP Journal on Wireless Communications and Networking, 2007, 2007.

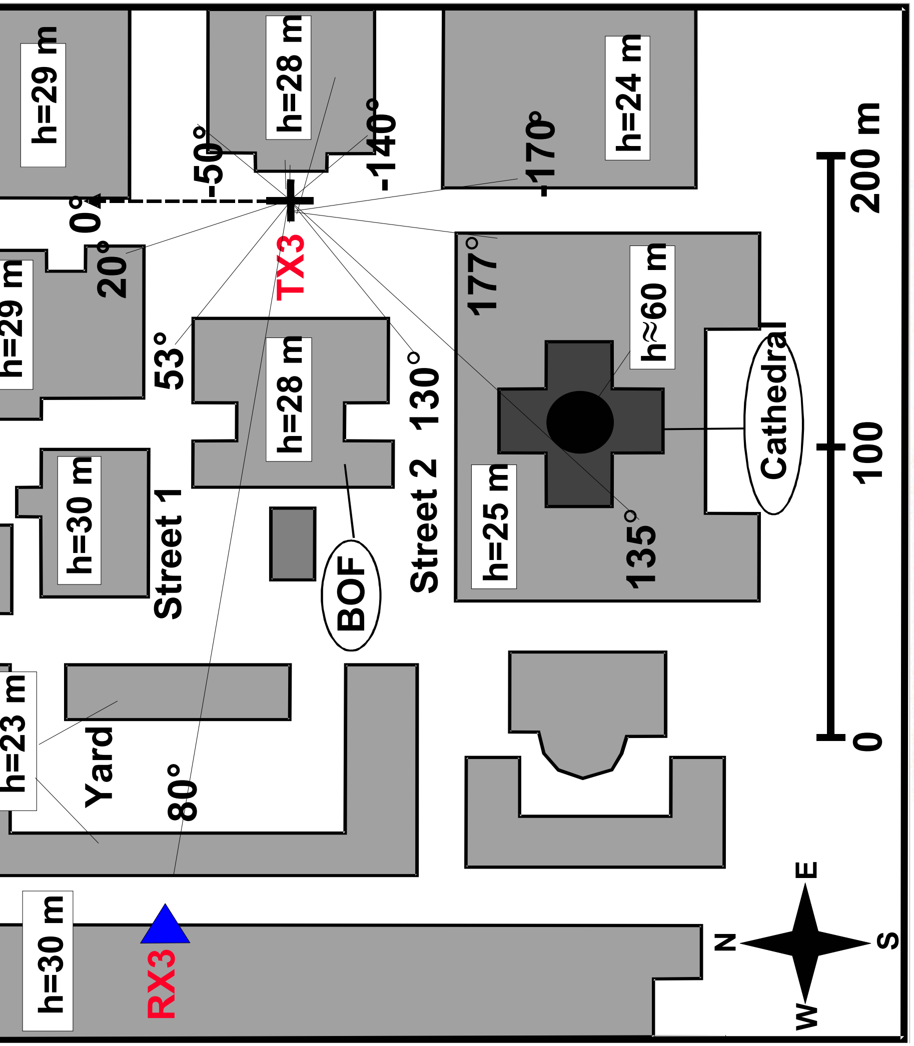
Contents

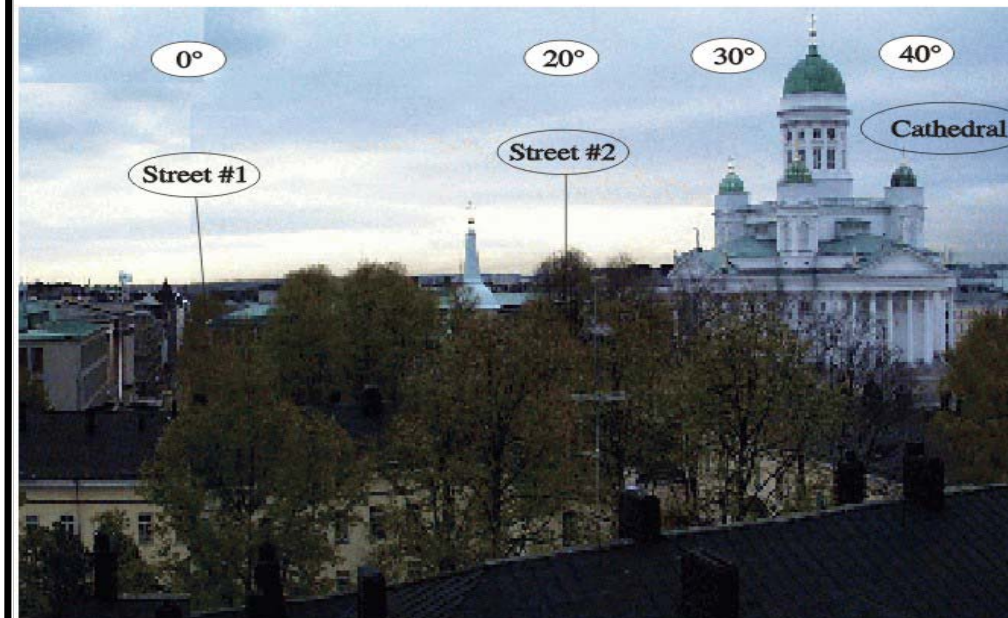
Multipath propagation causes angular dispersion

Important propagation mechanisms:

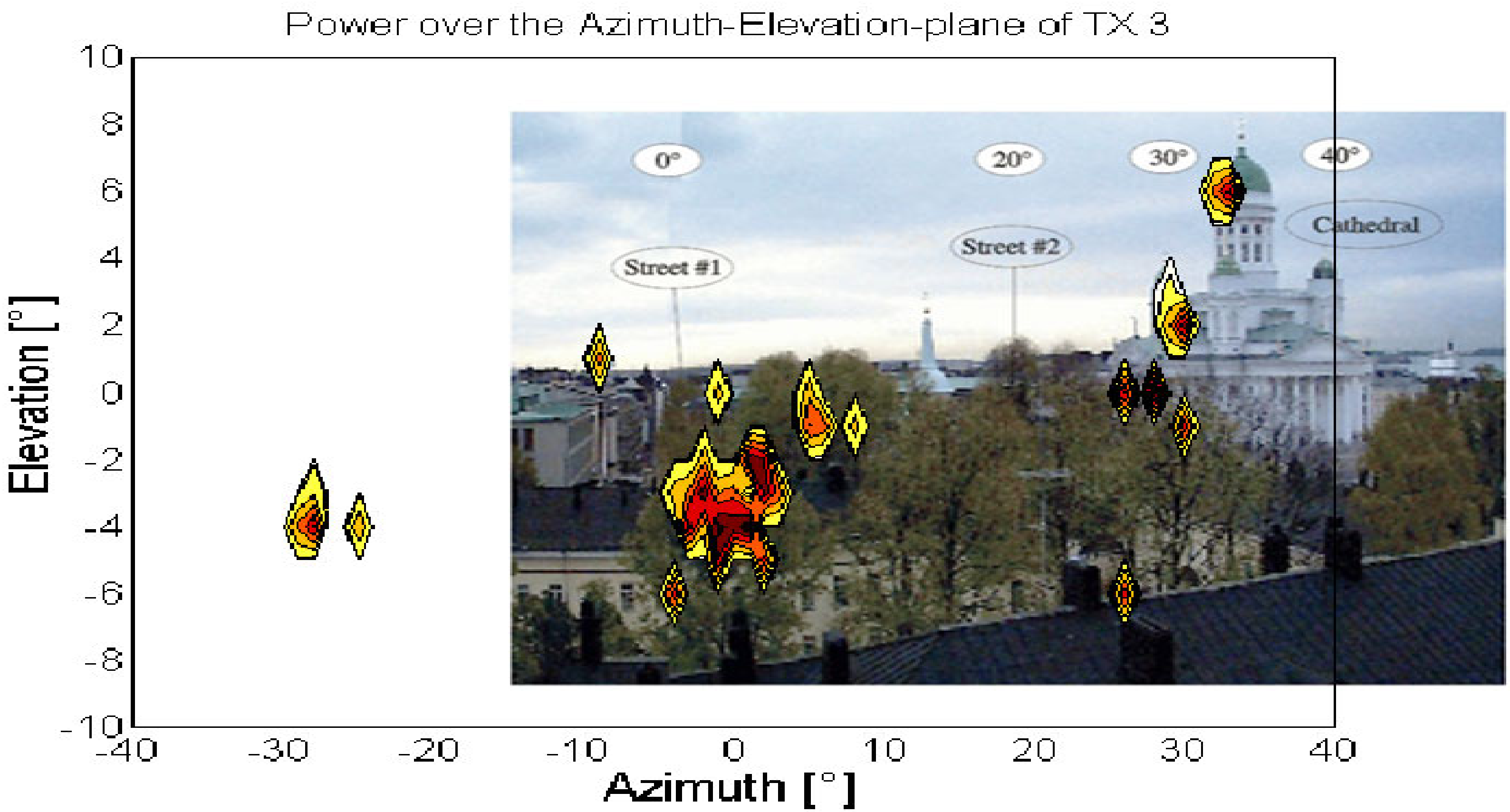
- Over-the-rooftop
- Waveguiding in street canyons
- Reflection at far scatterers

3D-measurements at BS – RX3 (microcell): setup





M. Töltsch, J. Laurila, A. F. Molisch, K. Kalliola, P. Vainikainen, and E. Bonek, „Spatial characterization of urban mobile radio channels“, IEEE JSAC 20, 539-549 (2002).



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Measurement Campaign

Macro/Microcell:

- same measurement routes
- same array orientation
- BS antenna height difference of 6.5m

Routes in Helsingin Energia Sector 160

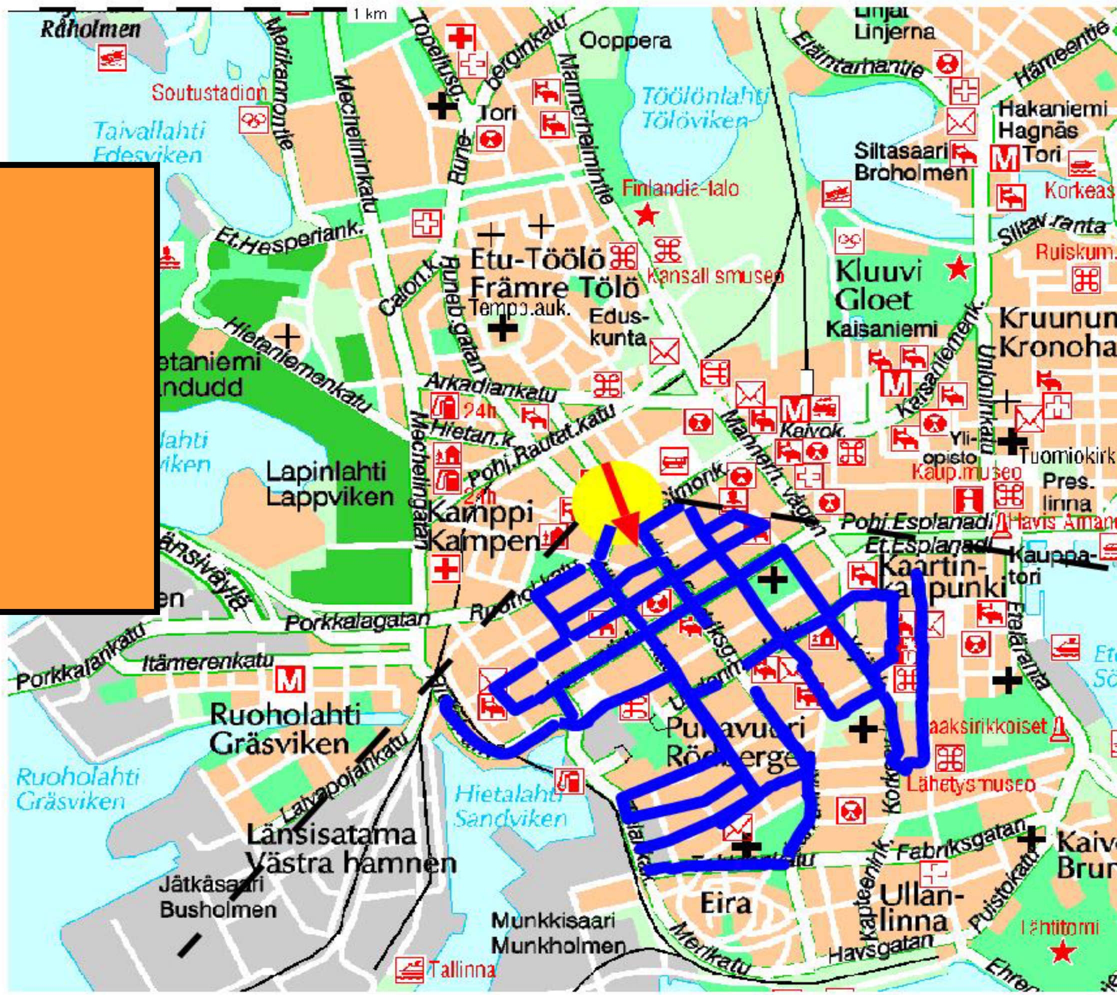
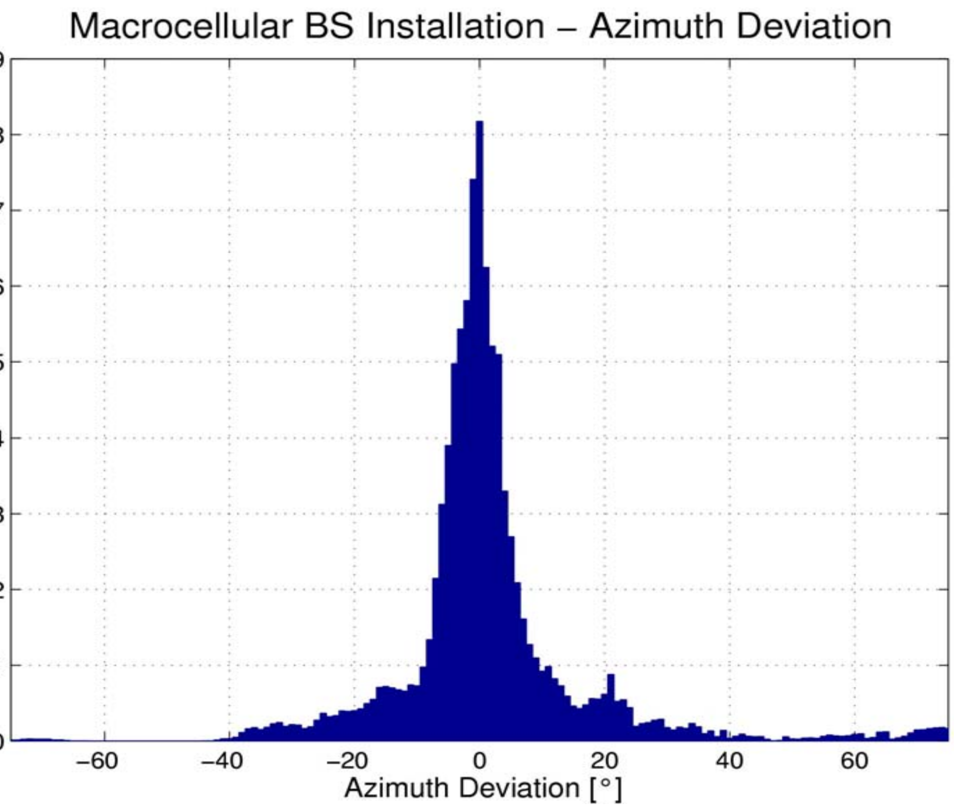
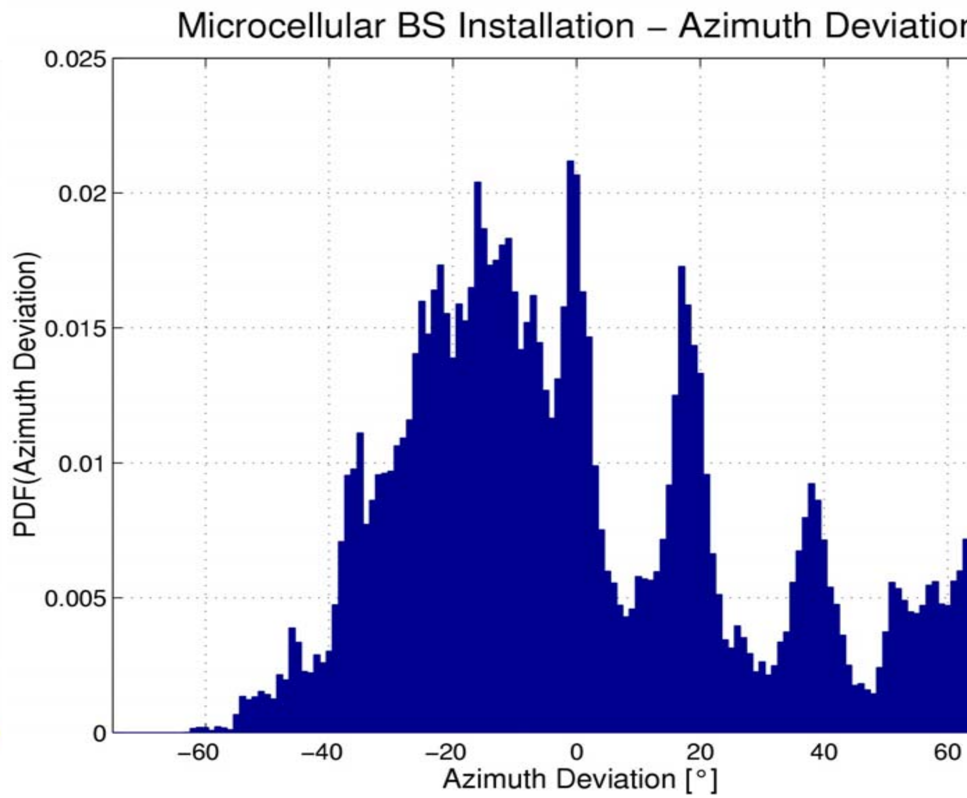


Figure courtesy of K. Hugl and E. Bonek;
Joint work with P. Vainikkainen

Deviation between geometrical MS position and DOA



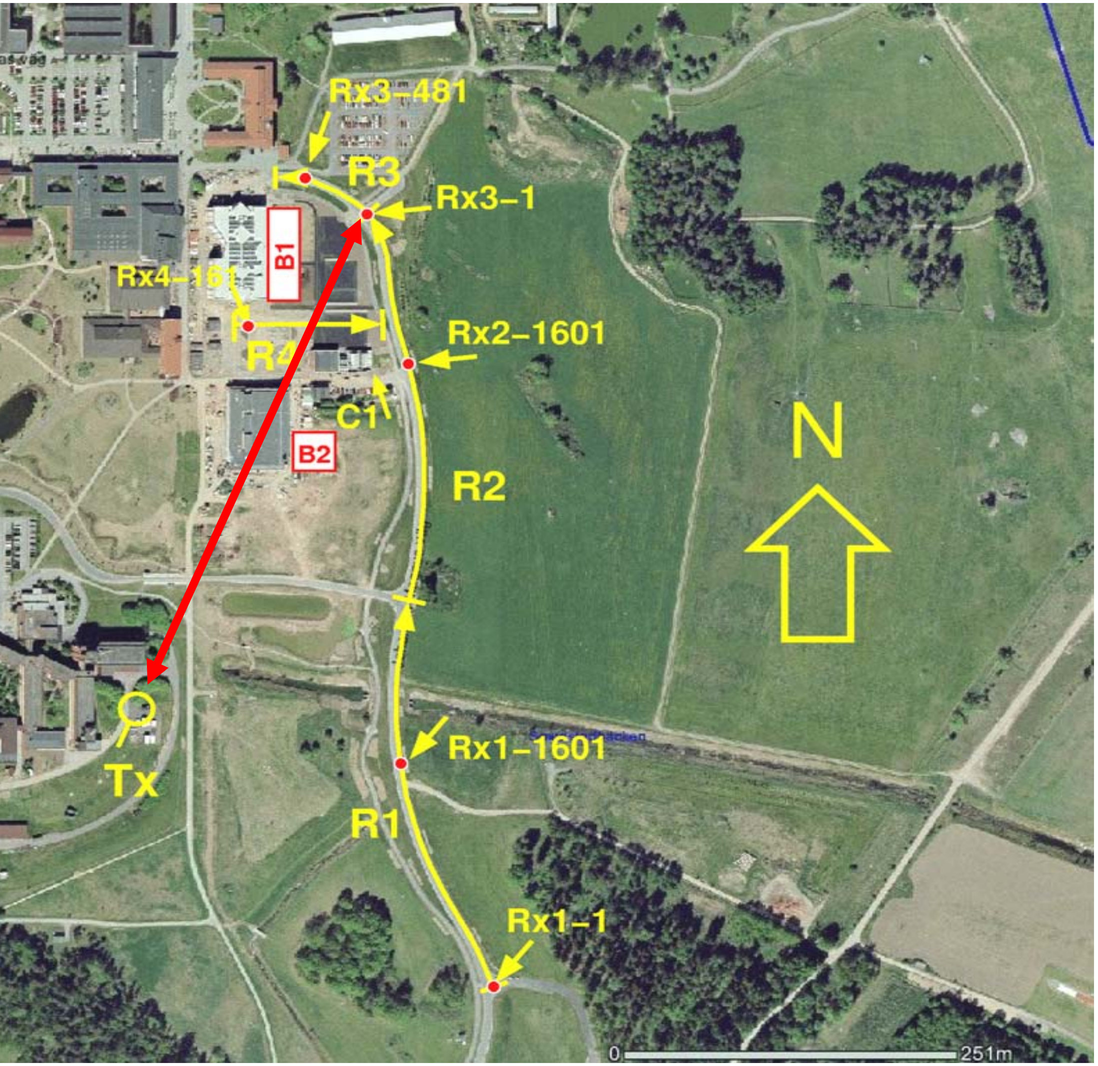


Above rooftop:
correlated!

Below rooftop:
not correlated!

Figure courtesy of K. Hugl and E. Bonek;
Joint work with P. Vainikkainen

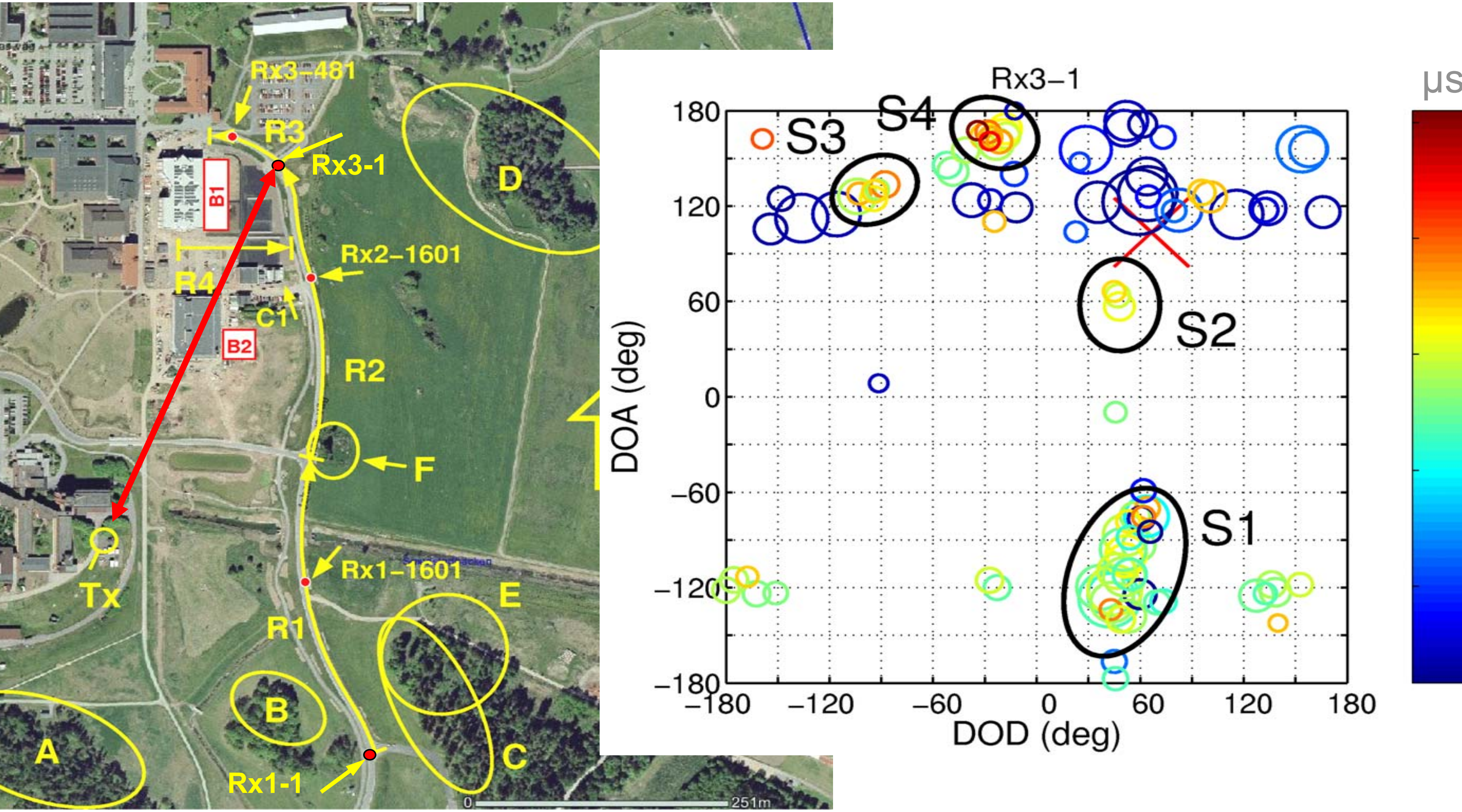
Results – Propagation mechanisms



- Non-LOS
- LOS path blocked by a building
- Other buildings close to the LOS path

G. Eriksson, F. Tufvesson, and A. F. Molisch, "Investigation of the Radio Channel for Peer-to-Peer Multiple Antenna Systems at 300 MHz", Proc. IEEE Globecom 2006, (2006).

Results – Propagation mechanisms



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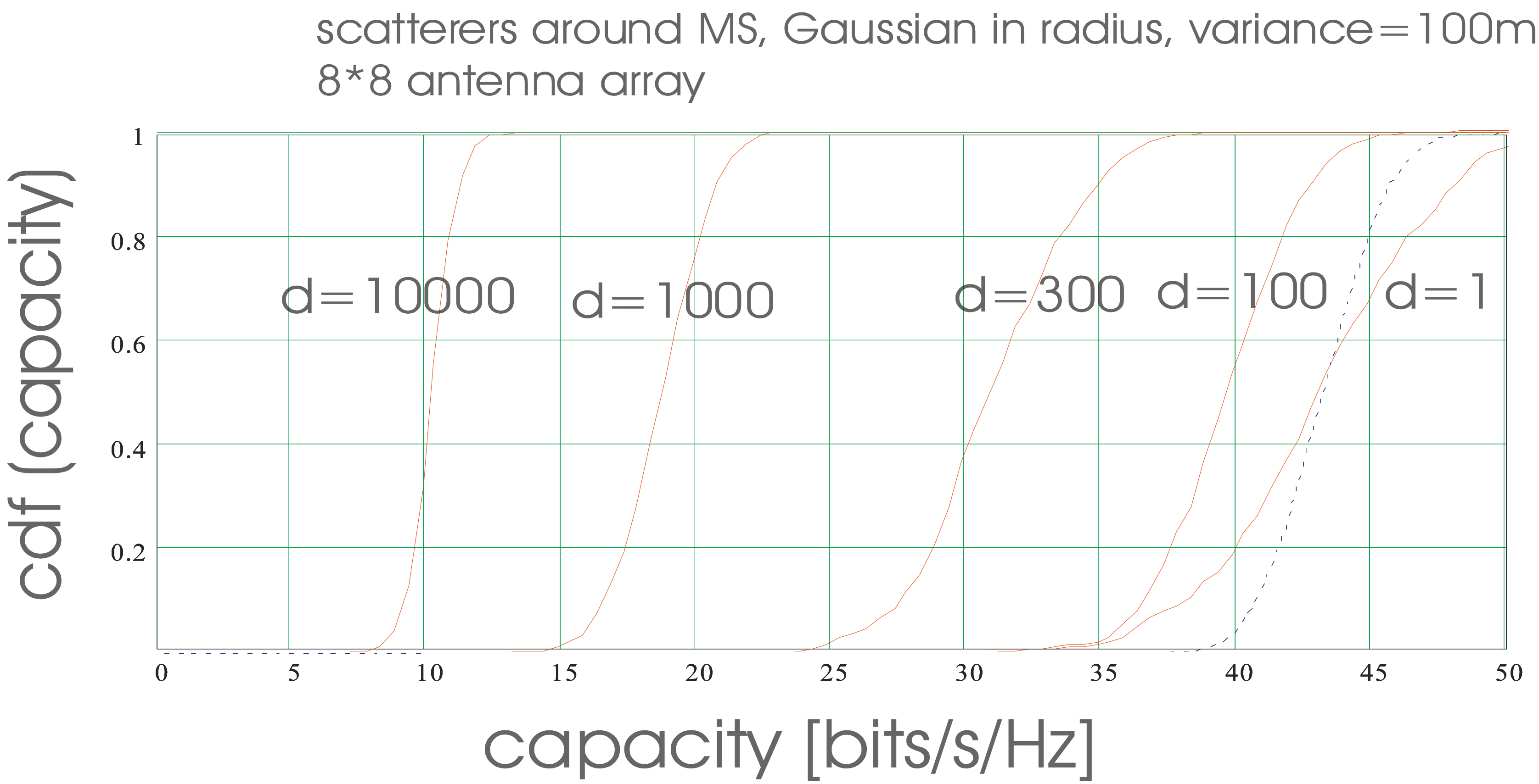
Why do we care about angular dispersion?

- Angular dispersion determines correlation between signals at antenna elements
  - For a fixed array structure: the bigger angular spread, the smaller the correlation
- Correlation determines the capacity of MIMO

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

$$= \sum \log_2 \left(1 + \frac{\gamma}{n_T} \lambda_i \right)$$

Capacity with correlation



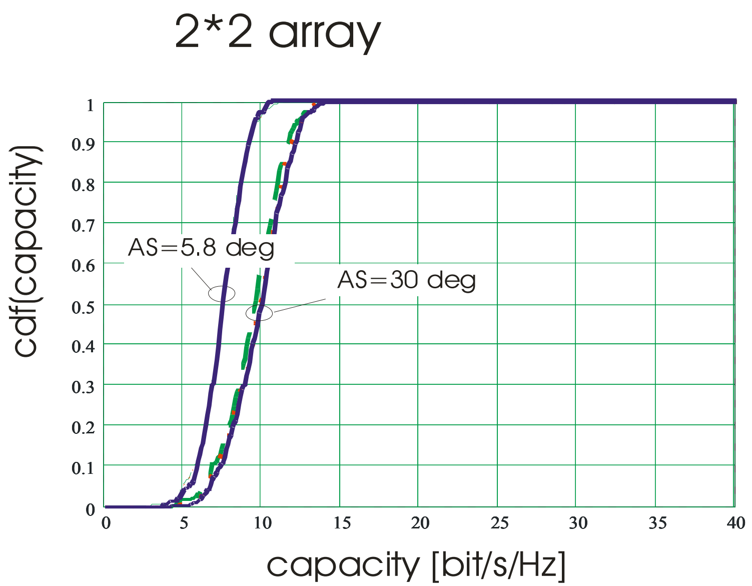
It all depends on the rms angular spread ?

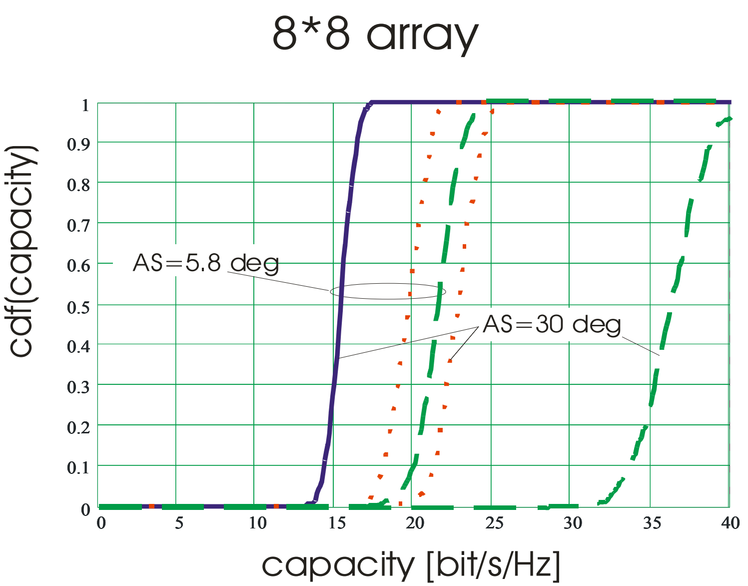
- Folk law: “MIMO and diversity properties determined by rms angular spread” $\Rightarrow$ can model far scatterers by increasing angular spread of local scatterers
- Where does it come from?
  - [Asztely and Ottersten 1996]: correlation coefficient can be approximated by function that depends only on rms angular spread

  BUT
  - requires several assumptions (stated in the paper !)
    - rms angular spread small
    - maximum angular spread small
    - Etc.

MIMO capacity

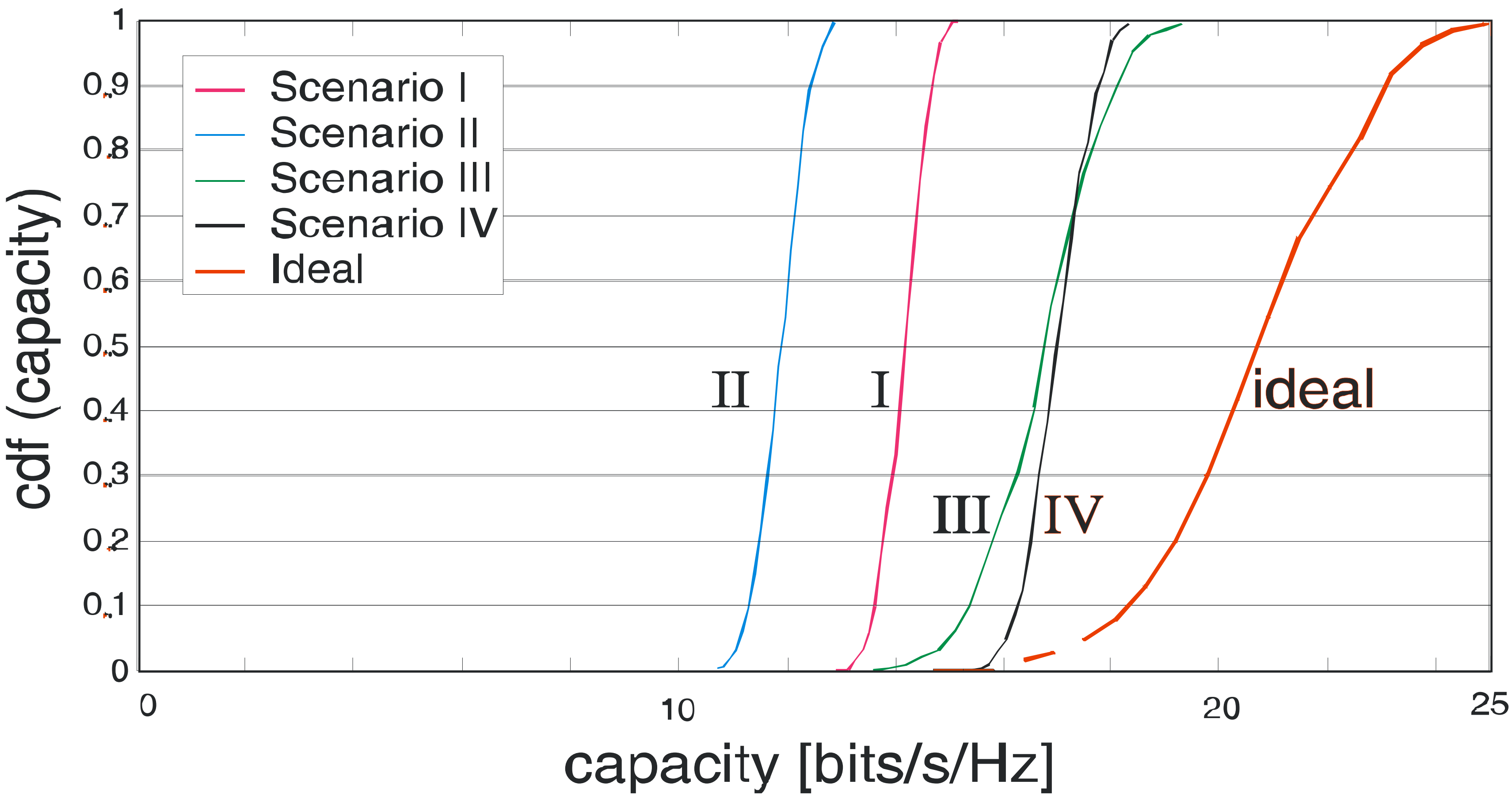
Cdf of the capacity for: two specular sources (solid), single cluster (dashed), two clusters (dotted).





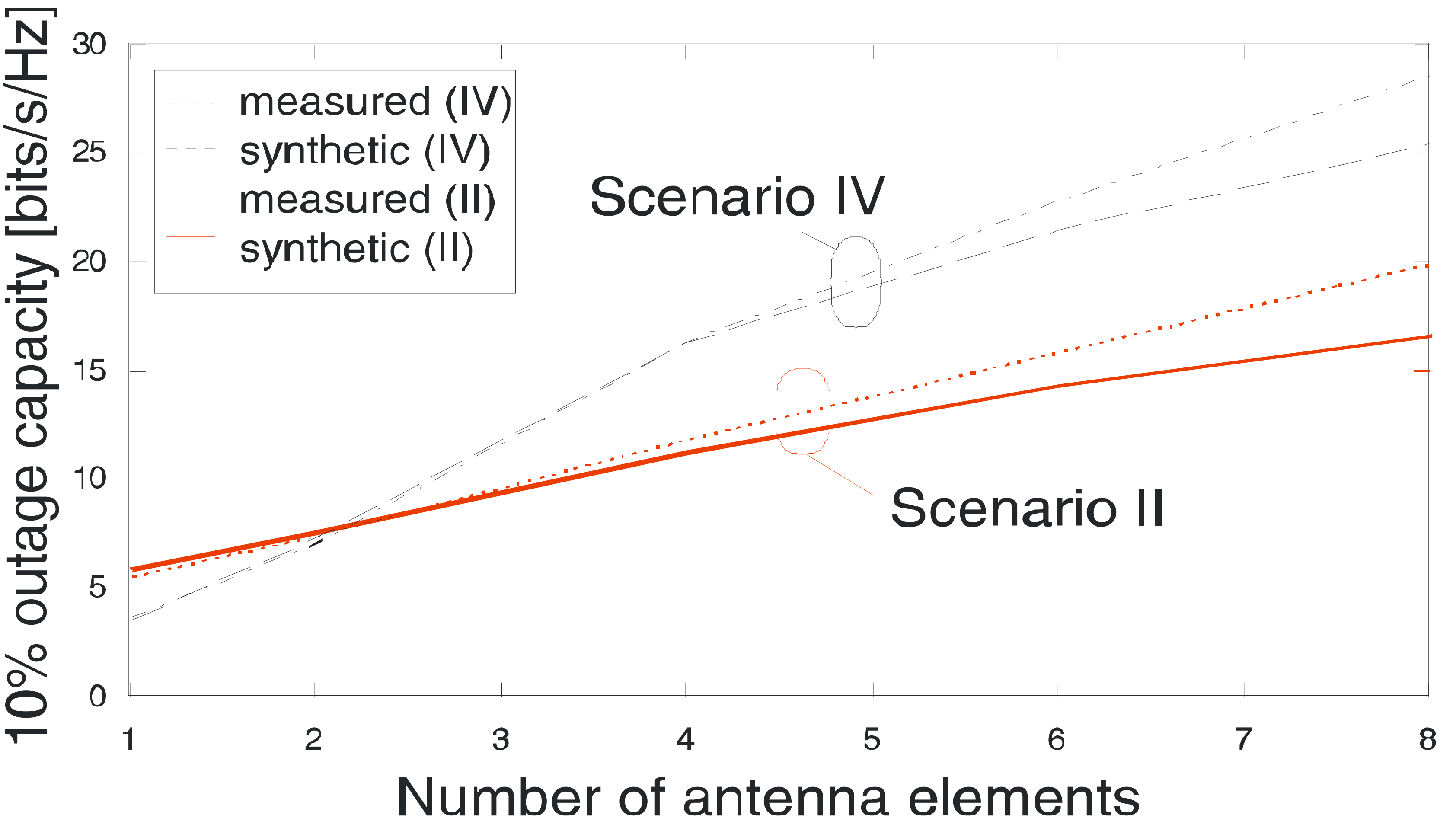
A. F. Molisch, "Effect of far scatterer clusters in MIMO outdoor channel models", Proc. 57th IEEE Vehicular Techn. Conf., 534-538 (2003).

Line-of-sight reduces capacity for constant receive power



A. F. Molisch, M. Steinbauer, M. Toeltsch, E. Bonek, and R. Thoma, „Capacity of MIMO systems based on measured wireless channels“, “, IEEE JSAC 20, 561-569 (2002).

Limited number of scatterers



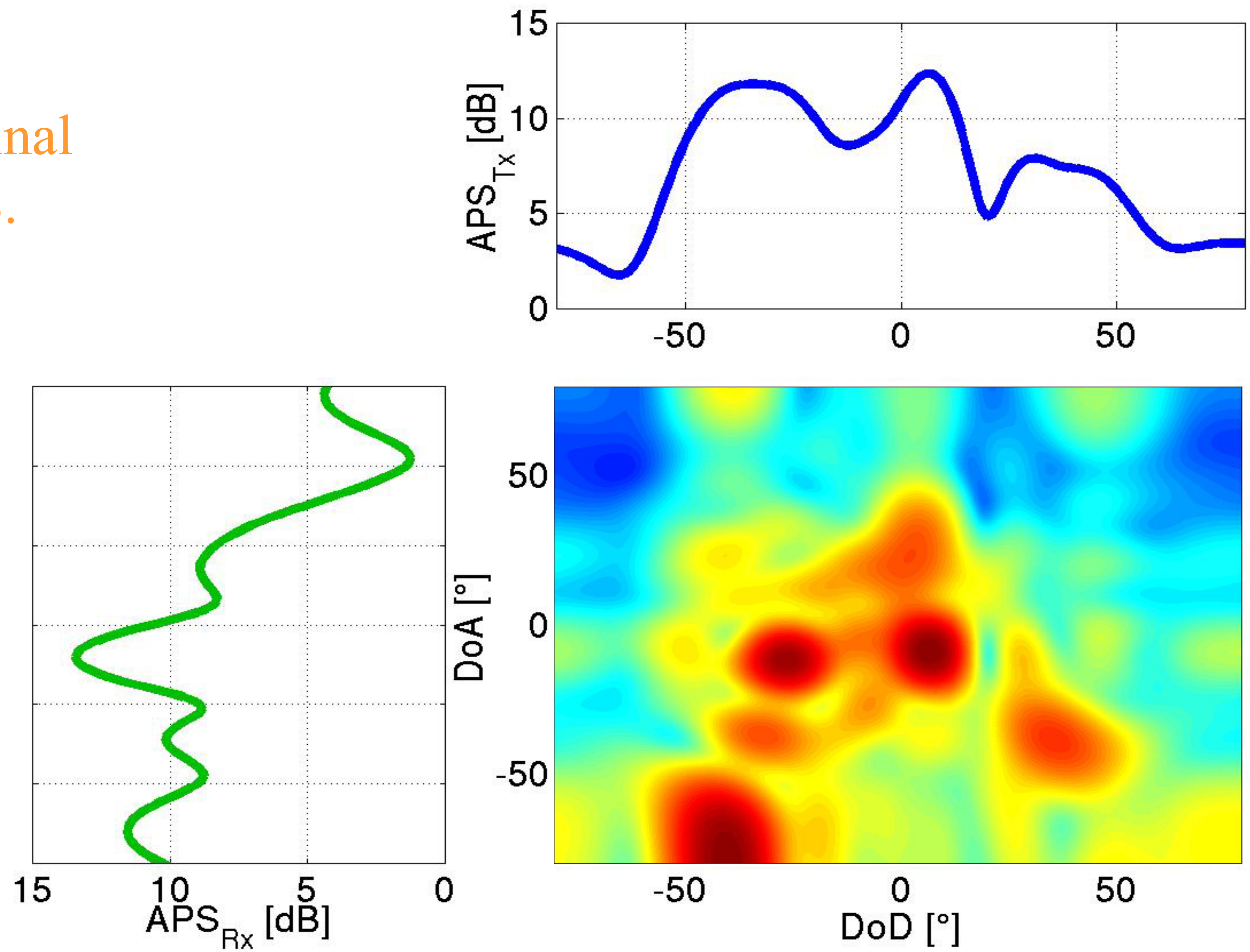
A. F. Molisch, M. Steinbauer, M. Toeltsch, E. Bonek, and R. Thoma, „Capacity of MIMO systems based on measured wireless channels“, “, IEEE JSAC 20, 561-569 (2002).

Are TX and RX directional spectra independent?

Joint APS is the product of marginal Rx- and Tx-APS.

W. Weichselberger, M. Herdin, H. Özcelik, E. Bonek, "A Stochastic MIMO Channel Model With Joint Correlation of Both Link Ends," IEEE Transactions on Wireless Communications, 5(1) , pages 90 - 99, 2006.

measurement



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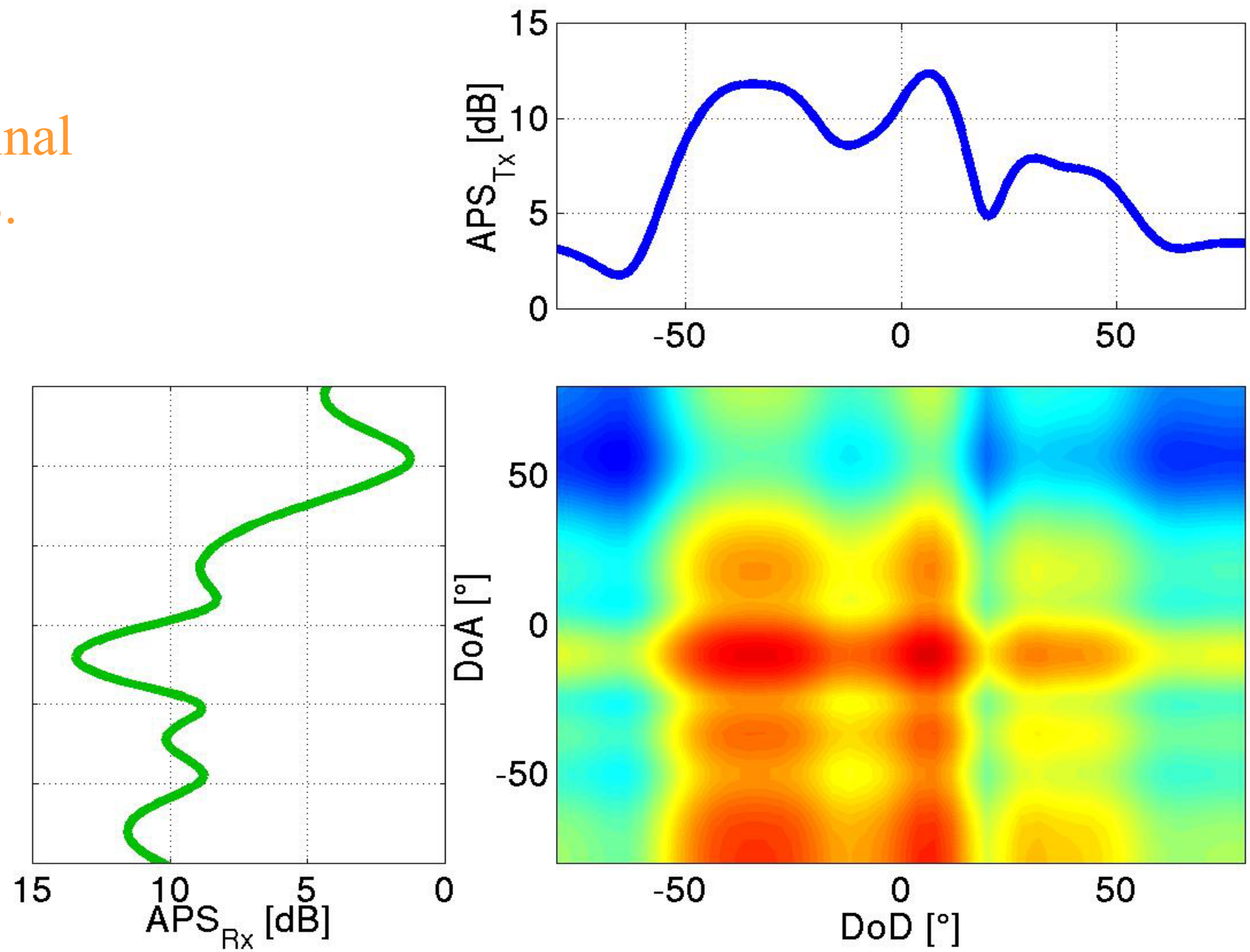

Kronecker approximation

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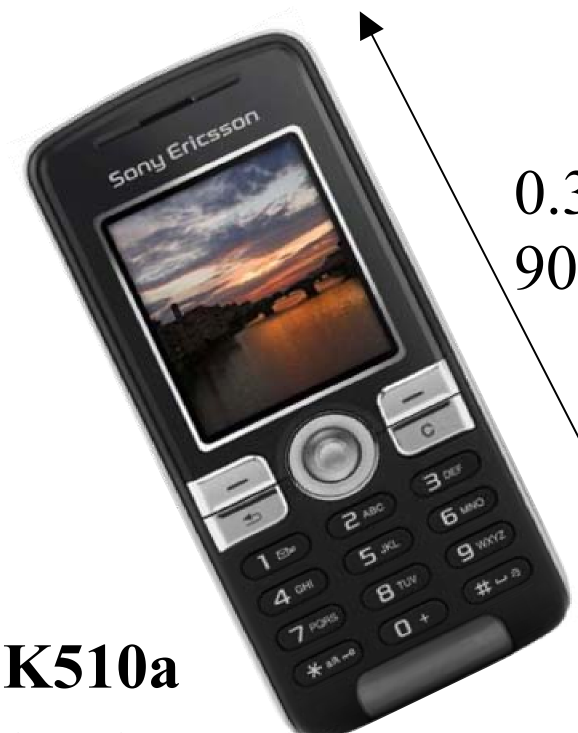
Limits on antenna spacing

- Trend towards compact mobile terminals, limited space for antenna system.

Figure courtesy of Sony-Ericsson

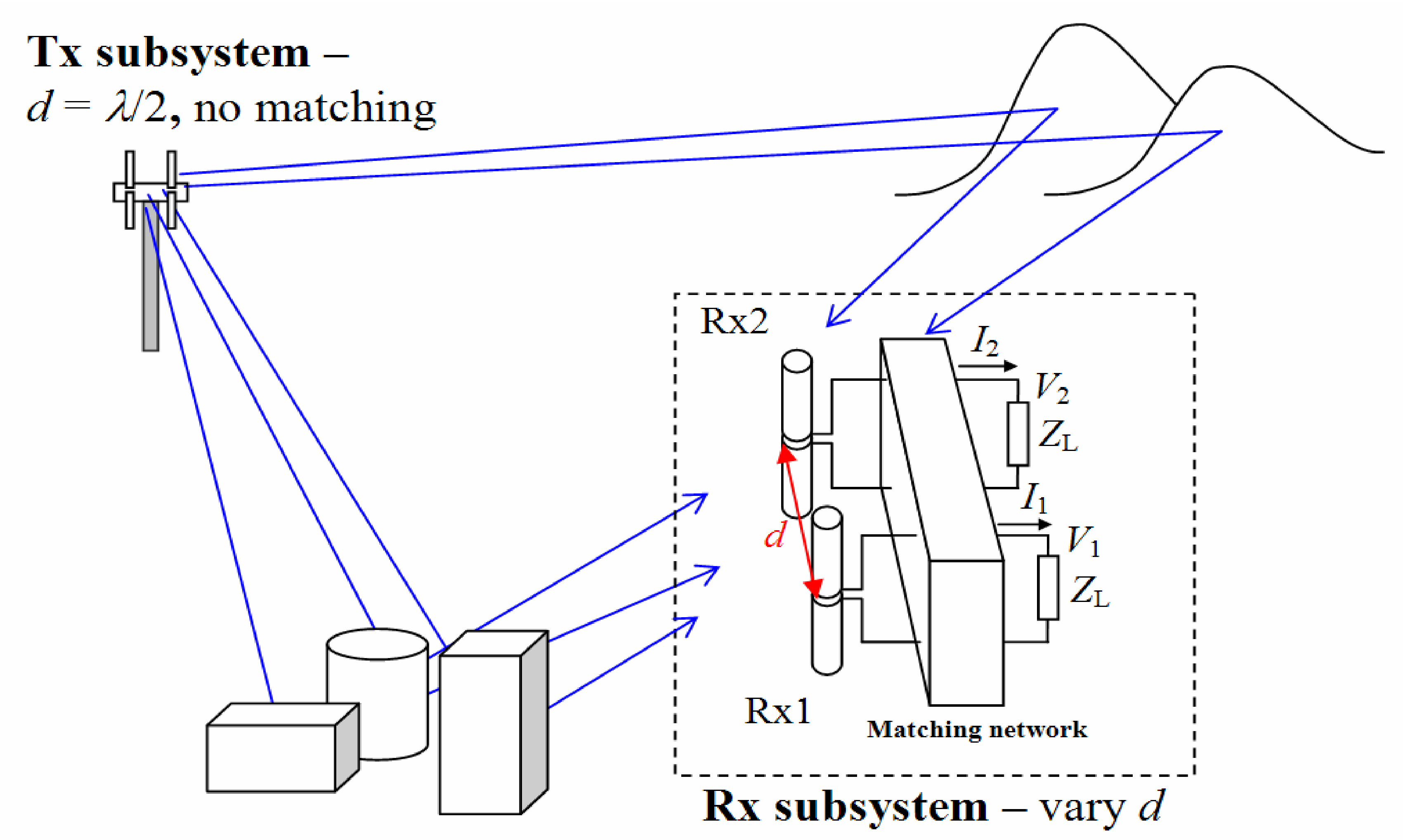


0.3λ @
900 MHz

K510a

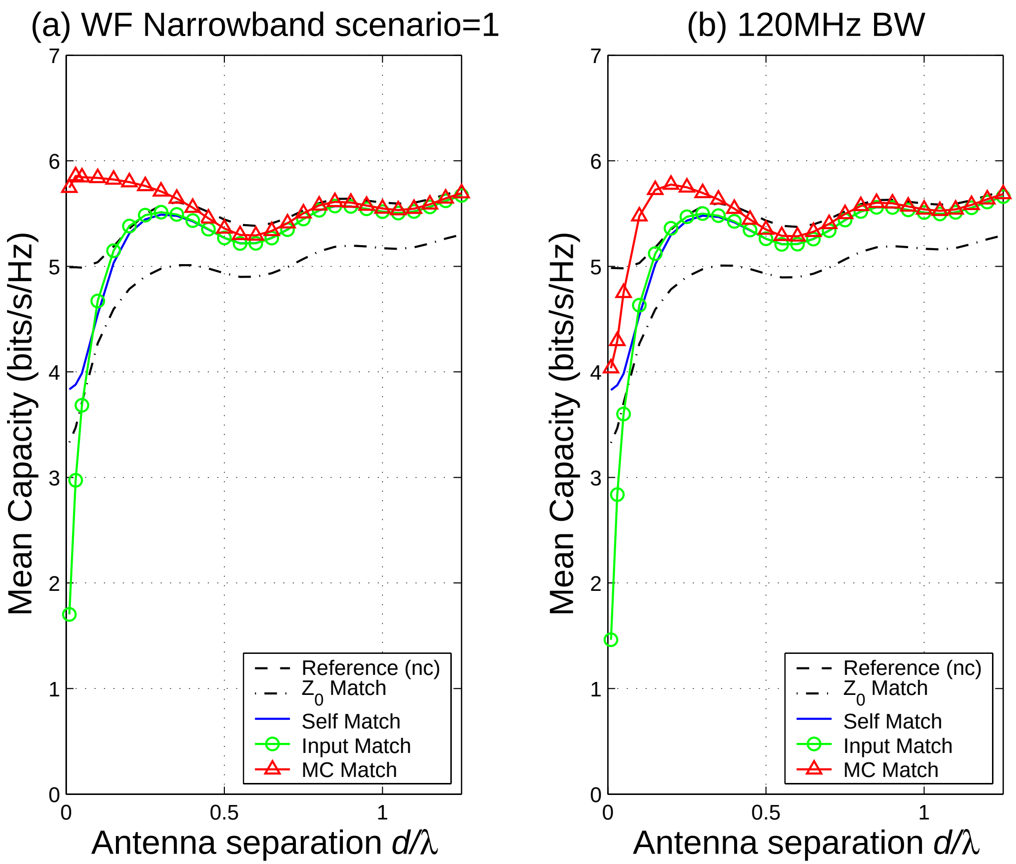
- Closely-spaced antennas have mutual coupling

Matching for mutual coupling



Minimum admissible antenna spacing

MIMO capacity with mutual coupling with different matching strategies



B. K. Lau, J. B. Andersen, G. Kristenson, and A. F. Moli
"Impact of Matching Network on the Capacity of Compa
MIMO systems", *Proc. Antennas 06 Conference*.

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When are uniform linear arrays possible?

- Base stations of cellular systems
  - Limit to number of antennas: wind load
  - Typical size of array: 4 elements
- Access points for wireless LAN
  - Limit to number of antennas: size of access point
  - Typical size of array: 4 elements
- Laptop
  - Limit to number of antennas: size of laptop; mounting on backplane of screen or on edges?
- Not possible on handsets

Consequences of non-ULA structure

- Different mean powers: e.g., antennas with maximum gain in LOS direction get more mean power than antennas pointing away
  - Consequences for system design: modulation alphabet size, waterfilling, based on mean power is possible

- Different fading statistics for different antenna elements

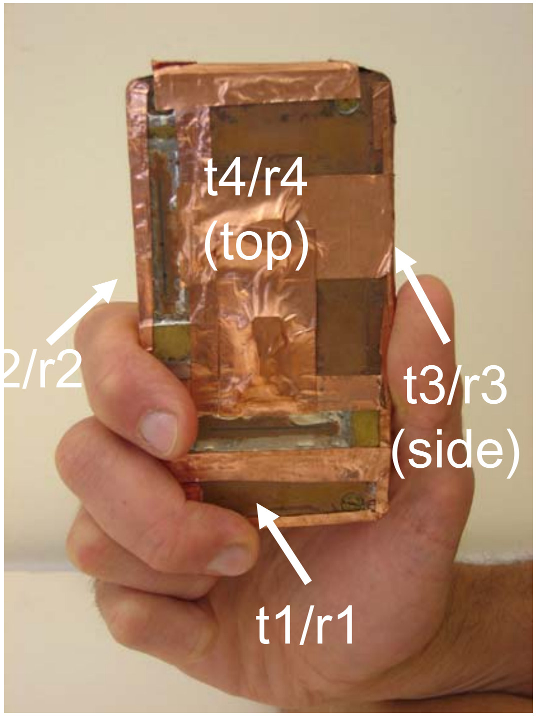
Small-Scale Amplitude Statistics

Rows – Tx elements

Columns – Rx elements

r1 r4

t1 t2 t3 t4



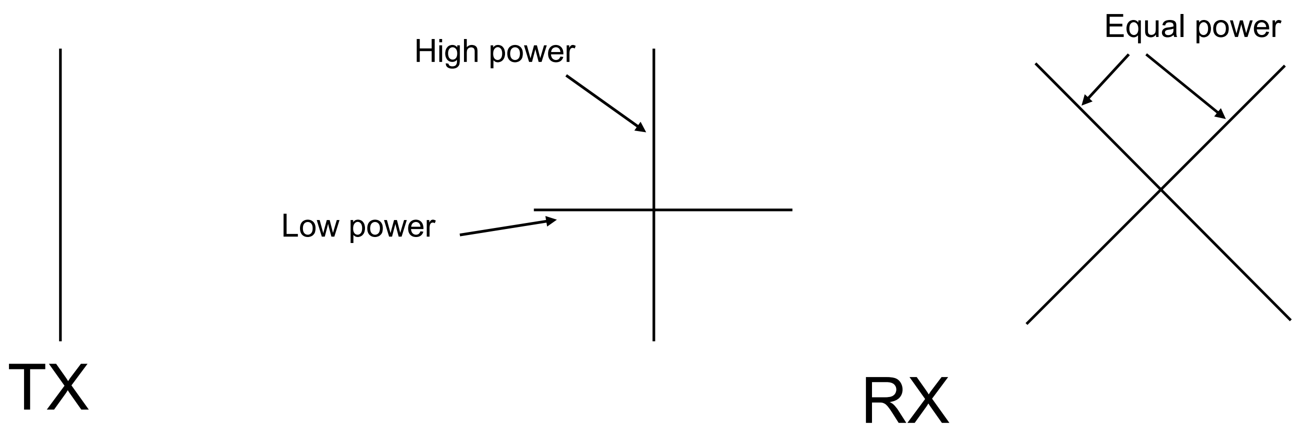
Norm. amp. Norm. amp. Norm. amp. Norm. amp.

- Some Tx-Rx combination exhibit Rayleigh statistics
- Some Tx-Rx combination exhibit Rice statistics
- Some Tx-Rx combination exhibit "other" statistics
- **Measurement is "LOS"!**

A. Johanson, J. Karedal, F. Tufvesson, and A.F. Molisch, "MIMO channel measurements for Personal Area Networks", Proc. 61st IEEE Vehicular Techn. Conf., 171-176 (2005).

Polarization

- Polarization offers more degrees of freedom without requiring more space
- One antenna element can have two ports for two orthogonal polarizations
- Fading of orthogonal polarizations is independent
- Mean power in co-polarized components is higher than in cross-polarized



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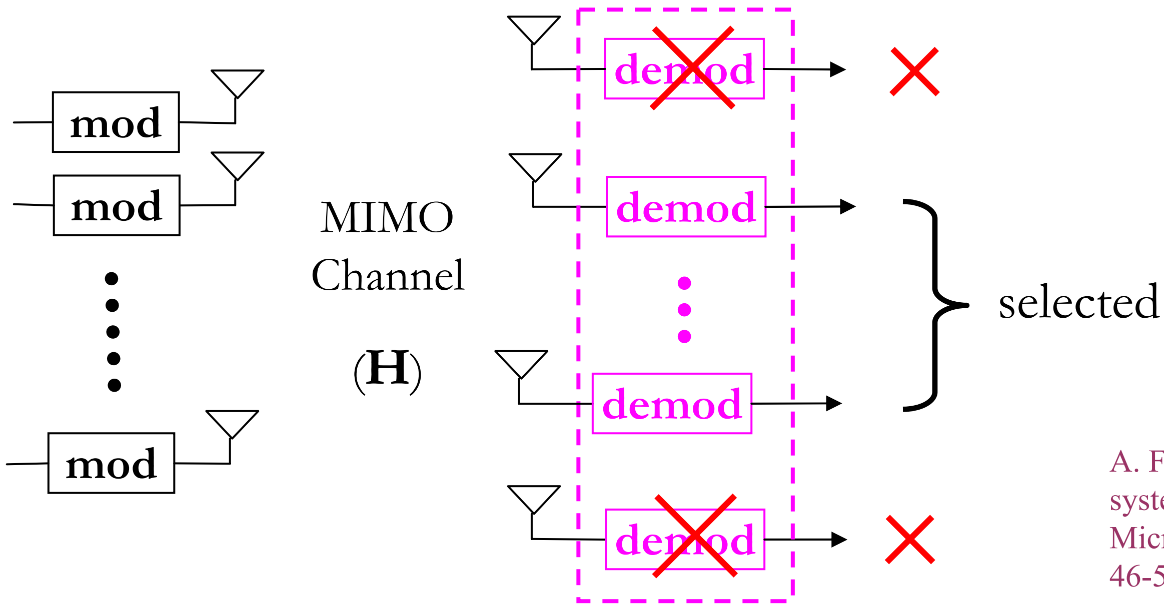
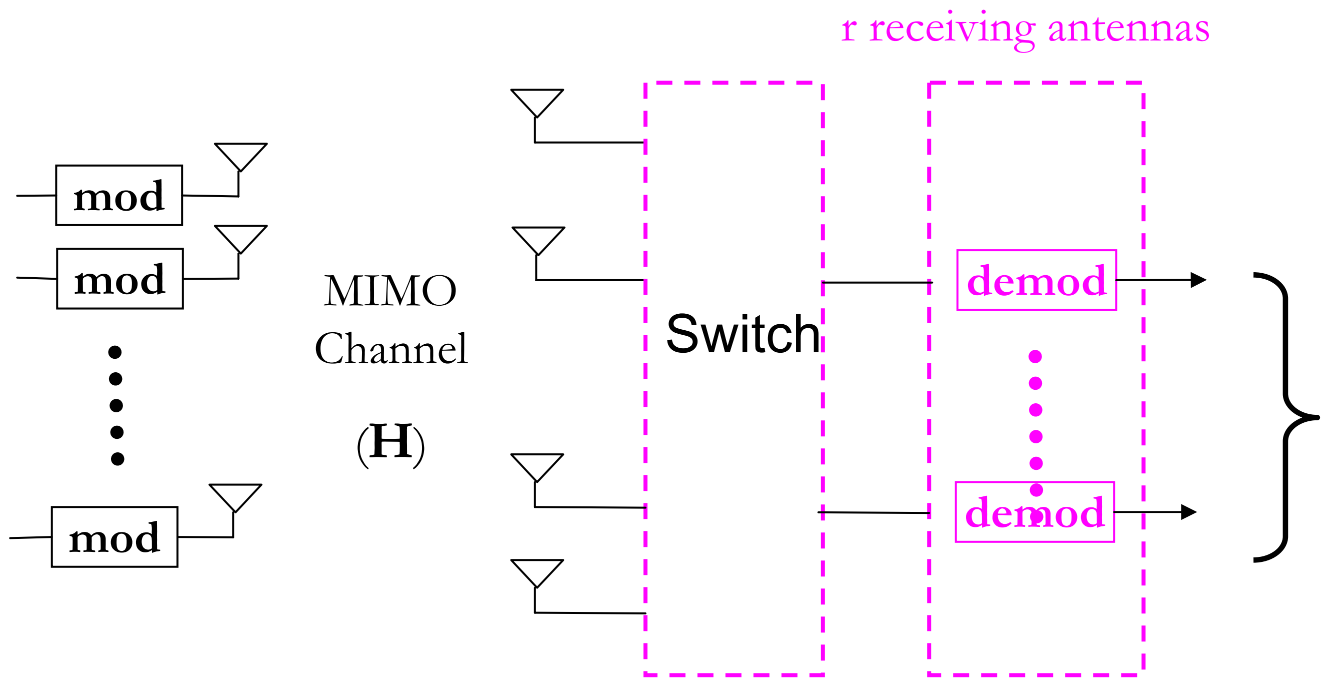
Antenna selection reduces complexity of MIMO



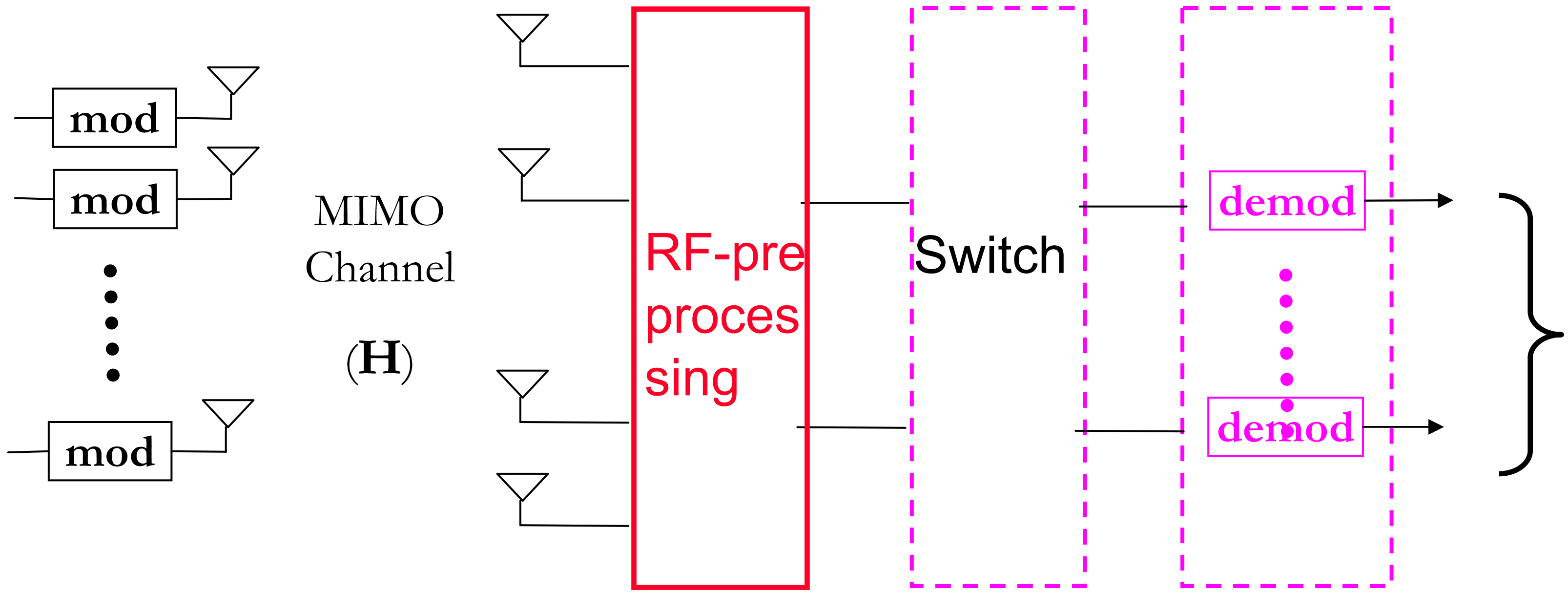
A. F. Molisch and M. Z. Win, “MIMO systems with antenna selection”, IEEE Microwave Magazine March 2004, 46-56 (2004).

- RF chains are major cost factor
- Antenna selection reduces number of chains, and thus costs and complexity
- Hybrid selection: use L out of N antennas

Switch implements adaptive antenna selection



RF-preprocessing recovers beamforming gain



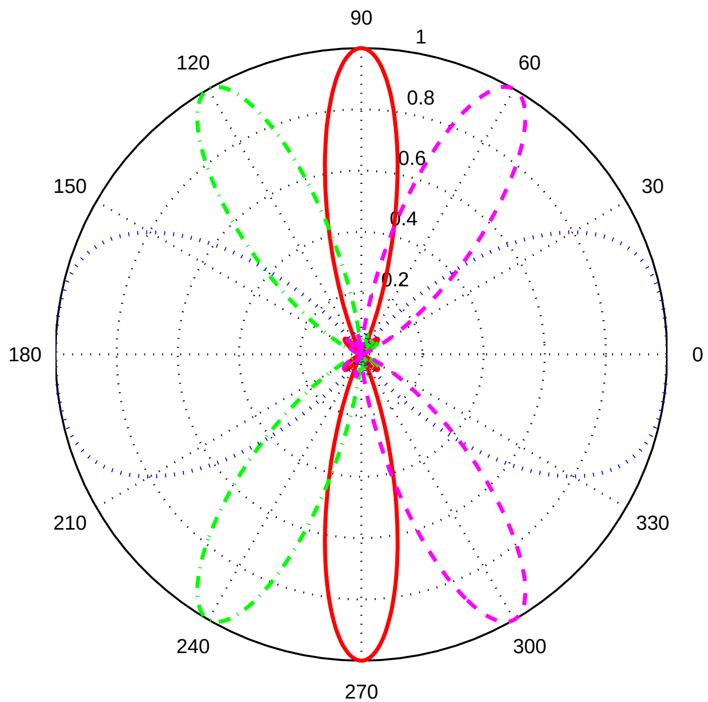
- Can be based on no channel state information (CSI), average CSI, or instantaneous CSI

A. F. Molisch and X. Zhang, „FFT-based Hybrid Antenna Selection Schemes for spatially correlated MIMO channels", *IEEE Comm. Lett*., 8, 36-38 (2004).

X. Zhang, A. F. Molisch, and S. Y. Kung, "Variable-phase-shift-based RF-baseband codesign for MIMO antenna selection", *IEEE Trans. Signal Proc.*, 53, 4091-4103 (2005).

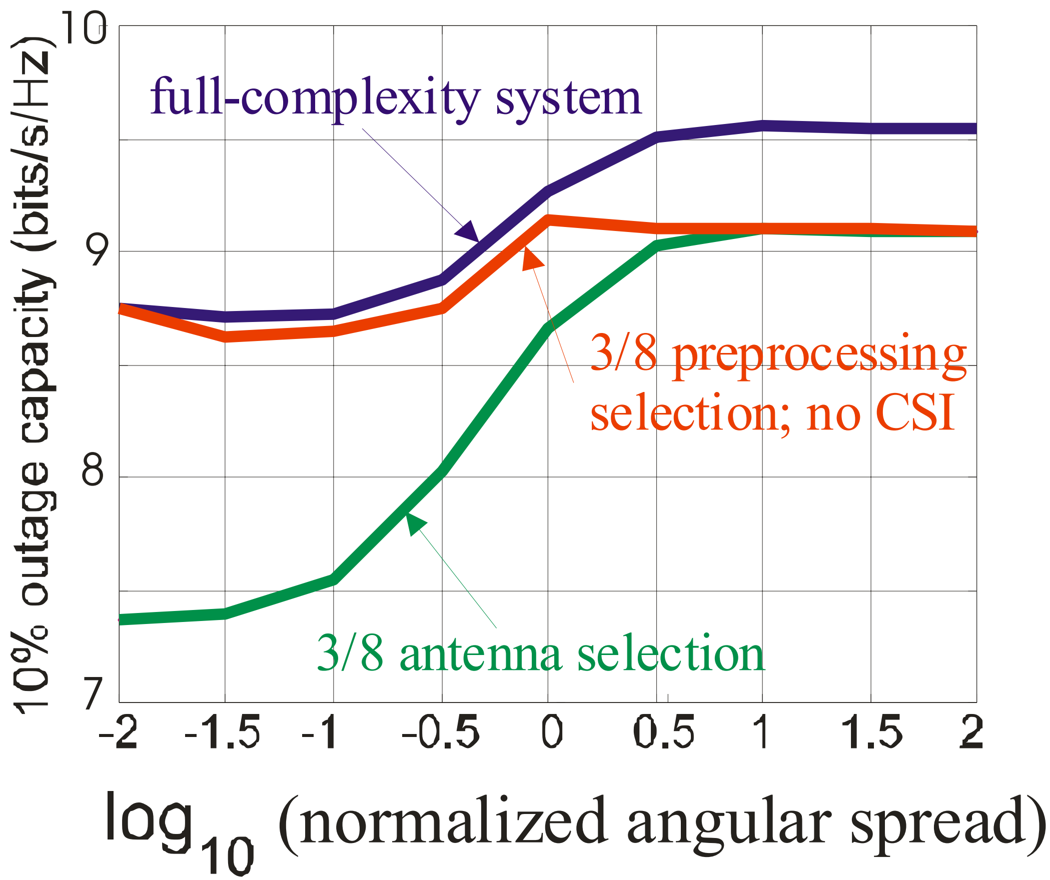
P. Sudarshan, N. B. Mehta, A. F. Molisch, and J. Zhang, „Channel Statistics-Based Joint RF-Baseband Design for Antenna Selection for Spatial Multiplexing", *IEEE Trans. Wireless Comm.* **5**, 3501-3511, (2006)

Interpretation of preprocessing: Converting antenna selection to beam selection



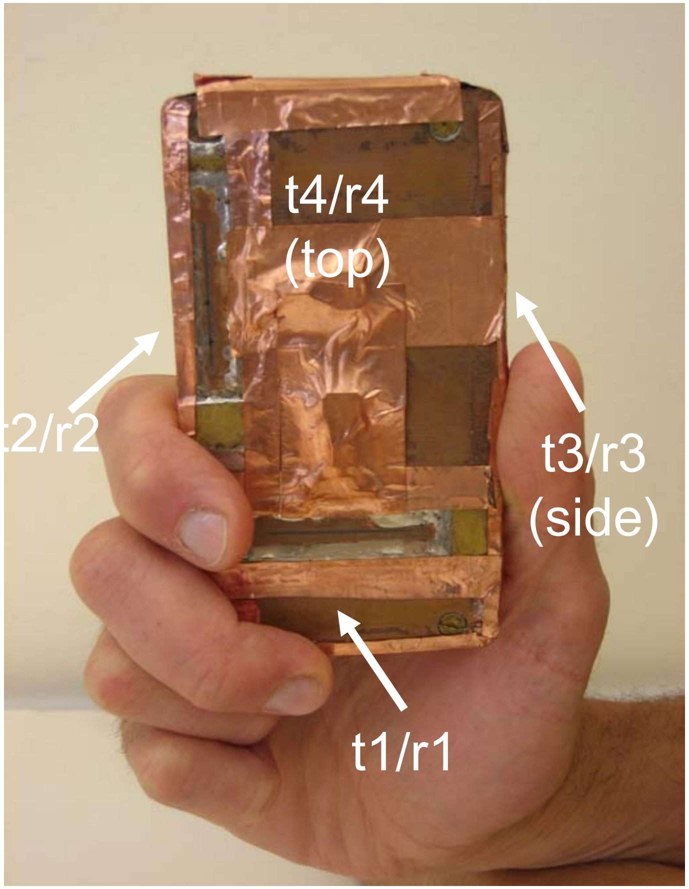
No CSI available

Performance simulations



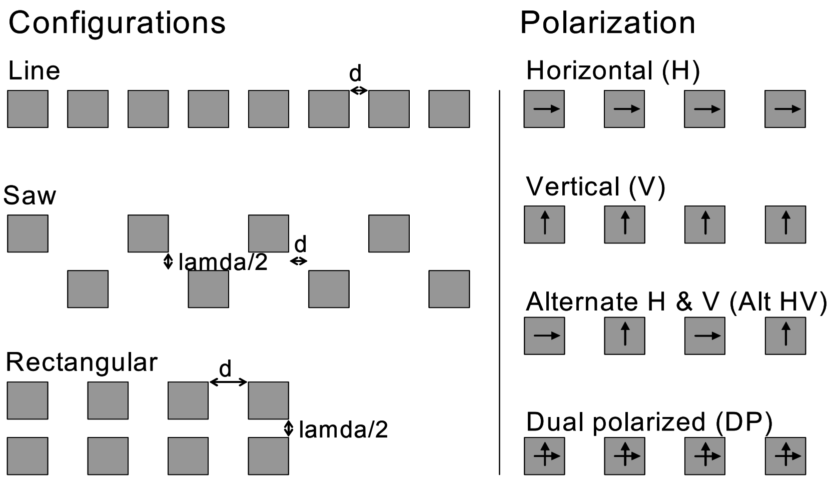
A. F. Molisch, M. Z. Win, Y. S. Choi, and J. H. Winters, "Capacity of MIMO systems with antenna selection", IEEE Trans. Wireless Comm., 4, 1759-1772 (2005).

Handheld device



Device held at chest height, in right hand of standing person (data mode)

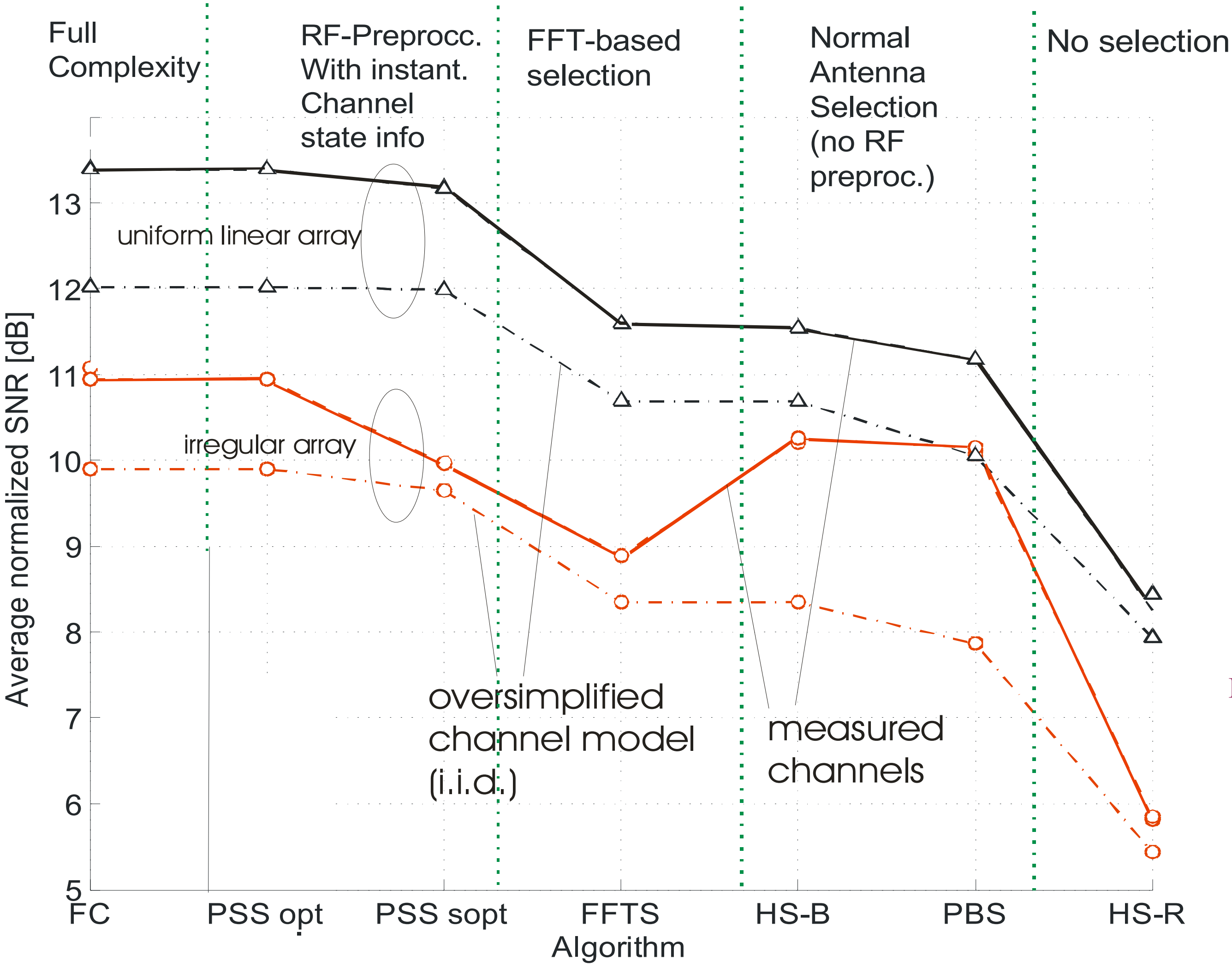
Impact of antenna configurations



P. Almers, T. Santos, F. Tufvesson, A. F. Molisch, J. Karedal, and A. Johansson, "Antenna selection in measured indoor channels", Proc. IEE Part H., in press.

Configuration comparison for the AP - PC scenario HS-B at PC only. LOS. 4:2×2:2.

Diversity gain



P. Almers, T. Santos, F. Tufvesson, A. F. Molisch, J. Karedal, and A. Johansson, "Antenna selection in measured indoor channels", Proc. IEE Part H., in press.

Summary

- MIMO signal processing and information theory deal with "effective" channel from TX antenna connectors to RX antenna connectors
- "Effective" channel is composed of (double-directional) propagation channel and antenna arrays; they interact
- Antenna array elements can be spaced closely, but only for narrowband case and only with appropriate matching
- For ULA, angular dispersion and antenna spacing determine capacity of MIMO system
- For non-ULA, signal statistics change; this can influence efficacy of signal processing schemes like antenna selection