Space-Time Propagation: MIMO Channel Models and Key Challenges

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  - Belgian NSF

Multi-dimensional outline

- **Motivation and introduction**
- **MIMO channel modeling**
  - Physical channel models
  - Non physical models
- **A few challenges**
  - Use of multiple polarizations
  - Antenna correlations vs. cross-channel correlations
  - Key hole effect

Motivation

- **Why do we need channel models ?**
  - Prediction models for network planning
    - Site-specific
    - Antenna-dependent
    - Excellent accuracy
  - Standard models for system design and testing of signal processing algorithms
    - Site- and antenna-independent
    - Reduced accuracy

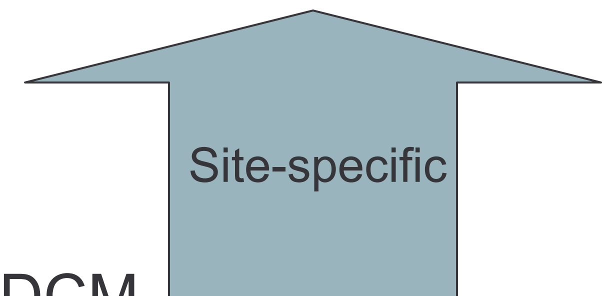
Introduction

- **MIMO channels**

- The channel is represented by a M_R x M_T matrix **H**
  - Need for modeling both **individual** matrix elements and **relationships** (correlations) between elements

MIMO channel models

- **Physical channel models**
  - Ray-tracing
  - Physical-statistical methods
  - Geometry-based stochastic models
  - (Double-)directional channel models (D)DCM



- **Non physical channel models**
  - Channel covariance matrix (full model)
  - Simplified or specific models

Ray-tracing techniques

- **Model features**
  - Buildings are represented by blocks with given material characteristics
  - Path-loss, shadowing and multipaths are implicitly modelled together
  - Geometrical optics: each mechanism is ray-modelled using Fresnel theory and Uniform Theory of Diffraction (UTD)

$$H_{ij}\left(\omega, \mathbf{T} \xrightarrow{Q_m} \mathbf{R}\right) = \sum_m F_m\left(s, s'\right) e^{-jks'} \cdot \mathbf{g}_m^{R^*} \cdot \mathbf{Q}_m \cdot \mathbf{g}_m^{E} K_m\left(s, s'\right) e^{-jks} + \ldots$$

antenna gain and polarisation — complex dyadic coefficient — spreading factor

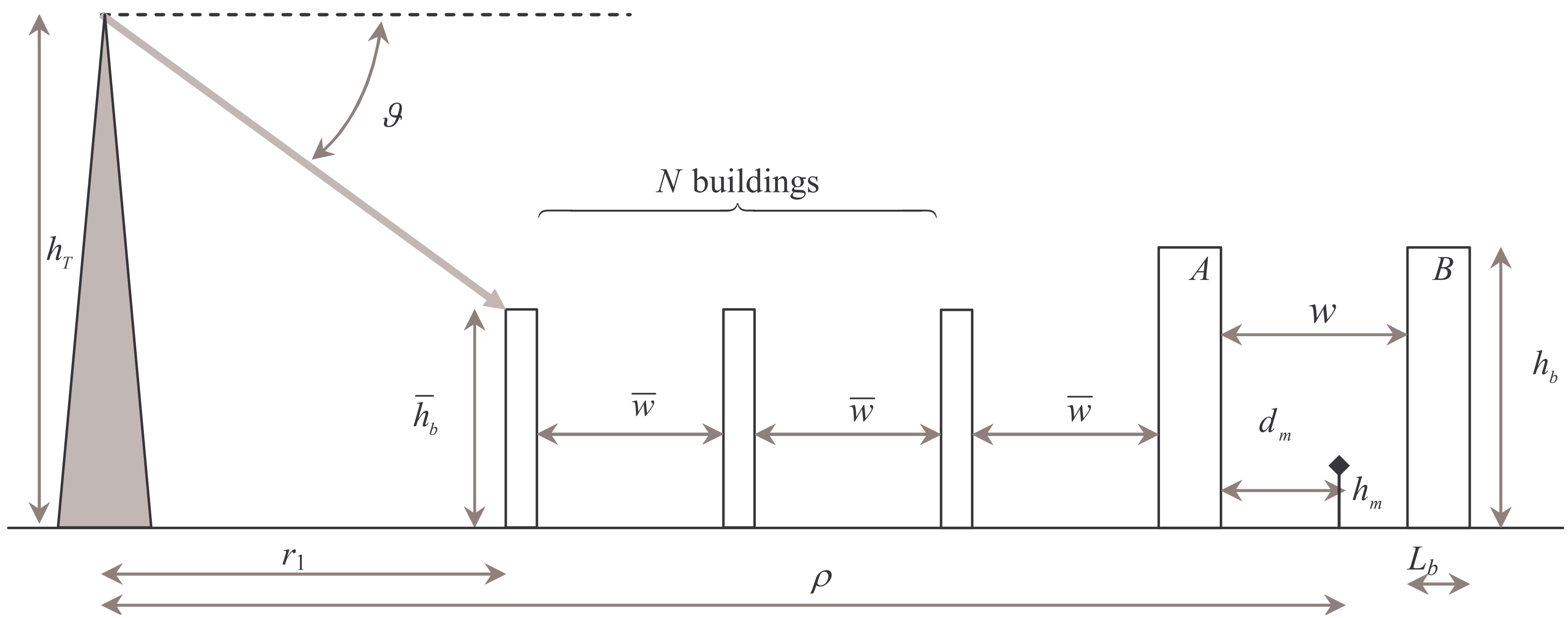
Physical-statistical methods (I)

- **Ray-tracing is highly site-specific**
- **More general model obtained by combining**
  - A physical model, i.e. electromagnetic relationships between environmental and propagation variables
  - Statistical distributions of the environmental parameters

- **Advantages**
  - Wide **parameter range** validity (frequency, etc.)
  - Reduced computational cost thanks to pre-calculation
  - High statistical accuracy

Physical-statistical methods (II)

- The link between physical and environmental parameters is established by applying a ray-tracing tool in a canonical area



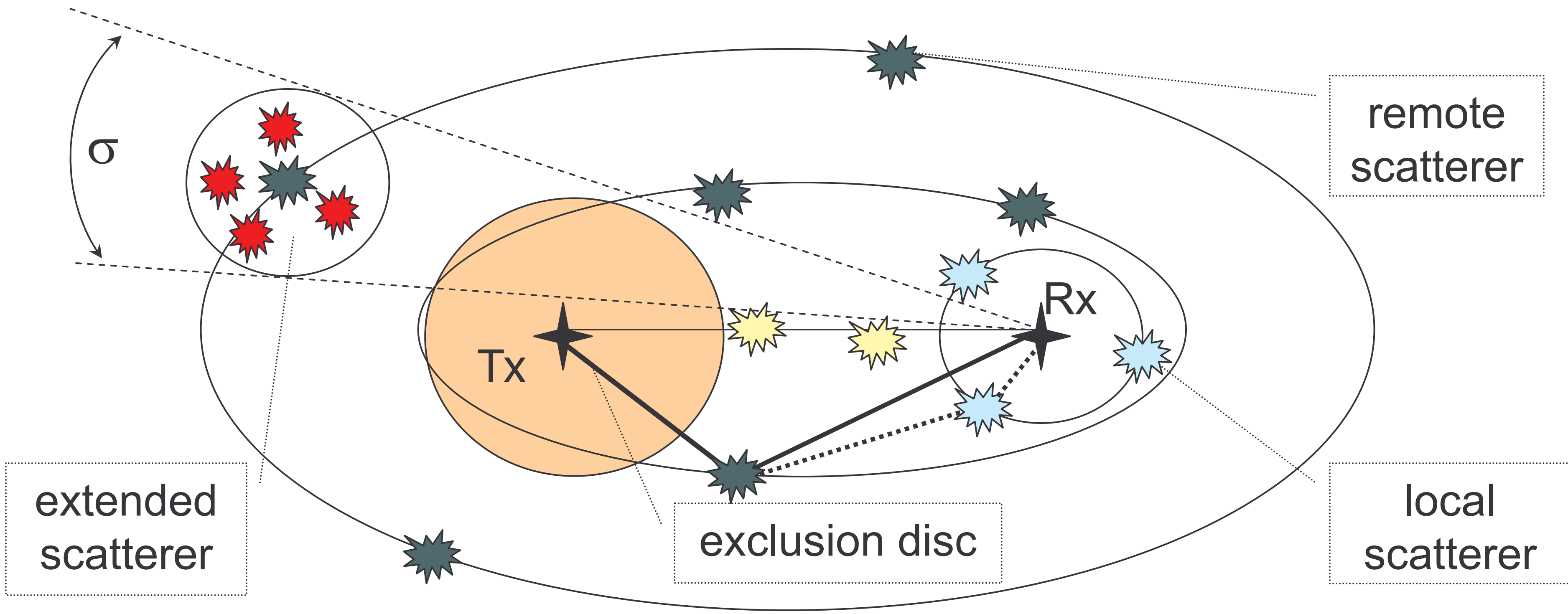
Geometry-based models (I)

- **Original approach**
  - Locate point scatterers according to a certain PDF (one-ring, two-ring, elliptical, Von Mises, etc.)
  - Single scattering only (but can be extended)
  - No range dependency (large-scale variations ?)
  - No direct relationship with TDL models
  - Easy implementation

Geometry-based models (II)

- **Proposed approach**
  - Derive a **geometrical** distribution of scatterers in order to match a given uni-polarized power-delay profile at a reference (maximal) range
  - **Scale** the scatterer distribution to any (smaller) range
  - Integrate fixed and mobile channel **dynamics** (appearance and disappearance of scatterers)
  - Integrate **dual-polarization** modeling (from ray-tracing results)
  - Combine with directional **antenna** patterns

Geometrical interpretation



- **Local scattering ratio** = Σ [light-blue scatterer] / [Σ [light-blue scatterer] + Σ [yellow scatterer]]
  - determined by Tx and Rx angle-spreads

Multi-polarized channels

- **For dual-polarized channels**
  - The reflection coefficient is a matrix: Γ_{ij} is the reflection coefficient for incident wave polarized as the j^{th} Tx antenna and reflected wave polarized as the i^{th} Rx antenna

    $\Rightarrow$ **Scattering XPD**

    (affecting scattered contribution only)

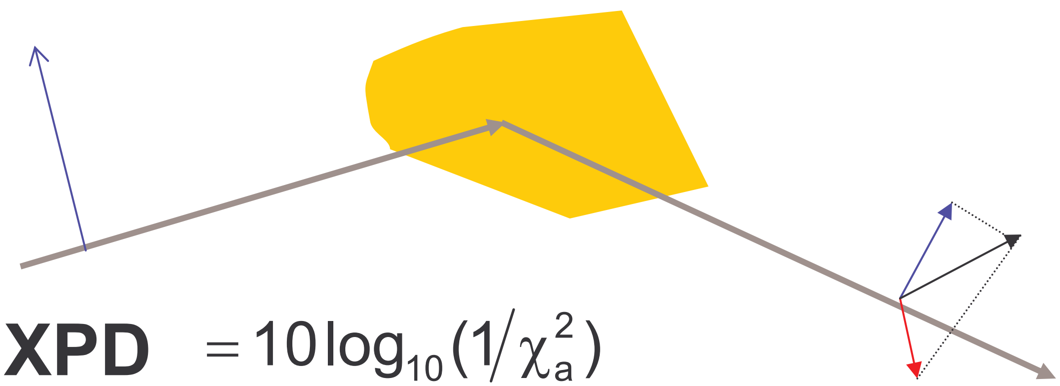
  - Antennas are not ideal

    $\Rightarrow$ **Antenna XPD**

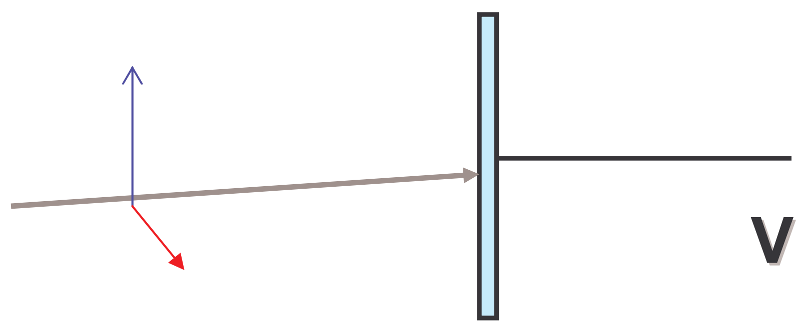
    (affecting both LOS and scattered paths)

Scattering and antenna XPD

- Scattering XPD



- Antenna XPD $= 10\log_{10}(1/\chi_a^2)$



$V \propto E_{pol} + \chi_a \cdot E_{Xpol}$

Dual-polarization modeling (I)

- **Scattered component**
  - For HV scheme, infer **matrix** reflection coefficient from electromagnetic and physical results

$$\begin{bmatrix} \Gamma_{vv} & \Gamma_{vh} \\ \Gamma_{hv} & \Gamma_{hh} \end{bmatrix}$$

  - Any orthogonal scheme is obtained by rotation of this matrix
  - Combine with antenna XPD matrix $\mathbf{C} \Rightarrow \quad \mathbf{\Omega} = \mathbf{C} \cdot \mathbf{\Gamma}$

Dual-polarization modeling (II)

- **HV-scheme matrix reflection coefficient**
  - Γ_{vv} : lognormal squared-amplitude, uniform phase
  - $\Gamma_{hh} = \Gamma_{vv} \cdot \frac{\exp(-j\psi)}{\beta}$
  - $\Gamma_{hv} = \Gamma_{vv} \cdot \frac{\exp(-j\phi)}{\chi}$ and $\Gamma_{vh} = \Gamma_{hh} \cdot \frac{\exp(-j\phi)}{\chi}$

Centered-Gaussian phase-shift with low variance (ψ)

H vs. V gain imbalance (logN, ~ 8 dB) (β)

Scattering XPD (logN, ~ 15 dB) (χ)

Uniform phase shift (ϕ)

Dual-polarization modeling (III)

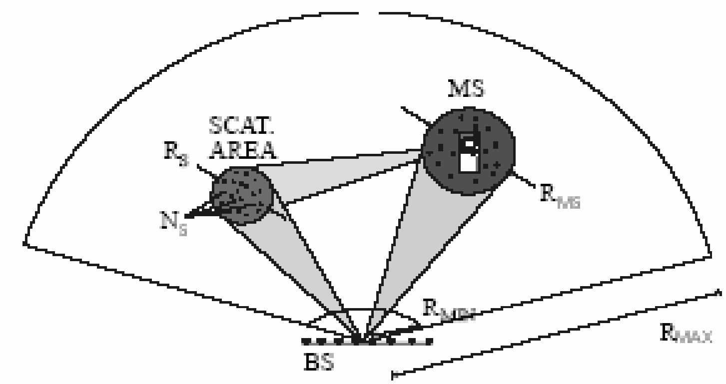
- **Dominant (Ricean) component**
  - Mix of LOS and coherent scattering on the link axis
  - LOS only affected by antenna XPD (matrix **C**)
  - Scattered contribution derived as before (but accounting for a coherence constraint)

$$H_{c,\,nm} \propto \sqrt{1-\alpha}\, C_{nm} + \sqrt{\alpha}\, \Omega'_{nm}$$

Shadow fading figure

= ratio of scattered vs. total power in the coherent dominant component

Double-directional (DD) models (I)



- **Directional models**
  - Originally, SIMO or MISO
- **Example: COST 259**
  - Radio environment (TU, etc.)
  - Large-scale effects (dynamic behavior of clusters, shadowing, etc.)
    - Mixed geometrical-stochastic approach
    - Concept of far and local clusters
    - Visibility regions
  - Small-scale effects : fading (multipaths)

Double-directional (DD) models (II)

- **DD channel models**
  - Truly MIMO
  - Related to physical propagation mechanisms
  - Finite number of scatterers easy to implement
  - Finite energy assumption is implicit
  - Correlation between DoA, DoD and Doppler implicit

Double-directional (DD) models (III)

- **Example: COST 273 (modeling in progress)**
  - Mixed DD-non physical approach
  - Based on COST 259, but extended to multiple antennas at the MS $\Rightarrow$ DoA and DoD joint distributions, DoA and DoD related by means of a coupling matrix
  - Parameterized model based on measurement data in different types of environments

MIMO channel models

- **Physical channel models**
  - Ray-tracing
  - Physical-statistical methods
  - Geometry-based stochastic models
  - (Double-)directional models
- **Non physical channel models**
  - Channel covariance matrix (full model)
  - Simplified or specific models

MIMO channel covariance matrix

- **General model (Rayleigh)**
  - **R** is semi-positive definite
  - Usual simplification: $r_1 = r_2$, $t_1 = t_2$

$$\mathrm{vec}(\mathbf{H}) = \mathbf{R}^{1/2}\,\mathrm{vec}(\mathbf{H}_w)$$

$$\begin{bmatrix} 1 & r & t & s_1 \\ r^* & 1 & s_2 & t \\ t^* & s_2^* & 1 & r \\ s_1^* & t^* & r^* & 1 \end{bmatrix}$$

- **Correlations**
  - Antenna correlations (r and t) are well-known in MIMO studies (detrimental to capacity/performance)
  - **Cross-channel correlations** (e.g. $\equiv s_1$ and s_2 in 2 x 2 channels) are less used

Dual-polarized covariance matrix

- **Channel matrix in dual-polarization schemes**
  - Hadamard product of the space-related matrix $\mathbf{H}_s$ (uni-polarized antennas) and the polarization-related matrix $\mathbf{H}_p$ (co-located antennas)
  - For HV/HV scheme:

$$\mathbf{H}_p \approx \begin{bmatrix} 1 & \chi\beta e^{j\phi} \\ \chi e^{j\phi} & \beta \end{bmatrix}$$

HV gain imbalance (β)

Scattering XPD (χ)

  - Each correlation is the product of the usual space-related correlation (r, t, s_1 or s_2) and a polarization-related correlation (ρ, ϑ, σ_1 or σ_2)

Kronecker model

- **Independence between DoAs and DoDs**
  - Example in 2 x 2 channels: $s_1 = r\,t$ and $s_2 = r^*\,t$
  - Rx and Tx correlation matrices (easy physical interpretation)

$$\Rightarrow \mathbf{H} = \mathbf{R}_R^{1/2}\,\mathbf{H}_w\,\mathbf{R}_T^{1/2}$$

- **Validity**
  - Confirmed by some measurements (Yu *et al*., 2002)
  - Questioned by recent measurement results (Oezcelik *et al*., 2003)

Weichselberger model

- **Joint correlation properties at Rx and Tx**
  - DoA and DoD relationship is preserved
  - 3 components
    - Spatial eigenbasis of Rx and Tx correlation matrices $\mathbf{U}_{Rx}$ and $\mathbf{U}_{Tx}$
    - Power coupling matrix Ω ($\tilde{\mathbf{\Omega}}$ is the element-wise square root)

$$\Rightarrow \mathbf{H} = \mathbf{U}_R \left(\tilde{\mathbf{\Omega}} \circ \mathbf{H}_w \right) \mathbf{U}_T^T$$

    - Structure of Ω strongly related to the radio environment
      - If Ω is diagonal, each single DoD is linked to a single DoA
      - If Ω is of rank one, the model reduces to the Kronecker model

COST 273 model

- **COST 273 model (continued)**
  - The full COST 273 model should **adequately** combine a geometry-based model (DoAs and DoDs at each end) and a non physical model (direction-coupling matrix)
  - Capable of representing uniquely-coupled modes (single and multiple –scattering) and Kronecker-structured diffuse scattering modes
  - Model parameters
    - Number of ones in each row of the coupling matrix
    - Ratio of most powerful “1” w.r.t. the other “1s”

Ricean channels

- **Ricean fading**
  - Existence of a dominant component (often LOS)
  - K-factor (K) = ratio of dominant (fixed, coherent) component to fading component
  - Rayleigh channel is combined with Ricean matrix $\mathbf{H}_{Rice}$
- **General model** $$\mathbf{H} = \sqrt{\frac{K}{K+1}}\mathbf{H}_{Rice} + \sqrt{\frac{1}{K+1}}\mathbf{H}_{Ray}$$
  - Elements of $\mathbf{H}_{Rice}$ have unit power, but phase factors depending on array geometry and orientation

Keyhole effect

- **What is it ?**
  - Correlation matrices at both link ends have high rank
  - Multipaths are forced to travel through a narrow keyhole, so the rank of the instantaneous channel matrix is low
  - Keyhole effect occurs very seldom (apparently …)

- **Gesbert model** $\mathbf{H} = \mathbf{H}_R \, \mathbf{R}_{Keyhole}^{1/2} \mathbf{H}_T$
  - Both $\mathbf{H}_T$ and $\mathbf{H}_R$ have low correlation matrix ($\rightarrow$ i.i.d.)
  - The channel is double-Rayleigh distributed

Channel model and mutual information (in Rayleigh fading)

- **Exact closed-form of mutual information ?**
- **Upper-bound:** inverse $\log_2$ and E

$$\overline{C} \leq \log_2 \overline{\kappa} = \log_2 E\left\{\det\left[\mathbf{I}_{M_R} + \gamma\,\mathbf{HH}^H\right]\right\}$$

  - Application to 2 x 2 schemes

$$\overline{\kappa} = 1 + 4\gamma + \gamma^2\left[1 + |s_1|^2 + 1 + |s_2|^2 - 2|r|^2 - 2|t|^2\right]$$

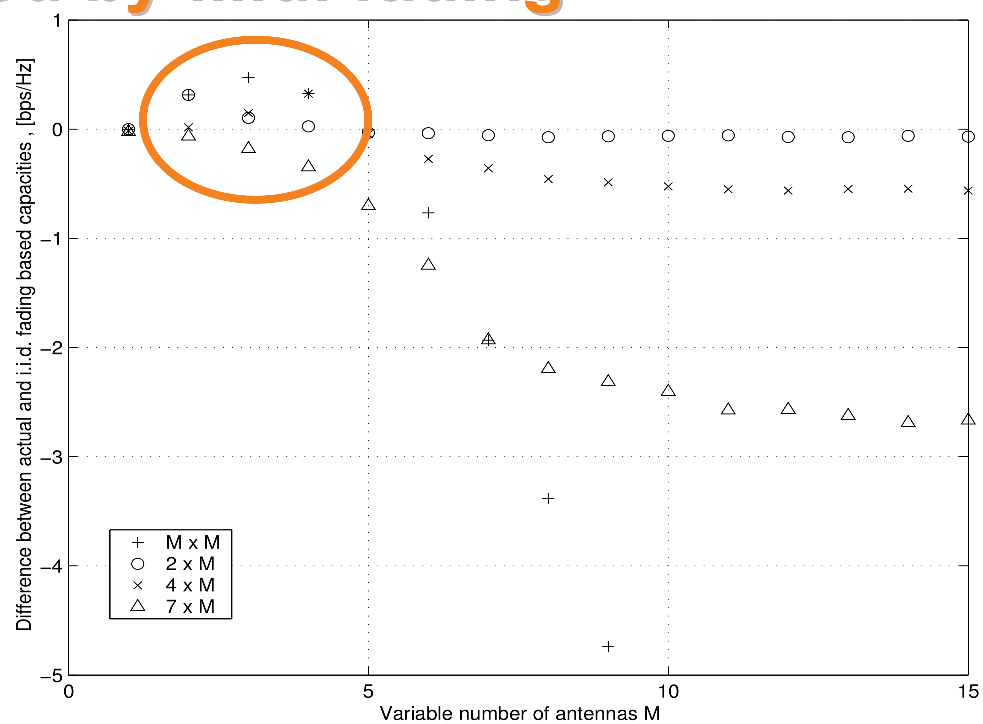
    - Cross-channel correlations s_k play a symmetrical **beneficial** role on ergodic capacity (at least for 2 x M or M x 2 schemes)
    - Generally not be true for outage capacity

Impact of cross-channel correlations (I)

- For equal average energy, **actual capacity is not always maximized by i.i.d. fading**

One-ring model

- Range-to-ring-radius ratio = 30
- Broadside arrays
- $d_R = 0.38\ \lambda$
- $d_T = 30\ d_R$
- SNR = 30 dB



Impact of cross-channel correlations (II)

- **Kronecker model will under-estimate capacity**

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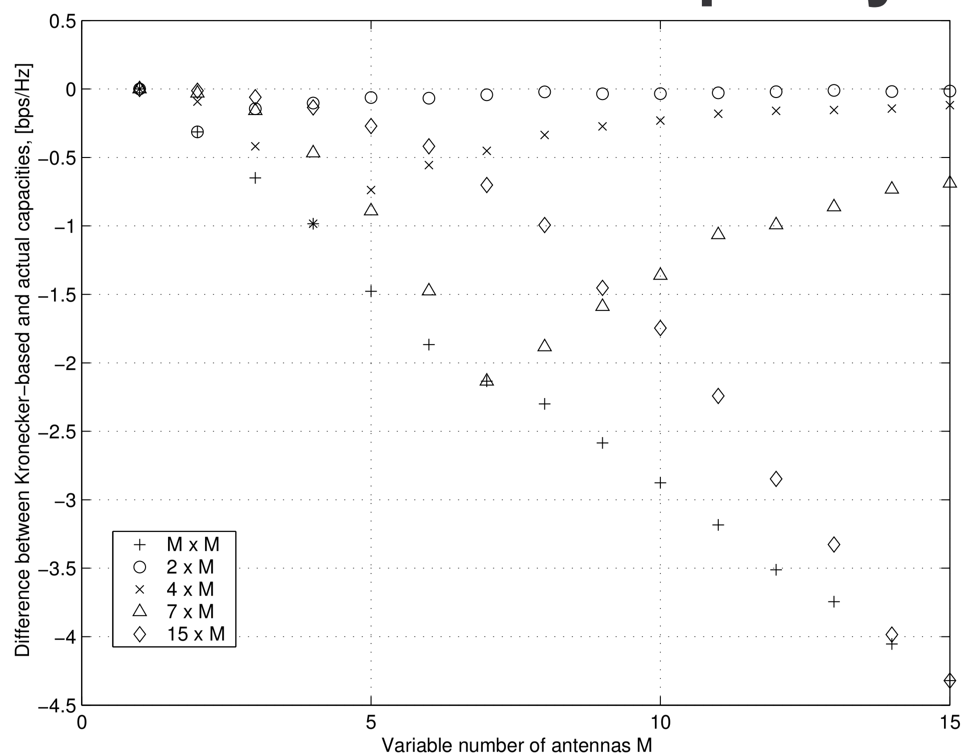

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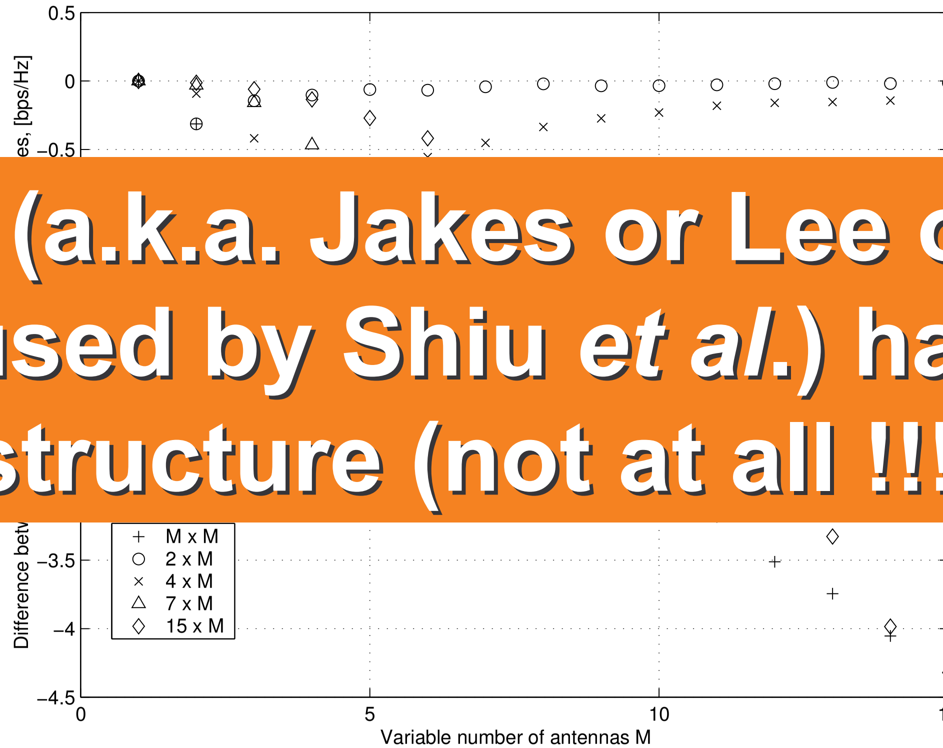

- $d_R = 0.38\ \lambda$
- $d_T = 30\ d_R$
- SNR = 30 dB

One-ring model (a.k.a. Jakes or Lee or Abdi *et al.* and used by Shiu *et al.*) has NO Kronecker structure (not at all !!!)

Diagonal channels

- **Let us consider M x M channels with**
  - All antenna correlations = 0
  - Maximum number of cross-channel correlations = 1
  - Example of 4 x 4 channel

$$\mathbf{H} = \begin{bmatrix} a & b & c & d \\ b & c & d & a \\ c & d & a & b \\ d & a & b & c \end{bmatrix}$$

- **For these channels, the ergodic mutual information is exactly linear in M**

$$\overline{C} = M \cdot \log_2 e \cdot \exp\left(\frac{1}{\gamma}\right) E_1\left(\frac{1}{\gamma}\right) > \overline{C}_{iid}(M)$$

Summary (I)

- **MIMO channel models are essential for system design and simulation**
  - Physical models
    - Independent of antenna configuration
    - Fully physical models (ray-tracing, etc.)
      - Prohibitive computation time
      - Site-specific
    - Parameterized models (e.g. DD models)
      - Need to take into account different propagation methods
      - For parameterized models, derivation from measured data might not be straightforward (parameter estimation methods, etc.)

Summary (II)

- Non physical models
  - Directly obtained from measurements (including antennas)
  - Manipulate with extra care (can lead to artifacts)
  - Kronecker model is oversimplified (most geometry-based models have NO Kronecker structure)
  - Diagonal channels: better than i.i.d. ?

Summary (III)

- **Challenges**
  - Polarization modeling
    - Experimental validation required
    - Optimization of multi-polarized (larger than 2 x 2) systems
  - Keyholes: where/when do they appear in real-world channels ?
  - What is an “ideal” MIMO channel ?