Review of MIMO Propagation Channel Models: Background, Comparison, and Some Progress

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Outline

I. MIMO and MIMO Channel Modelling
II. The SCM and Its Spatial Correlation Characteristics
III. The KBSM and Its Spatial Correlation Characteristics
IV. Comparisons Between the SCM and KBSM
V. Conclusions
I. MIMO and MIMO Channel Modelling

- **MIMO-Multiple Input Multiple Output:**
  - Both the transmitter and receiver are equipped with multiple antennas.
  - Exploits the spatial dimension of mobile propagation channels.
  - Works better in rich scattering multipath propagation environments.
  - Widely used in standards, e.g., 3GPP, next generation Wi-Fi (802.11n), WiMAX (802.16d), and mobile WiMAX (802.16e).
Benefits from MIMO

- **Spatial multiplexing gain** – increased data rates / throughput
  - Demultiplex data across sub-channels through space (multiple antennas).

- **Spatial diversity gain** – increased reliability
  - Additional data redundancy over space and time (multiple symbols)

- **Tradeoff** between spatial multiplexing gain and diversity gain

- Highest gains are achieved under spatially **uncorrelated** Rayleigh fading channels (multiple uncorrelated processes for MIMO channel models).

- In practice, **spatial correlations** are often observed, which greatly influence the link capacity of MIMO systems.

- MIMO channel models considering spatial correlation properties are necessary!
Classification of MIMO Channel Models

- **Deterministic channel models (DCM)**
  - Stored measured channel impulse responses
  - Ray tracing technique

- **Stochastic channel models**
  - **Physical models**
    - Geometric Based Stochastic Models (GBSM): distribution of scatterers
      - One ring, two ring, elliptical, …
    - Parametric Stochastic Models (PSM): tapped delay line structure
      - 3GPP SCM, COST 259, …
  - **Analytical models**
    - Correlation Based Stochastic Models (CBSM): spatial correlation matrix
      - Kronecker Based Stochastic Model (KBSM)
    - Virtual Channel Representation
    - Joint Correlation Models (Weichselberger model)
Tradeoffs in MIMO Channel Models

- Deterministic approach ↔ Stochastic approach
- Physical intuition ↔ Analytical traceability

Analytical

- High accuracy!
- High complexity!
- Low adaptability!
  (Radio propagation people)

Physical

- Low accuracy!
- Low complexity!
- Low adaptability!
  Analytical convenience!
  (Information theorists & Signal processing people)

Deterministic

- Enough accuracy!
- Moderate complexity!
- High adaptability!
  (Radio system engineers)
Mappings Between Stochastic MIMO Channel Models

GBSM
A. Cluster distribution
B. Scatterer distribution

PSM
A. Path angle distribution
B. Subpath angle distribution

CBSM
A. Spatially averaged correlation properties
B. Instant correlation coefficient

- Only a few papers addressing the relationship between a PSM and a CBSM.
  - The comparison of spatial temporal correlation (STC) properties of both types of models was not based on the same set of parameters.

- **Doubt**: Is the difference of STC properties caused by the model’s structural difference or different parameter generation mechanisms?
3GPP SCM and KBSM

- **3GPP SCM: a practical implementation of a PSM**
  - The STC properties are implicit. Difficult to connect SCM simulation results with theoretical analyses.
  - The implementation complexity is high since it has to generate many parameters.

- **KBSM: a simplified CBSM**
  - Elegant and concise analytical expressions for MIMO channel spatial correlation matrices → easy to be integrated into a theoretical framework!
  - Less input parameters. Has the KBSM been oversimplified?

- **Open issues:**
  - What is the major physical phenomenon that makes the fundamental difference of two models?
  - Under what conditions will two models exhibit similar STC properties?
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II. The SCM and Its Spatial Correlation Characteristics

1. Choose scenario
   - Suburban macro
   - Urban macro
   - Urban micro

2. Determine user parameters
   - Angle spread: $\sigma_{AS}$
   - Lognormal shadowing: $\sigma_{LN}$
   - Delay spread: $\sigma_{DS}$
   - Pathloss
   - Orientation, Speed Vector: $\theta_{BS} \theta_{MS} \Omega_{MS} v$
   - Antenna gains
   - $\delta_{n,AoD}$ Angles of departure (paths)
   - $\Delta_{n,m,AoD}$ Angles of departure (subpaths)
   - $\tau_n$ Path delays
   - $P_n$ Average path powers
   - $\delta_{n,AoA}$ Angles of arrival (paths)
   - $\Delta_{n,m,AoA}$ Angles of arrival (subpaths)

3. Generate channel coefficients

Options
- Far scattering cluster (urban macro)
- Urban canyon (urban macro)
- Polarization
- LOS (urban micro)
General Descriptions of the SCM

- Emulates the **double-directional** and **clustering effects** of small-scale fading mechanisms
- **Wideband tapped delay line model:**
  - The received signal consists of $N$ ($N = 6$ for the SCM) time-delayed paths of the transmitted signal:
    $$ h_{u,s}(t, \tau) = \sum_{n=1}^{N} h_{u,s,n}(t) \delta(\tau - \tau_n). $$
  - Each path further consists of $M$ ($M = 20$ for the SCM) subpaths.
  - A path is **resolvable** and corresponds to a cluster of scatterers. Within a resolvable path (cluster), the subpaths are regarded as **unresolvable** rays.
Downlink Angle Parameters

\[ \theta_{n,m,\text{AoD}} = \theta_{BS} + \delta_{n,\text{AoD}} + \Delta_{n,m,\text{AoD}} = \theta_{n,\text{AoD}} + \Delta_{n,m,\text{AoD}} \]

\[ \theta_{n,m,\text{AoA}} = \theta_{MS} + \delta_{n,\text{AoA}} + \Delta_{n,m,\text{AoA}} = \theta_{n,\text{AoA}} + \Delta_{n,m,\text{AoA}} \]

- \( \theta_{BS} / \theta_{MS} \) : Angle between the BS-MS LOS and the BS/MS broadside
- \( \delta_{n,\text{AoD}} / \delta_{n,\text{ AoA}} \) : AoD/AoA of the \( n \)th path with respect to the LOS AoD/AoA
- \( \Delta_{n,m,\text{AoD}} / \Delta_{n,m,\text{AoA}} \) : Subpath AoD/AoA offset
- \( \theta_{n,\text{ AoD}} / \theta_{n,\text{ AoA}} \) : Mean AoD/AoA

Cluster \( n \)
Subpath \( m \)
Three Level Definitions

- **Cluster (tap) level**
  - **Fixed** BS and MS locations
  - **Fixed** cluster locations
  - **Random** scatterer distributions
    - Subpath AoD/AoA offset values are specified in a table for the SCM: **fixed** values.

\[
\begin{align*}
\theta_{n,m,\text{AoD}} &= \theta_{BS} + \delta_{n,\text{AoD}} + \Delta_{n,m,\text{AoD}} \\
\theta_{n,m,\text{AoA}} &= \theta_{MS} + \delta_{n,\text{AoA}} + \Delta_{n,m,\text{AoA}}
\end{align*}
\]

- **Link level: averaging cluster level properties**
  - **Fixed** BS and MS locations
  - **Random** cluster distributions
  - **Random** scatterer distributions

\[
\begin{align*}
\theta_{n,m,\text{AoD}} &= \theta_{BS} + \delta_{n,\text{AoD}} + \Delta_{n,m,\text{AoD}} \\
\theta_{n,m,\text{AoA}} &= \theta_{MS} + \delta_{n,\text{AoA}} + \Delta_{n,m,\text{AoA}}
\end{align*}
\]

- **System level: averaging link level properties**
  - **Random** BS and MS locations
  - **Random** cluster distributions
  - **Random** scatterer distributions

\[
\begin{align*}
\theta_{n,m,\text{AoD}} &= \theta_{BS} + \delta_{n,\text{AoD}} + \Delta_{n,m,\text{AoD}} \\
\theta_{n,m,\text{AoA}} &= \theta_{MS} + \delta_{n,\text{AoA}} + \Delta_{n,m,\text{AoA}}
\end{align*}
\]
Channel Coefficient

For the $s$th ($s=1,2,\ldots,S$) BS antenna element and the $u$th ($u=1,2,\ldots,U$) MS antenna element of the $n$th path (cluster), it is given by

\[
h_{u,s,n}(t) = \sqrt{\frac{P_n}{M}} \sum_{m=1}^{M} \left( \exp[jkd_s \sin(\theta_{n,m,\text{AoD}})] \exp[jkd_u \sin(\theta_{n,m,\text{AoA}})] \right) \exp[jk\|v\|\cos(\theta_{n,m,\text{AoA}} - \theta_v)t] \exp(j\Phi_{n,m})
\]

- $P_n$ : Power of the $n$th path
- $M$ : Number of subpaths per path
- $k$ : Wave number
- $\theta_{n,m,\text{AoD}}$ : Subpath AoD
- $\theta_{n,m,\text{AoA}}$ : Subpath AoA
- $d_s$ : Relative BS antenna distance (meter)
- $d_u$ : Relative MS antenna distance (meter)
- $\Phi_{n,m}$ : Subpath random path
- $\|v\|$ : MS speed
- $\theta_v$ : MS direction
(Normalized) Spatial Cross-Correlation Functions (CCFs)

- **Between two arbitrary channel coefficients (at all 3 levels):**

\[
\rho_{\Delta d_s, \Delta d_u}^{\Delta d_s, \Delta d_u} = E \left\{ \frac{h_{u_1, s_1, n}(t) h^*_{u_2, s_2, n}(t)}{\sigma_{h_{u_1, s_1, n}} \sigma_{h_{u_2, s_2, n}}} \right\} \\
= E \left\{ \frac{1}{M} \sum_{m=1}^{M} \exp[jk\Delta d_s \sin(\theta_{n,m,AoD})] \exp[jk\Delta d_u \sin(\theta_{n,m,AoA})] \right\}
\]

- **At the BS (\(\Delta d_u = 0\)):**

\[
\rho_{s_1 s_2}^{BS}(\Delta d_s) = E \left\{ \frac{1}{M} \sum_{m=1}^{M} \exp[jk\Delta d_s \sin(\theta_{n,m,AoD})] \right\}
\]

- **At the MS (\(\Delta d_s = 0\)):**

\[
\rho_{u_1 u_2}^{MS}(\Delta d_u) = E \left\{ \frac{1}{M} \sum_{m=1}^{M} \exp[jk\Delta d_u \sin(\theta_{n,m,AoA})] \right\}
\]

- **The spatial CCF of the 3GPP SCM is in general not separable.**
Spatial CCFs When $M \to \infty$

- **Between any two channel coefficients**

\[
\lim_{M \to \infty} \rho_{s_1 u_1}^{s_2 u_2} (\Delta d_s, \Delta d_u) = \int_0^{2\pi} \int_0^{2\pi} \exp[jk\Delta d_s \sin(\phi_{n,AoD})] \exp[jk\Delta d_u \sin(\phi_{n,AoA})] \\
\times p_{us}(\phi_{n,AoD}, \phi_{n,AoA}) d\phi_{n,AoD} d\phi_{n,AoA}
\]

$p_{us}(\phi_{n,AoD}, \phi_{n,AoA})$: Joint PDF of $\phi_{n,AoD}$ and $\phi_{n,AoA}$

- **At the BS / MS**

\[
\lim_{M \to \infty} \rho_{s_1 s_2}^{BS} (\Delta d_s) = \int_0^{2\pi} \exp[jk\Delta d_s \sin(\phi_{n,AoD})] p_s(\phi_{n,AoD}) d\phi_{n,AoD}
\]

\[
\lim_{M \to \infty} \rho_{u_1 u_2}^{MS} (\Delta d_u) = \int_0^{2\pi} \exp[jk\Delta d_u \sin(\phi_{n,AoA})] p_u(\phi_{n,AoA}) d\phi_{n,AoA}
\]

$p_s(\phi_{n,AoD})$: PDF of $\phi_{n,AoD}$  
$p_u(\phi_{n,AoA})$: PDF of $\phi_{n,AoA}$

- **Still, the spatial separability is in general not a property of the SCM.**
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III. The KBSM and Its Spatial Correlation Characteristics

- **Basic assumptions**
  - The channel coefficients of a narrowband MIMO channel are complex Gaussian distributed with identical average powers.
  - The scattering environment around each end is independent of each other → inherent spatial separability.

- **Channel correlation matrix:**\[ \hat{R}_{MIMO} = \hat{R}_{BS} \otimes \hat{R}_{MS} \]
  \[ \hat{R}_{MS}: \text{MS array correlation matrix} \]
  \[ \hat{R}_{BS}: \text{BS array correlation matrix} \]
  \[ \otimes: \text{Kronecker product} \]
Spatial CCFs

- **At the BS:**
  \[ \hat{\rho}_{s_1s_2}^{BS}(\Delta d_s) = \frac{2\pi}{0} \exp\left[jk\Delta d_s \sin(\hat{\theta}_{AoD})\right] \hat{p}_s(\hat{\theta}_{AoD}) \, d\hat{\theta}_{AoD} \]
  \[ \hat{p}_s(\hat{\theta}_{AoD}) : \text{PAS of the AoD; normalized to be the PDF of } \hat{\theta}_{AoD} \]

- **At the MS:**
  \[ \hat{\rho}_{u_1u_2}^{MS}(\Delta d_u) = \frac{2\pi}{0} \exp\left[jk\Delta d_u \sin(\hat{\theta}_{AoA})\right] \hat{p}_u(\hat{\theta}_{AoA}) \, d\hat{\theta}_{AoA} \]
  \[ \hat{p}_u(\hat{\theta}_{AoA}) : \text{PAS of the AoA; normalized to be the PDF of } \hat{\theta}_{AoA} \]

- **Between two arbitrary channel coefficients:**
  \[ \hat{\rho}_{s_1u_1}^{s_2u_2}(\Delta d_s, \Delta d_u) = \hat{\rho}_{s_1s_2}^{BS}(\Delta d_s) \hat{\rho}_{u_1u_2}^{MS}(\Delta d_u) \]

- **The spatial separability is an inherent property of the KBSM.**
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- **Fundamental differences between the SCM & KBSM:**

<table>
<thead>
<tr>
<th></th>
<th>Num. of subpaths</th>
<th>AoA-AoD correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCM</td>
<td>Finite (20)</td>
<td>Correlated</td>
</tr>
<tr>
<td>KBSM</td>
<td>Infinite (Gaussian process)</td>
<td>Independent</td>
</tr>
</tbody>
</table>

- **Equivalent conditions:**
  1. The number $M$ of subpaths in each path for the SCM tends to infinity.
  2. Two links share the same antenna element at one end, i.e., at either the MS or the BS.
  3. The same set of angle parameters including the same PAS are used.

- Equivalent conditions will be used for the **calibration of two models.**
PAS Fitting

- For the SCM, **fixed values** are chosen for the subpath AoA and AoD offsets.

- For the KBSM, the subpath **Power Azimuth Spectrum (PAS)** function can have different candidates: Uniform, Gaussian, Laplacian.

- **First task**: find a PAS function for the KBSM in order to fit well its spatial CCFs to those of the SCM.

- **Equivalent conditions are applied for the model calibration.**
  - Interpolate the SCM subpath AoA/AoD offsets 100 times to approximate the assumption of the infinite $M \rightarrow \text{interpolated SCM}$
  - Spatial CCF at the BS or MS
PAS Fitting Results

Mean AoA/AoD = 60°
PAS Fitting Observations

- In all the cases, the KBSM with the Gaussian PAS fits best to the (interpolated) SCM.

  ! ! The Gaussian PAS is not the 3GPP SCM choice for link level calibrations.

- The spatial correlation functions obtained from the SCM have unstable fluctuations around the ideal values approximated by the interpolated SCM.
  - Caused by the insufficient number of $M$ → “implementation loss”
  - “Implementation loss” becomes significant when the AS is $35^\circ$.

- The original SCM has relatively poor performance compared with the ideal MIMO channel model in terms of the spatial CCF.

- Suggestion: increase the number $M$ of subpaths in the SCM to improve its simulation accuracy.

- In the following, using the same parameter generating procedure as in the 3GPP, we will compare the spatial CCFs of the SCM and KBSM with the subpath Gaussian PAS at the 3 levels.
Spatial CCFs at the Cluster Level

- The fundamental difference exists between two models at the cluster level since the spatial separability is not fulfilled for the SCM.
Spatial CCFs at the Link Level

- Good agreements are found! → The SCM has the same property of the spatial separability as the KBSM at the link level.
Spatial CCFs at the System Level

- The SCM has the same property of the spatial separability as the KBSM at the system level.
Spatial Temporal Correlation Functions of the SCM and KBSM

- Spatial temporal correlation function of the SCM:
  \[ \rho_{s_1u_1}^{s_2u_2}(\Delta d_s, \Delta d_u, \tau) = E\left\{ \frac{1}{M} \sum_{m=1}^{M} \left( \exp[jk\Delta d_s \sin(\theta_{n,m,AoD})] \exp[jk\Delta d_u \sin(\theta_{n,m,AoA})] \right) \right\} \]

  \[ \times \exp[jk\|v\|\cos(\theta_{n,m,AoA} - \theta_v)\tau] \]

- Temporal autocorrelation function of the SCM:
  \[ r_{su}(\tau) = E\left\{ \frac{1}{M} \sum_{m=1}^{M} \exp[jk\|v\|\cos(\theta_{n,m,AoA} - \theta_v)\tau] \right\} \]

- The spatial-temporal separability is in general not a property of the SCM.

- Temporal autocorrelation function of the KBSM:
  \[ \hat{r}_{su}(\tau) = J_0(2\pi\|v\|\tau / \lambda) \]

- The spatial-temporal separability is an inherent property of the KBSM.
Temporal Autocorrelation Functions at 3 Levels

- **KBSM**: remains static at all the 3 levels
  \[\Rightarrow\] Spatial temporal separability at any levels!

- **SCM**:
  - Cluster and link levels: shows wide variations across different runs.
  - System level: same as the KBSM
  \[\Rightarrow\] Spatial temporal separability only at the system level.

\[\Rightarrow\] The KBSM only models the **average** spatial temporal behavior of MIMO channels. Not sufficient for system level simulations!
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Conclusions

- The spatial properties of the SCM & KBSM are investigated at three levels: the cluster level, link level and system level.
- At all the three levels, the KBSM has both the spatial separability and spatial temporal separability.
- The SCM has the spatial temporal separability only at the system level, and has the spatial separability only at the link and system levels.
- The KBSM with the Gaussian PAS is found to best fit the SCM in terms of spatial correlation properties.
- The KBSM has the advantages of simplicity and analytical tractability, but is restricted to model only the averaging effects of spatial correlation properties of MIMO channels.
- The SCM is more complex but provides more insights of the variations of different MIMO channel realizations.
Related Publications


Thank you for your attention!