Space-Time Propagation: MIMO Channel Models and Key Challenges

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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 $M_R \times M_T$ 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)

\[
H_{ij}(\omega, T \rightarrow R) = \sum_m F_m(s, s') e^{-jks'} \cdot g_m^R \cdot Q_m \cdot g_m^E K_m(s, s') e^{-jks} + \ldots
\]

- 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** = $\Sigma \star / [\Sigma \star + \Sigma \star ]$
- determined by Tx and Rx angle-spreads
Multi-polarized channels

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

    $$\Rightarrow \text{Scattering XPD}$$

    (affecting scattered contribution only)

- Antennas are not ideal

    $$\Rightarrow \text{Antenna XPD}$$

    (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 \( \mathbf{C} \Rightarrow \Omega = \mathbf{C} \cdot \Gamma \)
Dual-polarization modeling (II)

- **HV-scheme matrix reflection coefficient**
  - $\Gamma_{ww}$: lognormal squared-amplitude, uniform phase
  - $\Gamma_{hh} = \Gamma_{ww} \cdot \frac{\exp(-j\psi)}{\beta}$
    - Centered-Gaussian phase-shift with low variance
  - $\Gamma_{hv} = \Gamma_{ww} \cdot \frac{\exp(-j\phi)}{\chi}$
    - Scattering XPD (logN, ~ 15 dB)
  - $\Gamma_{vh} = \Gamma_{hh} \cdot \frac{\exp(-j\phi)}{\chi}$
    - Uniform phase shift
  - $\beta$, $\chi$, $\psi$, $\phi$: parameters

H vs. V gain imbalance (logN, ~ 8 dB)
Dominant (Ricean) component

- Mix of LOS and coherent scattering on the link axis
- LOS only affected by antenna XPD (matrix $\mathbf{C}$)
- Scattered contribution derived as before (but accounting for a coherence constraint)

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

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 ⇒ 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)**
  - $\mathbf{R}$ is semi-positive definite
  - Usual simplification: $r_1 = r_2$, $t_1 = t_2$
  
  \[
  \text{vec}(\mathbf{H}) = \mathbf{R}^{1/2} \text{vec}(\mathbf{H}_w)
  \]

- **Correlations**
  - Antenna correlations ($r$ and $t$) are well-known in MIMO studies (detrimental to capacity/performance)
  - **Cross-channel correlations** (e.g. $s_1$ 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 $H_s$ (unipolarized antennas) and the polarization-related matrix $H_p$ (co-located antennas)
  - For HV/HV scheme:
    \[
    H_p \approx \begin{bmatrix}
    1 & \chi \beta e^{j\phi} \\
    \chi e^{j\phi} & \beta
    \end{bmatrix}
    \]
    - HV gain imbalance
    - Scattering XPD
  - Each correlation is the product of the usual space-related correlation ($r, t, s_1$ or $s_2$) and a polarization-related correlation ($\rho, \vartheta, \sigma_1$ or $\sigma_2$)
Kronecker model

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

\[
H = R_{R}^{1/2} H_{w} R_{T}^{1/2}
\]

- **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 $U_{Rx}$ and $U_{Tx}$
    - Power coupling matrix $\Omega$ ($\tilde{\Omega}$ is the element-wise square root)

  \[ H = U_R \left( \tilde{\Omega} \circ H_w \right) U_T^T \]

- Structure of $\Omega$ strongly related to the radio environment
  - If $\Omega$ is diagonal, each single DoD is linked to a single DoA
  - If $\Omega$ 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 $H_{Rice}$

- **General model**
  \[
  H = \sqrt{\frac{K}{K+1}} H_{Rice} + \sqrt{\frac{1}{K+1}} H_{Ray}
  \]
  - Elements of $H_{Rice}$ 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**
  \[
  H = H_R \cdot R_{Keyhole}^{1/2} H_T
  \]
  - Both \( H_T \) and \( H_R \) have low correlation matrix (\( \to \) 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 \( E \)

\[
\overline{C} \leq \log_2 \kappa = \log_2 E \left\{ \det \left[ I_{M_R} + \gamma HH^H \right] \right\}
\]

- Application to 2 x 2 schemes

\[
\kappa = 1 + 4\gamma + \gamma^2 \left[ 1 + |s_1|^2 + 1 + |s_2|^2 - 2|t|^2 - 2|t|^2 \right]
\]

- 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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Impact of cross-channel correlations (II)

- Kronecker model will under-estimate capacity

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 !!!)

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

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

\[
\bar{C} = M \cdot \log_2 e \cdot \exp\left(\frac{1}{\gamma}\right) E_1\left(\frac{1}{\gamma}\right) > \bar{C}_{\text{iid}}(M)
\]
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?