Realistic Cooperative MIMO Channel Models for (B)4G
--Modelling Multilink Spatial Correlation Properties

Prof. Cheng-Xiang Wang

Heriot-Watt University, Edinburgh, UK
School of Engineering & Physical Sciences
Electrical, Electronic and Computer Engineering

The Edinburgh Research Partnership in Engineering and Mathematics
Joint Research Institute of Signal and Image Processing

Phone: +44-131-4513329
Fax: +44-131-4514155
E-mail: cheng-xiang.wang@hw.ac.uk
URL: http://www.ece.eps.hw.ac.uk/~cxwang/
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I. Background and Motivation

II. A Unified Cooperative MIMO Channel Model Framework

III. A New Cooperative MIMO GBSM

IV. Numerical Results and Analysis

V. Conclusions
I. Background and Motivation

- **Conventional MIMO**: point-to-point (P2P) MIMO, single-user MIMO, or collocated MIMO
  - Only employs antennas belonging to a local terminal
  - **Collocated** antennas at the BS + **Collocated** antennas at each user
  - Independent MIMO signal processing between the BS and each user.

- **Cooperative MIMO**: distributed MIMO, network MIMO, or virtual antenna array (VAA)
  - Utilises distributed antennas that belong to other terminals
  - **Collocated** (or **Distributed**) antennas at the BS + **Distributed** (or **Collocated**) antennas at multiple users
  - Joint MIMO signal processing among multiple BSs and/or multiple users
  - **Disadvantages**: increased system complexity, large signalling overhead
  - **Advantages**: increased capacity, cell edge throughput, and coverage
Three Types of Cooperative MIMO Schemes

- **Coordinated multipoint transmission (CoMP):** coordinate the transmission and reception of signal from/to one user in several geographically separated BSs
- **Fix relays:** low-cost and fixed radio infrastructures without wired backhaul connections
- **Mobile relays:** mobile stations as relays, not deployed as the infrastructure of a network
  - Moving networks & Mobile user relays

Images of CoMP, Fixed relay, and Mobile relay configurations.
Challenges for Cooperative MIMO Channel Modelling

- Standardised cooperative MIMO channel models are not yet available.
- Can be constructed from the existing (standardised) P2P MIMO channel models + additional features/models
- Additional features to be addressed (challenges):
  - Heterogeneity of multiple links
  - Correlation of multiple links
  - Mobile-to-mobile (M2M) channel models
- Realistic cooperative MIMO channel models: accuracy-complexity-flexibility tradeoff
Heterogeneity of Links in Cooperative MIMO

- Cooperative MIMO operates over heterogeneous links/channels.

CoMP
- BS-MS channels: fixed-to-mobile (F2M) channels

Fixed relay
- BS-RS (fixed to fixed-F2F) channels
- RS-RS (F2F) channels
- BS-MS (F2M) channels
- RS-MS (F2M) channels

Mobile relay
- BS-RS (F2M) channels
- RS-RS (M2M) channels
- BS-MS (F2M) channels
- RS-MS (M2M) channels

- The heterogeneity of multiple links can be characterised by
  - Multiple scenarios
  - Different line-of-sight (LoS) probability
  - Different dynamics of time evolution
Multi-link Spatial Correlations (1/2)

- Exist due to the environment similarity arising from common shadowing objects and scatterers contributing to different links.
  - **Large-scale parameters**, such as shadow fading (SF), delay spread (DS) and azimuth spread (AS), may be correlated.
  - **Intra-site correlation** ($c_1$&$c_2$) v.s. **Inter-site correlation** ($a_1$&$a_2$)

<table>
<thead>
<tr>
<th></th>
<th>SCM</th>
<th>WINNER-II</th>
<th>IEEE 802.16j</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intra-site SF correlation</strong></td>
<td>0</td>
<td>Distance-dependent</td>
<td>Distance-dependent</td>
</tr>
<tr>
<td><strong>Inter-site SF correlation</strong></td>
<td>0.5</td>
<td>0</td>
<td>Distance-and-angle dependent</td>
</tr>
<tr>
<td><strong>Correlation of other LSPs</strong></td>
<td>Fixed values</td>
<td>Distance-dependent</td>
<td>Not considered</td>
</tr>
</tbody>
</table>
Multi-link Spatial Correlations (2/2)

- **Small scale fading correlations** are not well studied yet in the literature!

- Existing work on multi-link small-scale fading correlations: **scenario-specific**
  - Ref. [29]: a multiuser MIMO channel model investigating the impact of surface roughness on multi-link spatial correlations (scatterers located in streets)
  - Ref. [27]: Preliminary investigation on the multi-link spatial correlations for CoMP transmissions
  - Ref. [30]: Investigation on multi-link spatial correlations in **AF relay** systems

- A **unified channel model framework** to investigate multi-link small-scale fading correlations for different scenarios is therefore highly desirable.

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- The degree of the link heterogeneity highly depends on local scattering environments.
- Model framework: needs to reflect the impact of local scattering environments on the link heterogeneity for different scenarios while keeping the acceptable model complexity.

<table>
<thead>
<tr>
<th>LoS Component</th>
<th>$A_p \rightarrow B_q : h_{pq}^{\text{LOS}}(t,\tau)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$i=1$, Single-bounced Components</td>
<td>$A_p \rightarrow S_B \rightarrow B_q : h_{pq}^{12}(t,\tau)$, $A_p \rightarrow S_C \rightarrow B_q : h_{pq}^{13}(t,\tau)$, $A_p \rightarrow S_D \rightarrow B_q : h_{pq}^{14}(t,\tau)$</td>
</tr>
<tr>
<td>$i=2$, Double-bounced Components</td>
<td>$A_p \rightarrow S_A \rightarrow S_B \rightarrow B_q : h_{pq}^{21}(t,\tau)$, $A_p \rightarrow S_A \rightarrow S_C \rightarrow B_q : h_{pq}^{23}(t,\tau)$, $A_p \rightarrow S_D \rightarrow S_B \rightarrow B_q : h_{pq}^{24}(t,\tau)$</td>
</tr>
<tr>
<td>$i=3$, Triple-bounced Components</td>
<td>$A_p \rightarrow S_A \rightarrow S_D \rightarrow S_B \rightarrow B_q : h_{pq}^{31}(t,\tau)$, $A_p \rightarrow S_A \rightarrow S_D \rightarrow S_C \rightarrow B_q : h_{pq}^{32}(t,\tau)$, $A_p \rightarrow S_D \rightarrow S_C \rightarrow S_B \rightarrow B_q : h_{pq}^{34}(t,\tau)$</td>
</tr>
<tr>
<td>$i=4$, Quadruple-bounced Components</td>
<td>$A_p \rightarrow S_A \rightarrow S_D \rightarrow S_C \rightarrow S_B \rightarrow B_q : h_{pq}^{41}(t,\tau)$</td>
</tr>
</tbody>
</table>
Channel Gain

- **Channel Gain:**
  
  \[ h_{pq}(t, \tau) = h_{pq}^{LoS}(t, \tau) + \sum_{i=1}^{I} \sum_{g=1}^{f_I(i)} h_{pq}^{ig}(t, \tau) \]

  \( I: \text{total no. of local scattering areas} \)

  \( f_I(i): \text{total number of i-bounced components}, \text{obtained based on the following practical criterion:} \)

  The \( i \)-bounced waves are always bounced by \( i \) scatterers located in different local scattering areas from far to near relative to the receiver.

- **LoS component:**

  \[ h_{pq}^{LoS}(t, \tau) = \sqrt{\frac{K_{pq} N_{pq}}{K_{pq} + 1}} e^{-j2\pi\lambda^{-1} x_{pq}} e^{j[2\pi f_{max}^A t \cos(\alpha_{pq}^{LoS} - \gamma_A) + 2\pi f_{max}^B t \cos(\phi_{pq}^{LoS} - \gamma_B)]} \delta(\tau - \tau_{LoS}) \]

- **Scattered component:**

  \[ h_{pq}^{ig}(t, \tau) = \sqrt{\frac{N_{pq}^g}{K_{pq} + 1}} \lim_{\{N_k^g\}_{k=1} \rightarrow \infty} \sum_{\{n_k^g\}_{k=1} = 1}^{\{N_k^g\}_{k=1} = 1} \frac{1}{\sqrt{\prod_{k=1}^{i} N_k^g}} e^{j\left(\psi_{n_k^g}_{k=1}^{i} - 2\pi \lambda^{-1} x_{pq}, \{n_k^g\}_{k=1}^{i}\right)} \]

  \times e^{j\left[2\pi f_{max}^A t \cos(\alpha_{pq}, \{n_k^g\}_{k=1}^{i} - \gamma_A) + 2\pi f_{max}^B t \cos(\phi_{pq}, \{n_k^g\}_{k=1}^{i} - \gamma_B)\right]} \delta(\tau - \tau_{\{n_k^g\}_{k=1}^{i}}) \]
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- **Scenario:** a wideband cooperative relay communication environment including three different links: BS-RS, RS-MS, and BS-MS.

**Definition of parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>$D_1, D_2, D_3$</td>
<td>distances of BS-MS, RS-MS, and BS-RS, respectively</td>
</tr>
<tr>
<td>$R_{1n_1}, R_{1n_2}, R_{1n_3}$</td>
<td>min and max radii of the circular rings around the MS, RS and BS, respectively</td>
</tr>
<tr>
<td>$R_{2n_2}, R_{2n_3}$</td>
<td>orientations of the BS-RS link and BS-MS link, respectively</td>
</tr>
<tr>
<td>$\delta_1, \delta_2, \delta_3$</td>
<td>antenna element spacings of MS, RS and BS, respectively</td>
</tr>
<tr>
<td>$\beta_1, \beta_2, \beta_3$</td>
<td>orientations of the MS, RS and RS antenna arrays in the x-y plane (relative to the x-axis), respectively</td>
</tr>
<tr>
<td>$\alpha_{1n_1}, \alpha_{2n_1}, \alpha_{3n_1}$</td>
<td>azimuth angles of $S_{n_1}$-MS, $S_{n_1}$-RS, and $S_{n_1}$-BS links in the x-y plane (relative to the x-axis), respectively</td>
</tr>
<tr>
<td>$\xi_{R_1}, \xi_{R_2}, \xi_{R_3}$</td>
<td>distances $d(BS, S_{n_1}), d(BS, S_{n_2}),$ and $d(BS, S_{n_3})$, respectively</td>
</tr>
<tr>
<td>$\xi_{S_{n_1}}, \xi_{S_{n_2}}, \xi_{S_{n_3}}$</td>
<td>distances $d(RS, S_{n_1}), d(RS, S_{n_2}),$ and $d(RS, S_{n_3})$, respectively</td>
</tr>
<tr>
<td>$\epsilon_{M_{n_1}}, \epsilon_{M_{n_2}}, \epsilon_{M_{n_3}}$</td>
<td>distances $d(MS, S_{n_1}), d(MS, S_{n_2}),$ and $d(MS, S_{n_3})$, respectively</td>
</tr>
<tr>
<td>$\epsilon_{n_{1n_2}}, \epsilon_{n_{1n_3}}, \epsilon_{n_{2n_3}}$</td>
<td>distances $d(p_1, S_{n_2}), d(p_1, p_3),$ and $d(S_{n_2}, S_{n_3})$, respectively</td>
</tr>
</tbody>
</table>
Channel Gains of Three Different Links

\[ h_{p_3p_2} = h_{p_3p_2}^{LoS} + \sum_{i=1}^{3} \sum_{g=1}^{f_3(i)} h_{p_3p_2}^{i,g} \]

\[ h_{p_3p_1} = h_{p_3p_1}^{LoS} + \sum_{i=1}^{3} \sum_{g=1}^{f_3(i)} h_{p_3p_1}^{i,g} \]

\[ h_{p_2p_1} = h_{p_2p_1}^{LoS} + \sum_{i=1}^{3} \sum_{g=1}^{f_3(i)} h_{p_2p_1}^{i,g} \]

**BS-RS link**

\[ h_{p_2p_1}^{LoS} = \sqrt{\frac{K_{p_2p_1} \Omega_{p_2p_1}}{K_{p_2p_1} + 1}} e^{-j2\pi\lambda^{-1}x_{p_2p_1}} \]

\[ h_{p_2p_1}^{1g} = \sqrt{\frac{\eta_{p_2p_1} \Omega_{p_2p_1}}{K_{p_2p_1} + 1}} \lim_{N_g \to \infty} \sum_{n_g=1}^{N_g} \frac{1}{\sqrt{N_g}} e^{j(\psi_{n_g} - 2\pi\lambda^{-1}x_{p_2p_1},n_g)} \]

\[ h_{p_2p_1}^{2g} = \sqrt{\frac{\eta_{p_2p_1} \Omega_{p_2p_1}}{K_{p_2p_1} + 1}} \lim_{N_{g_1},N_{g_2} \to \infty} \sum_{n_{g_1},n_{g_2}=1}^{N_{g_1},N_{g_2}} \frac{1}{\sqrt{N_{g_1}N_{g_2}}} e^{j(\psi_{n_{g_1},n_{g_2}} - 2\pi\lambda^{-1}x_{p_2p_1},n_{g_1},n_{g_2})} \]

\[ h_{p_2p_1}^{31} = \sqrt{\frac{\eta_{p_2p_1} \Omega_{p_2p_1}}{K_{p_2p_1} + 1}} \lim_{N_1,N_2,N_3 \to \infty} \sum_{n_1,n_2,n_3=1}^{N_1,N_2,N_3} \frac{1}{\sqrt{N_1N_2N_3}} e^{j(\psi_{n_1,n_2,n_3} - 2\pi\lambda^{-1}x_{p_2p_1},n_1,n_2,n_3)} \]
Adjustment of Key Model Parameters

- The proposed cooperative MIMO GBSM is adaptable to 12 cooperative scenarios by adjusting key model parameters.

- The proposed GBSM has three key model parameters.

- Basic criterion of setting the key model parameters: the longer distance of the link and/or the higher the local scattering density, the smaller the Ricean factors and the larger the energy-related parameters of multi-bounced components, i.e., the multi-bounced components bear more energy than single-bounced components.
Multi-Link Spatial Correlation Functions

- The normalized spatial correlation function:

\[ \rho_{pq,p'q'} = \frac{\mathbf{E}[h_{pq}h^*_{p'q'}]}{\sqrt{\Omega_{pq}\Omega_{p'q'}}} \]

- Correlation function between BS-RS link and BS-MS link:

\[ \rho_{p_3p_2,p'_3p_1} = \rho_{p_3p_2,p'_3p_1}^{LoS} + \sum_{g=1}^{3} (\rho_{p_3p_2,p'_3p_1}^{1g} + \rho_{p_3p_2,p'_3p_1}^{2g}) + \rho_{p_3p_2,p'_3p_1}^{31} \]

- Correlation function between BS-RS link and RS-MS link:

\[ \rho_{p_3p_2,p'_2p_1} = \rho_{p_3p_2,p'_2p_1}^{LoS} + \sum_{g=1}^{3} (\rho_{p_3p_2,p'_2p_1}^{1g} + \rho_{p_3p_2,p'_2p_1}^{2g}) + \rho_{p_3p_2,p'_2p_1}^{31} \]

- Correlation function between BS-MS link and RS-MS link:

\[ \rho_{p_3p_1,p_2p_1'} = \rho_{p_3p_1,p_2p_1'}^{LoS} + \sum_{g=1}^{3} (\rho_{p_3p_1,p_2p_1'}^{1g} + \rho_{p_3p_1,p_2p_1'}^{2g}) + \rho_{p_3p_1,p_2p_1'}^{31} \]
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Parameters

- Carrier frequency: $f = 2.4$ GHz
- Multi-element antenna tilt angles: $\beta_1 = \beta_2 = \pi/3$
- Antenna element spacings: $\delta_3 = \delta_2 = \delta_1 = 0$
- Link distance: $D_1 = D_2 = 100$ m
- Radii of rings: $R_{1n1} = R_{1n2} = R_{1n3} = 5$ m, $R_{2n1} = R_{2n2} = R_{2n3} = 50$ m
- Ricean factors: $K_{p3p2} = K_{p'3p2} = 0$
- Environment parameters: $k_1 = k_2 = k_3 = 10$, $\mu_1 = 120^\circ$, $\mu_2 = 300^\circ$, $\mu_3 = 60^\circ$
Spatial Correlation Properties of Different Components

- High multi-link spatial correlations can occur at some cases.
Spatial Correlation Properties of Scattered Components

- Spatial correlation properties vary significantly for different scattered components.
- Scattered components that include more bounced rays exhibit lower spatial correlation properties.

\[ \delta_3 = \delta_2 = \delta_1 = 3\lambda \]

\[ k_1 = k_2 = k_3 = 3 \]
The increase of the environment parameter $k_g$ will enhance the spatial correlation.

Impact of Environment Parameters on Spatial Correlation Properties (I)
Local scattering area with smaller size leads to higher spatial correlation.
Impact of Antenna Parameters on Spatial Correlation Properties

- The increase of antenna spacing $\delta_g$ will decrease spatial correlations.
- The impact of parameters $\delta_g$ and $\beta_g$ on spatial correlation properties tends to be marginal for the scattered components with more bounced rays.
Parameters of the Proposed Model for Outdoor Scenario

Outdoor Macro-cell MS Cooperation Scenario:

- Common parameters: \( \eta_{p_3p_2}^{13} = \eta_{p_3p_1}^{13} = \eta_{p_3p_2}^{21} = \eta_{p_3p_1}^{21} = \eta_{p_3p_2}^{22} = \eta_{p_3p_1}^{22} = \eta_{p_3p_2}^{31} = \eta_{p_3p_1}^{31} = 0 \)

\[ D_1 = D_3 = 1500m \quad K_{p_3p_2} = K_{p_3p_1} = 0 \]

- Low local scattering density (LSD):
  - Energy-related parameters: \( \eta_{p_3p_2}^{11} = \eta_{p_3p_1}^{11} = \eta_{p_3p_2}^{12} = \eta_{p_3p_1}^{12} = 0.2 \quad \eta_{p_3p_2}^{23} = \eta_{p_3p_1}^{23} = 0.6 \)
  - Environment parameters: \( k_1 = k_2 = 10, \quad R_{1n_1} = R_{1n_2} = 5m \quad R_{2n_1} = R_{2n_2} = 20m \)

- High LSD:
  - Energy-related parameters: \( \eta_{p_3p_2}^{11} = \eta_{p_3p_1}^{11} = \eta_{p_3p_2}^{12} = \eta_{p_3p_1}^{12} = 0.05 \quad \eta_{p_3p_2}^{23} = \eta_{p_3p_1}^{23} = 0.9 \)
  - Environment parameters: \( k_1 = k_2 = 1, \quad R_{1n_1} = R_{1n_2} = 5m \quad R_{2n_1} = R_{2n_2} = 200m \)

- Mixed LSD:
  - Energy-related parameters: \( \eta_{p_3p_1}^{11} = \eta_{p_3p_1}^{12} = 0.2, \quad \eta_{p_3p_1}^{23} = 0.6, \quad \eta_{p_3p_2}^{11} = \eta_{p_3p_2}^{12} = 0.1 \quad \eta_{p_3p_2}^{23} = 0.8 \)
  - Environment parameters: \( k_1 = 10 \quad k_2 = 2, \quad \mu_1 = 60^\circ, \quad \mu_2 = 120^\circ, \quad R_{1n_1} = R_{1n_2} = 5m \quad R_{2n_1} = 20m \quad R_{2n_2} = 100m \)
Parameters of the Proposed Model for Indoor Scenario

Indoor MS Cooperation Scenario:

- **Low LSD:**
  - Energy-related parameters: \(\eta_{p_3p_2}^{11} = \eta_{p_3p_1}^{11} = \eta_{p_3p_2}^{12} = \eta_{p_3p_1}^{12} = \eta_{p_3p_2}^{13} = \eta_{p_3p_1}^{13} = 0.3\)
  - Environment parameters: \(k_1 = k_2 = k_3 = 10,\ R_{1n_1} = R_{1n_2} = R_{1n_3} = 2m\)

- **High LSD:**
  - Environment parameters: \(R_{2n_1} = R_{2n_2} = R_{2n_3} = 8m\)
  - Energy-related parameters: \(\eta_{p_3p_2}^{11} = \eta_{p_3p_1}^{11} = \eta_{p_3p_2}^{12} = \eta_{p_3p_1}^{12} = \eta_{p_3p_2}^{13} = \eta_{p_3p_1}^{13} = 0.05\)

- **Mixed LSD:**
  - Environment parameters: \(k_1 = k_2 = k_3 = 1,\ R_{1n_1} = R_{1n_2} = R_{1n_3} = 2m\)
  - Energy-related parameters: \(\eta_{p_3p_2}^{11} = \eta_{p_3p_1}^{12} = \eta_{p_3p_2}^{13} = 0.25,\ \eta_{p_3p_2}^{11} = \eta_{p_3p_1}^{12} = \eta_{p_3p_2}^{13} = 0.05,\ \eta_{p_3p_2}^{31} = 0.15\)

\(K_{p_3p_2} = K_{p_3p_1} = 0.5,\ K_{p'_3p_1} = 2.5,\ \eta_{p_3p_2}^{23} = 0.3,\ \eta_{p_3p_1}^{23} = 0.05,\ \eta_{p_3p_2}^{21} = \eta_{p_3p_1}^{22} = 0.1\)

- Environment parameters:
  - \(k_1 = 6, k_2 = 2, k_3 = 15,\ \mu_1 = 60^\circ,\ \mu_2 = 120^\circ,\ \mu_3 = 240^\circ\)
  - \(R_{1n_1} = R_{1n_2} = R_{1n_3} = 2m,\ R_{2n_1} = 12m,\ R_{2n_2} = 20m,\ R_{2n_3} = 5m\)
Spatial Correlation Properties of the Proposed Model

- The higher the LSD, the lower the spatial correlation properties.
- A high multi-link spatial correlation normally appears in a scenario with lower LSDs and LoS components.

![Graph showing spatial correlation properties for Indoor and Outdoor scenarios](image-url)
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- Developed a novel unified cooperative MIMO channel model framework.

- Proposed a new GBSM for cooperative wideband MIMO Ricean fading channels.
  - Sufficiently general and suitable for a wide variety of scenarios, e.g., 12 cooperative scenarios.
  - The first cooperative GBSM that has the ability to consider the impact of the LSD on spatial correlation properties.

- Derived the multi-link spatial correlation functions based on the proposed GBSM.

- Analyzed the multi-link spatial correlations in terms of important parameters, e.g., environment parameters, energy-related parameters, antenna parameters, LSD, etc.
  - LSD has great impacts on multi-link spatial correlation properties.
  - A high multi-link spatial correlation may exist if the underlying propagation environments have low LSDs and LoS component.
Acknowledgement

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- **Coauthors: in particular Dr Xiang CHENG & Dr Xuemin Hong**


Thank you for your attention!