MIMO Channel Models

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Outline

• The wireless channel
• Model categories
• Propagation-based models
• Analytical models
• Standardized models
• Which model is “best”? 
Outline of Part 3

• The wireless channel
  – Multipath propagation
  – The double-directional propagation channel
  – Clusters and dispersion
  – Diversity

• Model categories
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Multipath Propagation (1)

• Interacting objects (scatterers) cause multipath propagation
• Movement of Tx, Rx, and/or scatterers causes Doppler shifts
• Each path has its reflectivity, delay, and Doppler shift

\[ A_2 e^{j2\pi f_2 t} \delta(\tau - \tau_2) \]
\[ A_0 e^{j2\pi f_0 t} \delta(\tau - \tau_0) \]
\[ A_1 e^{j2\pi f_1 t} \delta(\tau - \tau_1) \]

\( v_{TX} \) \( v_{RX} \)

\( v_i \ldots \text{object velocity} \)
\( A_i \ldots \text{path weight} \)
\( \tau_i \ldots \text{path delay} \)
\( f_i \ldots \text{Doppler frequency} \)
The Double-Directional Radio Channel

- Multiple antennas enable spatial resolution:

  - Angles of departure (azimuth $\varphi_{T,i}$, elevation $\theta_{T,i}$)
  - Angles of arrival (azimuth $\varphi_{R,i}$, elevation $\theta_{R,i}$)

  \[ h(t, \tau, \varphi_{T}, \varphi_{R}, \theta_{T}, \theta_{R}) = \sum_{i} A_i \delta(\tau - \tau_i(t)) \cdot \delta(\varphi_{T} - \varphi_{T,i}(t)) \cdot \delta(\varphi_{R} - \varphi_{R,i}(t)) \cdot \delta(\theta_{T} - \theta_{T,i}(t)) \cdot \delta(\theta_{R} - \theta_{R,i}(t)) \]

- Additional properties:
  - Angles of departure (azimuth $\varphi_{T,i}$, elevation $\theta_{T,i}$)
  - Angles of arrival (azimuth $\varphi_{R,i}$, elevation $\theta_{R,i}$)

Multiple Antennas

- MIMO channel:

  - Input-output relation:
    \[ y(t) = \int_{-\infty}^{\infty} H(t, \tau) x(t - \tau) \, d\tau \]
    with $M_R \times M_T$ channel impulse response matrix
    \[ H(t, \tau) = \begin{bmatrix} h_{1,1}(t, \tau) & \cdots & h_{1,M_T}(t, \tau) \\ \vdots & \ddots & \vdots \\ h_{M_R,1}(t, \tau) & \cdots & h_{M_R,M_T}(t, \tau) \end{bmatrix} \]
**Multipath Clusters**

- **Clusters** lead to temporal and angular dispersion:
  - Tx cluster spreads
  - Rx cluster spreads
  - Rx azimuth spread

- **Global dispersion parameters:**
  - rms delay spread
  - rms angular spreads

- **Cluster dispersion parameters:**
  - cluster rms delay spread
  - cluster rms angular spread

  Global dispersion parameters are no meaningful description of propagation environments!

**Observing Clusters**

- Indoor scenario, NLOS, Laboratory environment
- Rx fixed, Tx is moved through the room
**Diversity** is the presence of multiple copies of the transmitted signal

- at different times (time diversity),
- at different delays or frequencies (delay/frequency diversity),
- in space (spatial diversity),

where the different paths are **fading independently**.

**Diversity Example**

Demonstrating spatial diversity:
- only weak eigenvalues fade
- strong eigenvalues stay constant

Video of the environment

Source: Tokyo Institute of Technology
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- Analytical models
- Standardized models
- Which model is “best”?

Why do we need channel modelling?

- For MIMO deployment and network planning
  - site specific
- For system design and test
  - site independent

...but not: one model serves all
MIMO Model Categories

**System parameters**
- Antenna configuration
- Bandwidth

**Propagation-based models**
Focus: physical wave propagation
- **deterministic:**
  - ray launching / tracing
  - stored measurements
- **geometry-based stochastic:**
  - GSCM
  - COST 259
  - COST 273

**Analytical Models**
Focus: MIMO channel matrix
- **correlation-based:**
  - full correlation model
  - iid model
  - Kronecker model
  - Weichselberger model
- **propagation-motivated:**
  - virtual channel representation
  - finite scatterer model

**Standardized models:**
- 3GPP SCM
- IEEE 802.11n
- IEEE 802.16 WiMAX

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Propagation-Based Models

• Modelling of all system parameters possible
  – Time-variance (moving Tx/Rx/scatterers)
  – Frequency selectivity
  – Spatial structure

• Important for link-level simulations and hardware channel simulators

• More art than science
  – Who decides on the scenario?
    ⇒ Canonical scenarios

Deterministic Models – Ray Launching / Tracing

• Model environment by geometry, place scatterers
• Launch or follow rays from Tx to Rx
Deterministic Models – Stored Measurements

- Conduct measurements
- Store impulse responses
- Use impulse responses in channel simulator “Playback Simulations”

Question: Which scenario shall be used?

Geometry-Based Stochastic Channel Models (GSCM)

- Model environment by scattering clusters placed in space
- Within clusters, paths are modelled by statistic means
- Use ray tracing to calculate channel response
COST 259 Approach

- Single-bounce model, no scatterers around BS
- Fixed relationship between AOD, AOA, and delay
- Well suited for smart antenna systems, but nature is not single bounced

AOA: angle of arrival; AOD: angle of departure; BS/MS: base/mobile station

COST 273 Approach (1)

- Model based on clusters
- 3 different cluster types
- Clusters are placed geometrically and stochastically
COST 273 Approach (2)

- Local clusters around MS and/or BS may occur, depending on the scenario

- Any combination of delay ($\tau$) and angles ($\varphi_T$, $\varphi_R$, $\theta_T$, $\theta_R$) can be modelled, not limited to double scattering

- All parameters are given per cluster; there are no global spreads

- Direct coupling between AOAs and AODs; no “Kronecker” structure

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    - Correlation-based
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Analytical Channel Models

- Analytical channel models focus on modelling only the spatial structure (up to now)

- **Narrow-band models**
  - Delay spreads neglected
  - No Doppler shifts possible

- Number of antennas is predetermined

- Well suited for testing signal processing algorithms

- Can be used in combination with propagation-based models

Analytical Channel Models – Overview

**Correlation-based models**

- Full-correlation model:
  \[ H = \text{unvec}\left(R_{h}^{1/2}\text{vec}(G)\right) \]

- Weichselberger model:
  \[ H = U_{RX}(\tilde{\Omega}_{WB} \odot G)U_{TX}^{T} \]

- Kronecker model:
  \[ H = c \cdot R_{RX}^{1/2}G(R_{TX}^{1/2})^{T} = U_{RX}(\tilde{\Omega}_{Kron} \odot G)U_{TX}^{T} \]

- iid model ("canonical model"):
  \[ H = G \]

**Propagation-motivated models**

\[ H = A_{RX}(\tilde{\Omega}_{cpl} \odot G)A_{TX}^{T} \]

… to be explained presently!
Channel Correlation Matrix

- The channel correlation matrix
  \[ R_h = E\{hh^H\}, \quad \text{with} \quad h = \text{vec}(H) \]
  sufficiently characterizes the spatial structure of the channel. Size of \( R_h \):
  \[ M_T M_R \times M_T M_R \]
  Note: The \( \text{vec}(\cdot) \) operator stacks the columns of a matrix into a vector.

- Underlying assumption: Rayleigh fading channel
  \[ h \sim \mathcal{CN}(0, R_h) \]

- If this assumption is not fulfilled, all the following models will inevitably fail!

\( \mathcal{CN}(\mu, R) \)… distributed circular symmetric complex gaussian with mean \( \mu \) and covariance \( R \)

Correlation-Based Analytical Models

- Full-correlation model
  - Very complex
  - Most accurate

- Weichselberger model
  - Good approximation
  - Good performance-complexity compromise

- Kronecker model
  - “Separates” channel into Tx and Rx sides
  - Very limited validity

- iid model
  - Most simple
  - No physical relevance
**Full-Correlation Model**

- Synthetic channel realizations consistent with channel correlation matrix $R_h$ can be generated by
  \[ \mathbf{H} = \text{unvec} \left( R_h^{1/2} \mathbf{g} \right), \quad \text{with } \mathbf{g} \sim \mathcal{C}\mathcal{N}(0, \mathbf{I}), \]
  where $\mathbf{g}$ is an iid white Gaussian random vector.

- Can be interpreted as a noise-coloring process:

```
g \rightarrow R_h^{1/2} \rightarrow h \rightarrow \text{unvec}(\cdot) \rightarrow H
```

**iid Model**

- All elements of the channel matrix $\mathbf{H}$ are
  - complex Gaussian
  - independent identically distributed (iid) $\Rightarrow$ uncorrelated

- Channel correlation matrix is modelled as
  \[ R_h = \rho \cdot \mathbf{I} \]

- Channel realizations can be generated by
  \[ \mathbf{H} = \sqrt{\rho} \cdot \mathbf{G}, \quad \text{with } \mathbf{G} \sim \mathcal{C}\mathcal{N}(0, \mathbf{I}) \]

- Implications:
  - no spatial structure is modelled
  - only valid for (very) rich scattering environments

  **BUT**
  - cannot even be validated by measurements in indoor environments!
Kronecker Model – Definition

- Full-correlation matrix has too many parameters
  - treat correlation independently at Tx and Rx:
    - Transmit correlation matrix: $R_{TX} = E\{H^H H\}$
    - Receive correlation matrix: $R_{RX} = E\{HH^H\}$

- Channel correlation matrix is modelled by
  \[
  R_h \approx \frac{1}{\sqrt{\text{tr}\{R_{RX}\}}} R_{RX} \otimes R_{TX}^T \quad \otimes \ldots \quad \text{Kronecker matrix product}
  \]

- Channel realizations can be generated by
  \[
  H = c \cdot R_{RX}^{1/2} G R_{TX}^{1/2}, \quad \text{with} \quad G \sim \mathcal{CN}(0, I)
  \]

Kronecker Model – Implications

- Kronecker model holds true only if channel can be separated into Tx side and Rx side
- Rx directions are independent of Tx directions
- Only satisfied for few antennas or large antenna spacing
Weichselberger Model – Definition

- Relaxes assumptions of Kronecker model by using power coupling of Tx and Rx eigenmodes, defined by
  \[ R_{TX} = U_{TX} \Lambda_{TX} U_{TX}^H \]
  \[ R_{RX} = U_{RX} \Lambda_{RX} U_{RX}^H \]

- Power coupling of eigenmodes is described by coupling matrix
  \[ \Omega_{WB} = \mathbb{E} \left\{ \left( U_{RX}^H H U_{TX}^* \right) \odot \left( U_{RX}^T H U_{TX} \right) \right\} \]

- Channel correlation matrix is modelled as
  \[ R_h = \sum_{i=1}^{M_T} \sum_{j=1}^{M_R} \omega_{ji} (u_{TX,i} \otimes u_{RX,j})(u_{TX,i} \otimes u_{RX,j})^H, \quad \text{with } \omega_{ji} = (\Omega_{WB})_{j,i} \]

- Channel realizations can be generated by
  \[ \Pi - U_{RX} (\tilde{\Omega}_{WB} \odot G) U_{TX}^T, \]
  where \( \tilde{\Omega}_{WB} \) is element-wise square-root of \( \Omega_{WB} \), and \( G \sim \mathcal{CN}(0, I) \)

\( \odot \ldots \) element-wise matrix product (Hadamard product)

Weichselberger Model – Parameters

What are “eigenmodes” and the coupling matrix \( \Omega_{WB} \)?

- Eigenmodes represent the scattering environment.
- The coupling matrix \( \Omega_{WB} \) describes the interaction betweenTx and Rx eigenmodes, indicating power coupling.
- Elements in \( \Omega_{WB} \) reflect the strength and direction of power coupling, with hot/cold representing strong/weak power.
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  – 3GPP SCM
  – IEEE 802.11n
  – IEEE 802.16 WiMAX (?)
• Which model is “best”?  

3GPP Spatial Channel Model (SCM)

SCM is a geometry-based stochastic channel model, based on COST 259

1. Choose scenario
   Suburban macro Urban macro Urban micro

2. Determine user parameters
   - Angle spread
   - Lognormal shadowing
   - Delay spread
   - Pathloss
   - Orientation, Speed Vectors
   - Antenna gains
   - Angles of departure (paths)
   - Angles of departure (subpaths)
   - Path delays
   - Average path powers
   - Angles of arrival (paths)
   - Angles of arrival (subpaths)

3. Generate channel coefficients
   - Polarization
   - LOS (urban micro)
   - Far scattering cluster (urban macro)
   - Urban canyon (urban macro)

Options
IEEE 802.11n MIMO Channel Model – Principles

1. Choose scenario
   - Delay models (A-F)

2. Physical model
   - GSCM model
   - Cluster position is uniform in AOA/AOD
   - Cluster angular spreads are defined for different models
   - Add Doppler shift

3. Analytical model
   - Impose antenna structure
   - Use Kronecker model for each channel tap
   - Parameters are extracted from simulated physical model

802.11n MIMO Channel Model – Discrepancies

- GSCM model (physical model used) is well-defined and reasonable
  
  BUT

- Kronecker model (analytical model used) is only valid for small number of antennas and large antenna spacing

- Tap-wise Kronecker model is even more inaccurate

➤ Model is NOT WELL SUITED for indoor channels!
No MIMO model available at this point

Models already available for
  - pathloss
  - fading
  - delay spread
  - Doppler spread
Which Propagation-Based MIMO Model is “Best”?

- Physical (propagation-based) channel models
  - … should be motivated by measurements
  - … should be able to model the behavior of different environments
  - Accuracy-complexity tradeoff

- Challenges
  - Find one model that can be parameterized for many environments
  - Environments/scenarios must be parameterized accurately; parameters should be extracted from extensive measurements
  - Reduce complexity

- The “best” propagation-based model is not developed yet, but COST 273 may come close.

Which Analytical MIMO Model is “Best”?

- Analytical channel models
  - … should accurately reflect the spatial structure of the channel
  - … should be validated by measurements
  - Accuracy-complexity tradeoff

- Challenges
  - Optimal accuracy-complexity compromise
  - Extend analytical models to frequency-selective and time-varying channels

- The “best” analytical model?
  - There is no “best” one, but a “most suitable” one for specific requirements
  - When no specific requirements are in focus, the model should reflect the spatial structure accurately