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

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# Outline

I. Background and Motivation

II. A Unified Cooperative MIMO Channel Model Framework

III. A New Cooperative MIMO GBSM

IV. Numerical Results and Analysis

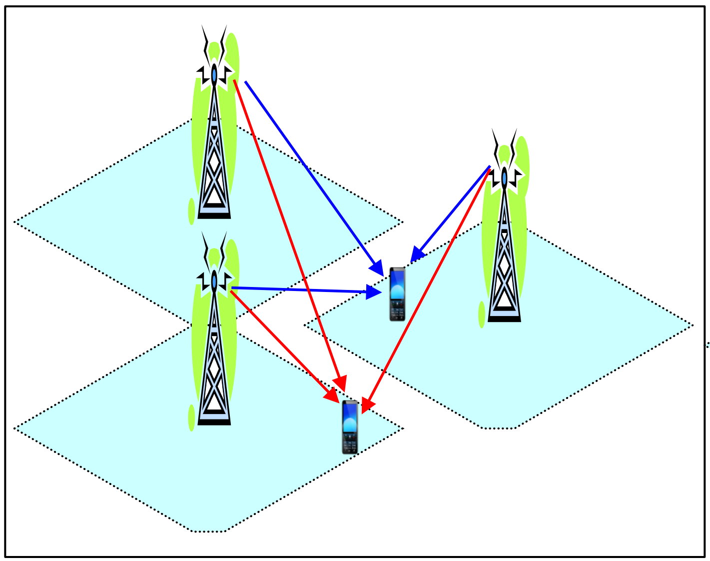
V. Conclusions

# I. Background and Motivation

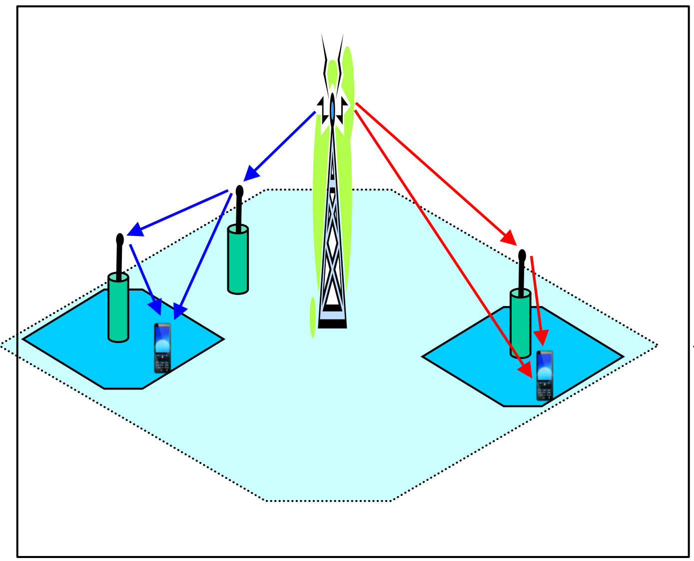
- **Conventional MIMO**: point-to-point (P2P) MIMO, single-user MIMO, or collocated MIMO
  - Only employs antennas belonging to a local terminal
  - **Collocated** antennas at the BS+ **Collocated** antennas at each user
  - Independent MIMO signal processing between the BS and each user.
- **Cooperative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

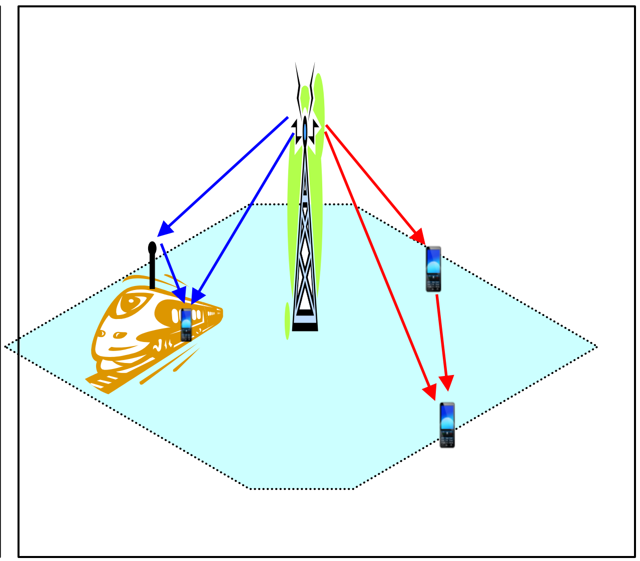
- **Coordinated multipoint transmission (CoMP)**: coordinate the transmission and reception of signal from/to one user in several geographically separated BSs
- **Fix relays**: low-cost and fixed radio infrastructures without wired backhaul connections
- **Mobile relays**: mobile stations as relays,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



CoMP



Fixed relay



Mobile relay

# 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

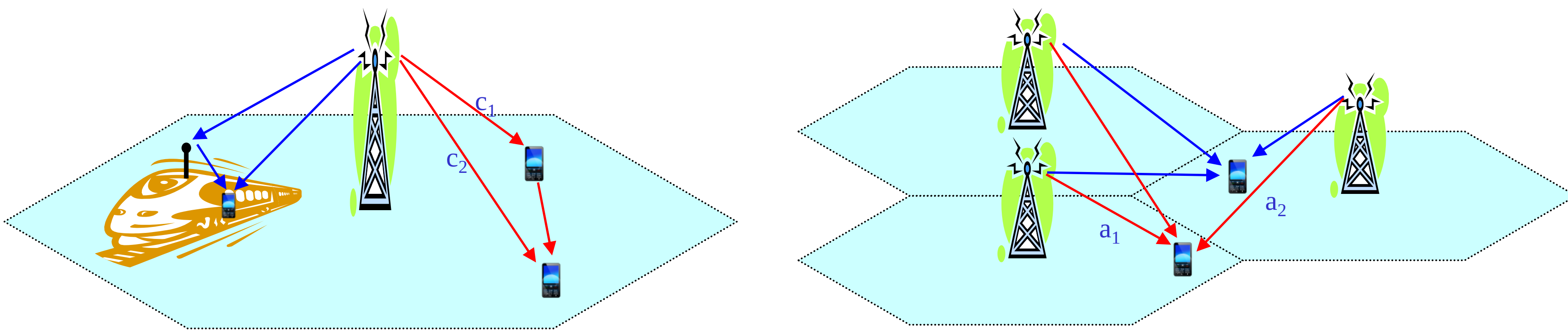
**Mobile relay**

- 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** (c1&c2) v.s. **Inter-site correlation** (a1&a2)




| | **SCM** | **WINNER-II** | **IEEE 802.16j** |
|---|---|---|---|
| **Intra-site SF correlation** | 0 | Distance-dependent | Distance-dependent |
| **Inter-site SF correlation** | 0.5 | 0 | Distance-and-angle dependent |
| **Correlation of other LSPs** | Fixed values | Distance-dependent | Not considered |

# Multi-link Spatial Correlations (2/2)

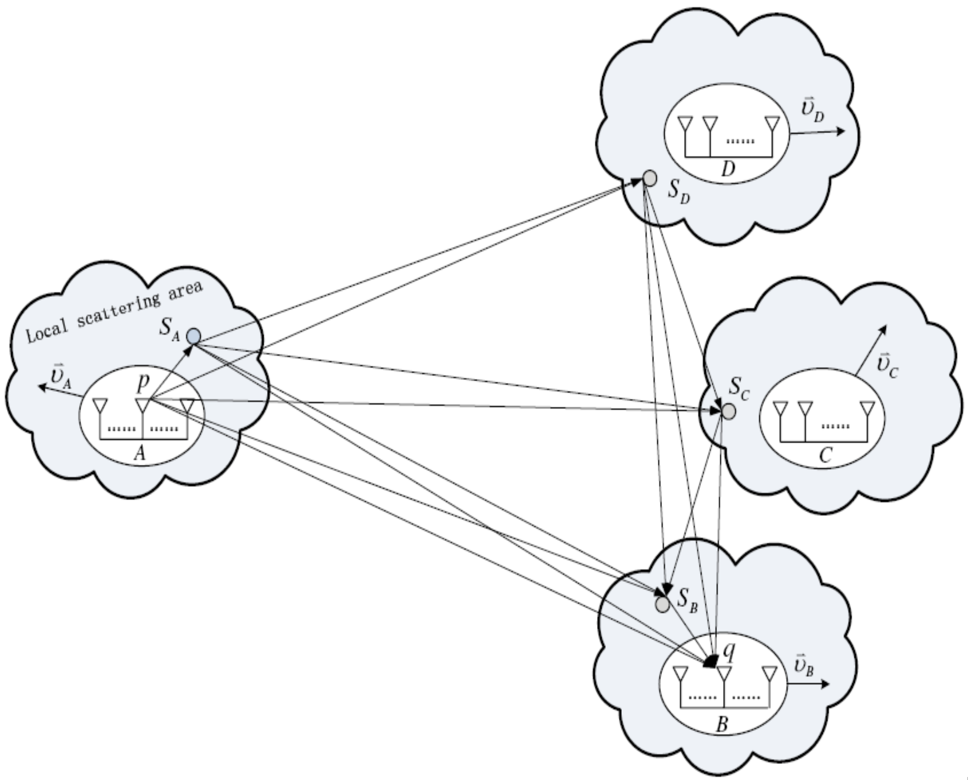
- **Small scale fading correlations** are not well studied yet in the literature!
- Existing work on multi-link small-scale fading correlations: **scenario-specific**
  - Ref. [29]: a multiuser MIMO channel model investigating the impact of surface roughness on multi-link spatial correlations (scatterers 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.

- X. Cheng, **C.-X. Wang**, H. Wang, X. Gao, X.-H. You, D. Yuan, B. Ai, Q. Huo, L. Song, and B. Jiao, "Cooperative MIMO channel modeling and multi-link spatial correlation properties," *IEEE Journal on Selected Areas in Communications(JSAC)*, vol. 30, no. 2, Feb. 2012.

# Outline

# II. A Unified Cooperative MIMO Channel Model Framework

- 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.




| | |
|---|---|
| LoS Component | $A_p \to B_q : h_{pq}^{LOS}(t,\tau)$ |
| $i$=1, Single-bounced Components | $A_p \to S_B \to B_q : h_{pq}^{11}(t,\tau)$ $A_p \to S_C \to B_q : h_{pq}^{12}(t,\tau)$<br>$A_p \to S_D \to B_q : h_{pq}^{13}(t,\tau)$ $A_p \to S_A \to B_q : h_{pq}^{14}(t,\tau)$ |
| $i$=2, Double-bounced Components | $A_p \to S_A \to S_B \to B_q : h_{pq}^{21}(t,\tau)$ $A_p \to S_A \to S_C \to B_q : h_{pq}^{22}(t,\tau)$<br>$A_p \to S_A \to S_D \to B_q : h_{pq}^{23}(t,\tau)$ $A_p \to S_D \to S_B \to B_q : h_{pq}^{24}(t,\tau)$<br>$A_p \to S_D \to S_C \to B_q : h_{pq}^{25}(t,\tau)$ $A_p \to S_C \to S_B \to B_q : h_{pq}^{26}(t,\tau)$ |
| $i$=3, Triple-bounced Components | $A_p \to S_A \to S_D \to S_B \to B_q : h_{pq}^{31}(t,\tau)$ $A_p \to S_A \to S_D \to S_C \to B_q : h_{pq}^{32}(t,\tau)$<br>$A_p \to S_A \to S_C \to S_B \to B_q : h_{pq}^{33}(t,\tau)$ $A_p \to S_D \to S_C \to S_B \to B_q : h_{pq}^{34}(t,\tau)$ |
| $i$=4, Quadruple-bounced Components | $A_p \to S_A \to S_D \to S_C \to S_B \to B_q : h_{pq}^{41}(t,\tau)$ |

# 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: total no. of local scattering areas

  - $f_I(i)$: total number of *i*-bounced components, 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:

Ricean factor

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

- Scattered component:

Energy-related parameter

$$h_{pq}^{ig}(t,\tau) = \sqrt{\frac{\eta_{pq}^{ig}\Omega_{pq}}{K_{pq}+1}} \lim_{\{N_k^g\}_{k=1}^{i}\to\infty} \sum_{\{n_k^g\}_{k=1}^{i}=1}^{\{N_k^g\}_{k=1}^{i}} \frac{1}{\sqrt{\prod_{k=1}^{i} N_k^g}} e^{j\left(\psi_{\{n_k^g\}_{k=1}^{i}} - 2\pi\lambda^{-1}\chi_{pq,\{n_k^g\}_{k=1}^{i}}\right)}$$

$$\times e^{j\left[2\pi f_{max}^{A} t \cos\left(\alpha_{pq,\{n_k^g\}_{k=1}^{i}}-\gamma_A\right)+2\pi f_{max}^{B} t \cos\left(\phi_{pq,\{n_k^g\}_{k=1}^{i}}-\gamma_B\right)\right]} \delta\left(\tau-\tau_{\{n_k^g\}_{k=1}^{i}}\right)$$

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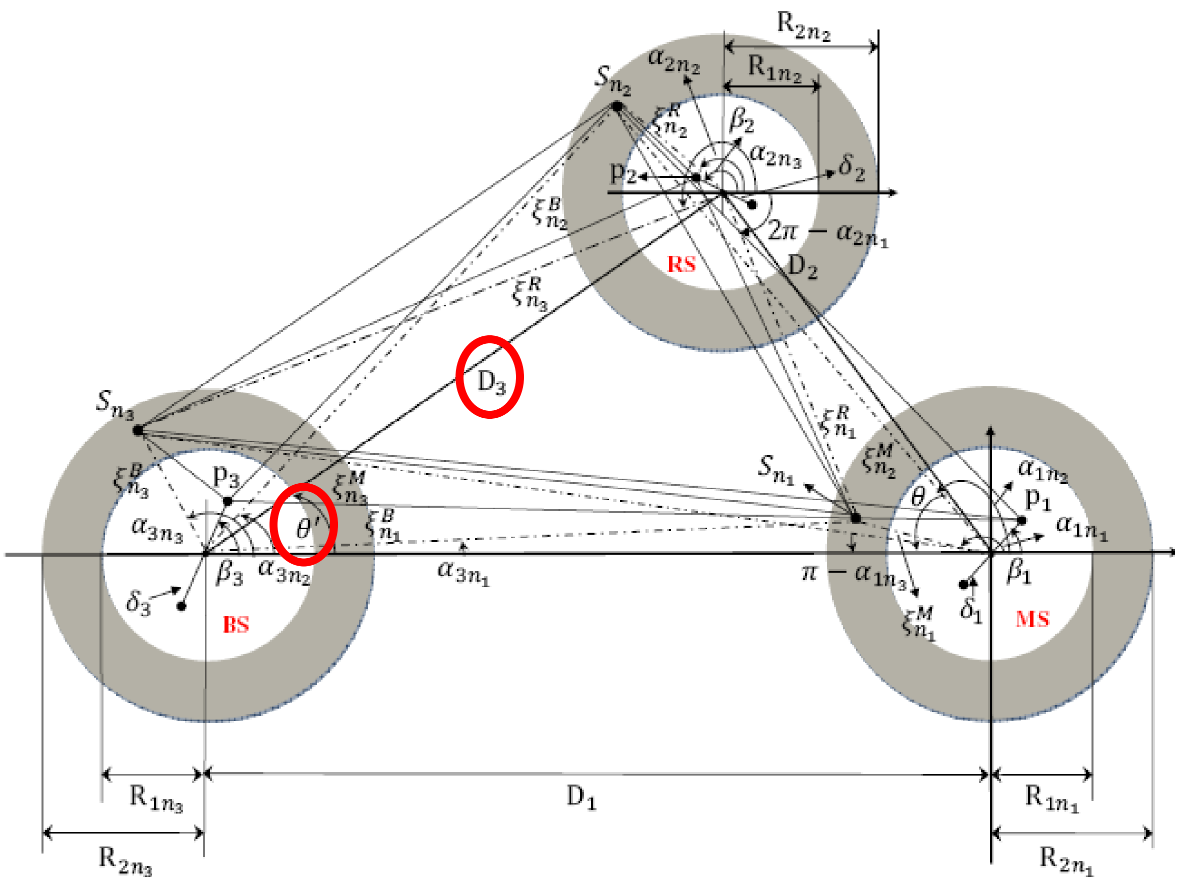
# III. A New Cooperative MIMO GBSM

- **Scenario:** a wideband cooperative relay communication environment including three different links: BS-RS, RS-MS, and BS-MS.




Definition of parameters

| | |
|---|---|
| $D_1, D_2, D_3$ | distances of BS-MS, RS-MS, and BS-RS, respectively |
| $R_{1n_1}, R_{2n_1}; R_{1n_2}, R_{2n_2}; R_{1n_3}, R_{2n_3}$ | min and max radii of the circular rings around the MS, RS and BS, respectively |
| $\theta, \theta'$ | angles between the RS-MS link and BS-MS link, and between the BS-RS link and BS-MS link, respectively |
| $\delta_1, \delta_2, \delta_3$ | antenna element spacings of MS, RS and BS, respectively |
| $\beta_1, \beta_2, \beta_3$ | orientations of the MS, RS and RS antenna arrays in the x-y plane (relative to the x-axis), respectively |
| $\alpha_{1n_i}, \alpha_{2n_i}$, and $\alpha_{3n_i}$ | azimuth angles of $S_{n_i}$-MS, $S_{n_i}$-RS, and $S_{n_i}$-BS links in the x-y plane (relative to the x-axis), respectively |
| $\xi^B_{n_1}, \xi^B_{n_2}, \xi^B_{n_3}$ | distances $d(\mathrm{BS}, S_{n_1})$, $d(\mathrm{BS}, S_{n_2})$, and $d(\mathrm{BS}, S_{n_3})$, respectively |
| $\xi^R_{n_1}, \xi^R_{n_2}, \xi^R_{n_3}$ | distances $d(\mathrm{RS}, S_{n_1})$, $d(\mathrm{RS}, S_{n_2})$, and $d(\mathrm{RS}, S_{n_3})$, respectively |
| $\xi^M_{n_1}, \xi^M_{n_2}, \xi^M_{n_3}$ | distances $d(\mathrm{MS}, S_{n_1})$, $d(\mathrm{MS}, S_{n_2})$, and $d(\mathrm{MS}, S_{n_3})$, respectively |
| $\varepsilon_{p_i n_g} (\varepsilon_{n_g p_i})$, $\varepsilon_{p_i p_j}$, and $\varepsilon_{n_g n_k}$ | distances $d(p_i, S_{n_g})$, $d(p_i, p_j)$, and $d(S_{n_g}, S_{n_k})$, respectively |

# Channel Gains of Three Different Links

BS-RS link

$$h_{p_3p_2} = h_{p_3p_2}^{LoS} + \sum_{i=1}^{3}\sum_{g=1}^{f_3(i)} h_{p_3p_2}^{ig}$$

BS-MS link

$$h_{p_3p_1} = h_{p_3p_1}^{LoS} + \sum_{i=1}^{3}\sum_{g=1}^{f_3(i)} h_{p_3p_1}^{ig}$$

RS-MS link

$$h_{p_2p_1} = h_{p_2p_1}^{LoS} + \sum_{i=1}^{3}\sum_{g=1}^{f_3(i)} h_{p_2p_1}^{ig}$$

$$h_{p_2p_1}^{LoS} = \sqrt{\frac{K_{p_2p_1}\Omega_{p_2p_1}}{K_{p_2p_1}+1}} e^{-j2\pi\lambda^{-1}\chi_{p_2p_1}}$$

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

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

$$h_{p_2p_1}^{31} = \sqrt{\frac{\eta_{p_2p_1}^{31}\Omega_{p_2p_1}}{K_{p_2p_1}+1}} \lim_{N_1,N_2,N_3\to\infty}\sum_{n_1,n_2,n_3=1}^{N_1,N_2,N_3}\frac{1}{\sqrt{N_1N_2N_3}} e^{j\left(\psi_{n_1,n_2,n_3}-2\pi\lambda^{-1}\chi_{p_2p_1,n_1,n_2,n_3}\right)}$$

# 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.

| The Proposed Cooperative MIMO GBSM | | | |
|---|---|---|---|
| Links | Three different links: BS-RS, RS-MS, and BS-MS links. (can be easily extended to include more links) | | |
| Scenarios | 12 cooperative scenarios | | |
| | Physical scenarios | | Application scenarios |
| | Outdoor Macro-cell<br>Outdoor Micro-cell<br>Outdoor Pico-cell<br>Indoor scenarios | | BS cooperation<br>MS cooperation<br>Relay cooperation |
| Key Parameters | $I$ | $k_{p_3p_2}$<br>$k_{p_3p_1}$<br>$k_{p_2p_1}$ | $\eta^{1g}_{p_3p_2/p_3p_1/p_2p_1}$<br>$\eta^{2g}_{p_3p_2/p_3p_1/p_2p_1}$<br>$\eta^{31}_{p_3p_2/p_3p_1/p_2p_1}$<br>$(g=1,2,3)$ |
| | The number of local scattering areas. | Ricean factor of the BS-RS link, BS-MS link, and RS-MS link, respectively. | Energy-related parameters that specify how much the single-, double-, and triple-bounced rays contribute to the total scattered power of the BS-RS/ BS-MS/ RS-MS link, respectively. |
| | By properly adjusting the key parameters, the proposed cooperative MIMO GBSM is suitable for 12 cooperation scenarios. | | |

# Multi-Link Spatial Correlation Functions

- The normalized spatial correlation function:

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

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

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

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

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

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

$$\rho_{p_3p_1,p_2p'_1} = \rho^{LoS}_{p_3p_1,p_2p'_1} + \sum_{g=1}^{3}(\rho^{1g}_{p_3p_1,p_2p'_1} + \rho^{2g}_{p_3p_1,p_2p'_1}) + \rho^{31}_{p_3p_1,p_2p'_1}$$

# Outline

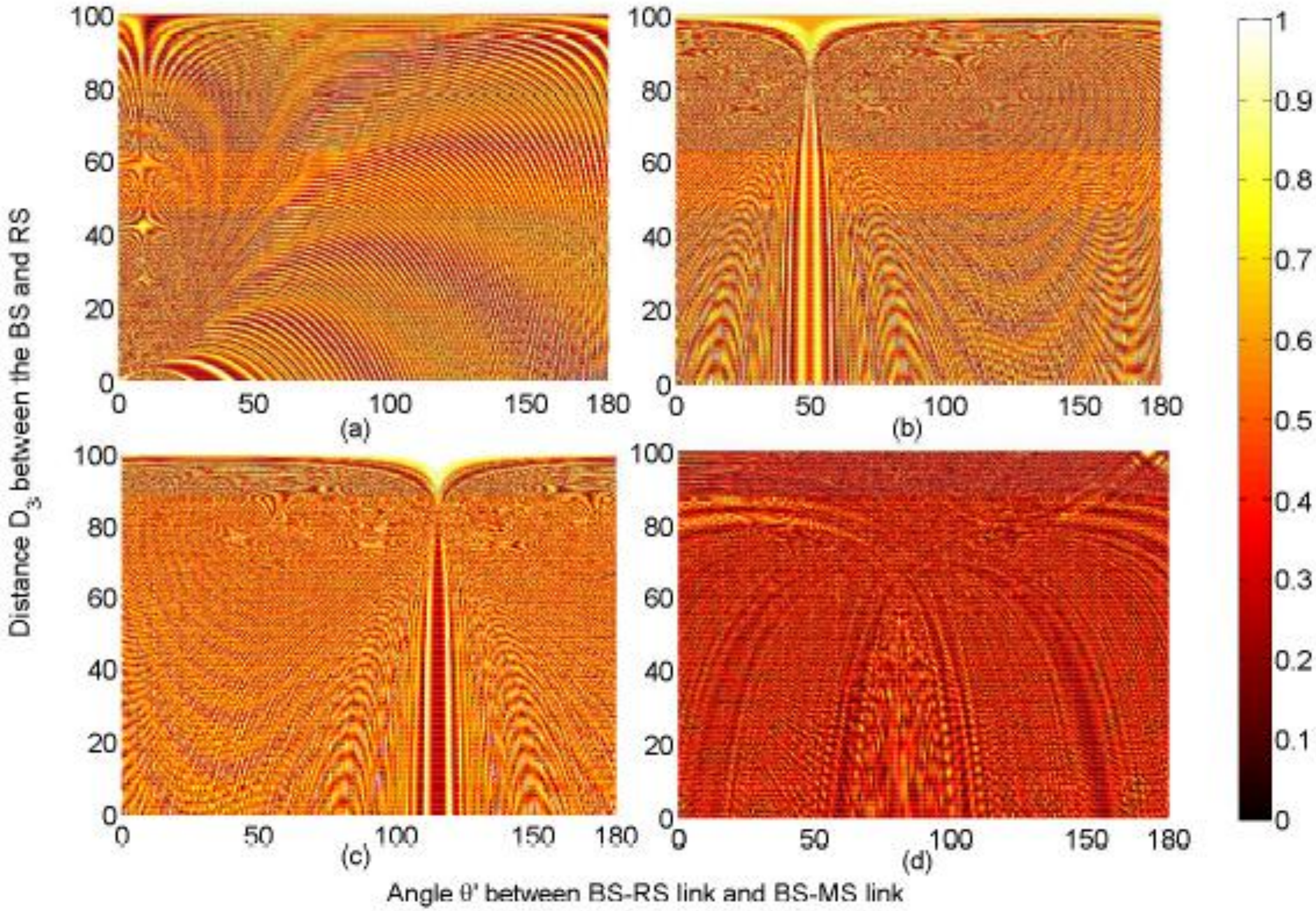
# IV. Numerical Results and Analysis

## 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: $k_1 = k_2 = k_3 = 10$, $\mu_1 = 120°$, $\mu_2 = 300°$, $\mu_3 = 60°$

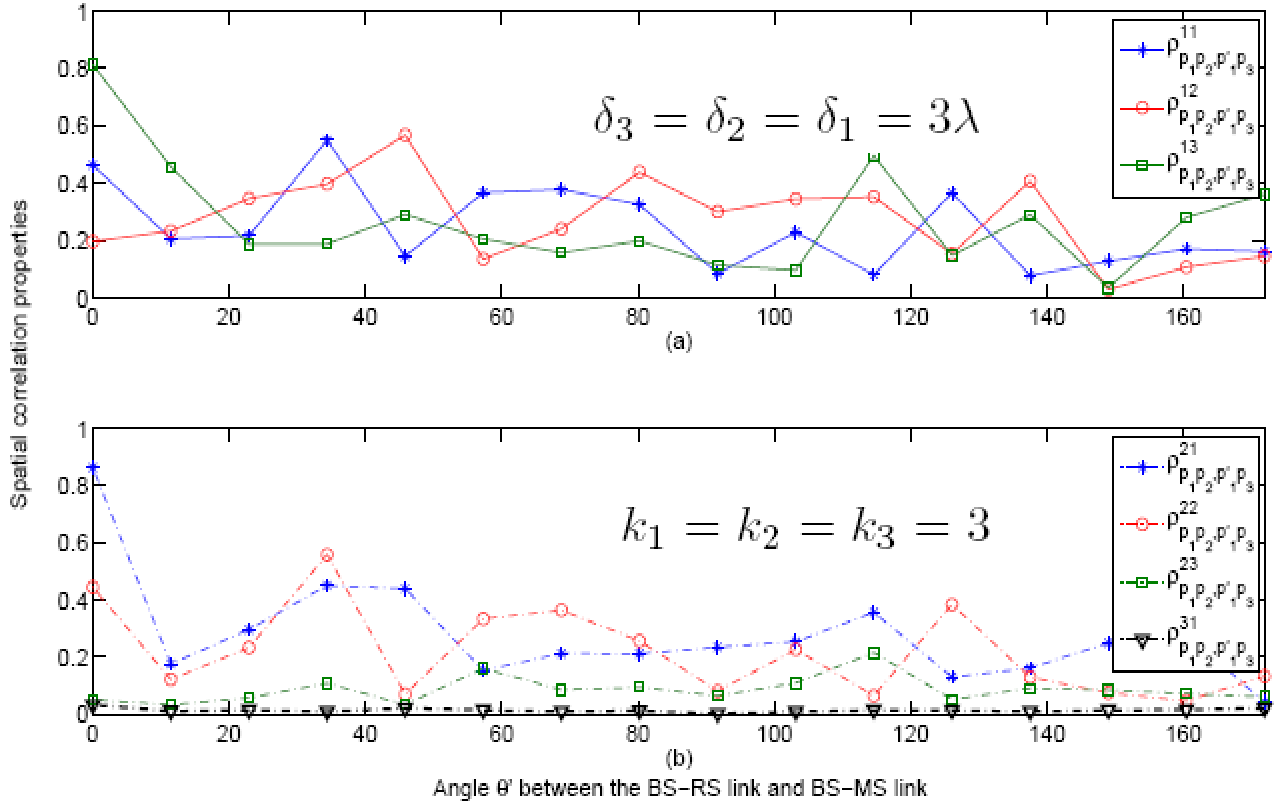
# Spatial Correlation Properties of Different Components

- High multi-link spatial correlations can occur at some cases.



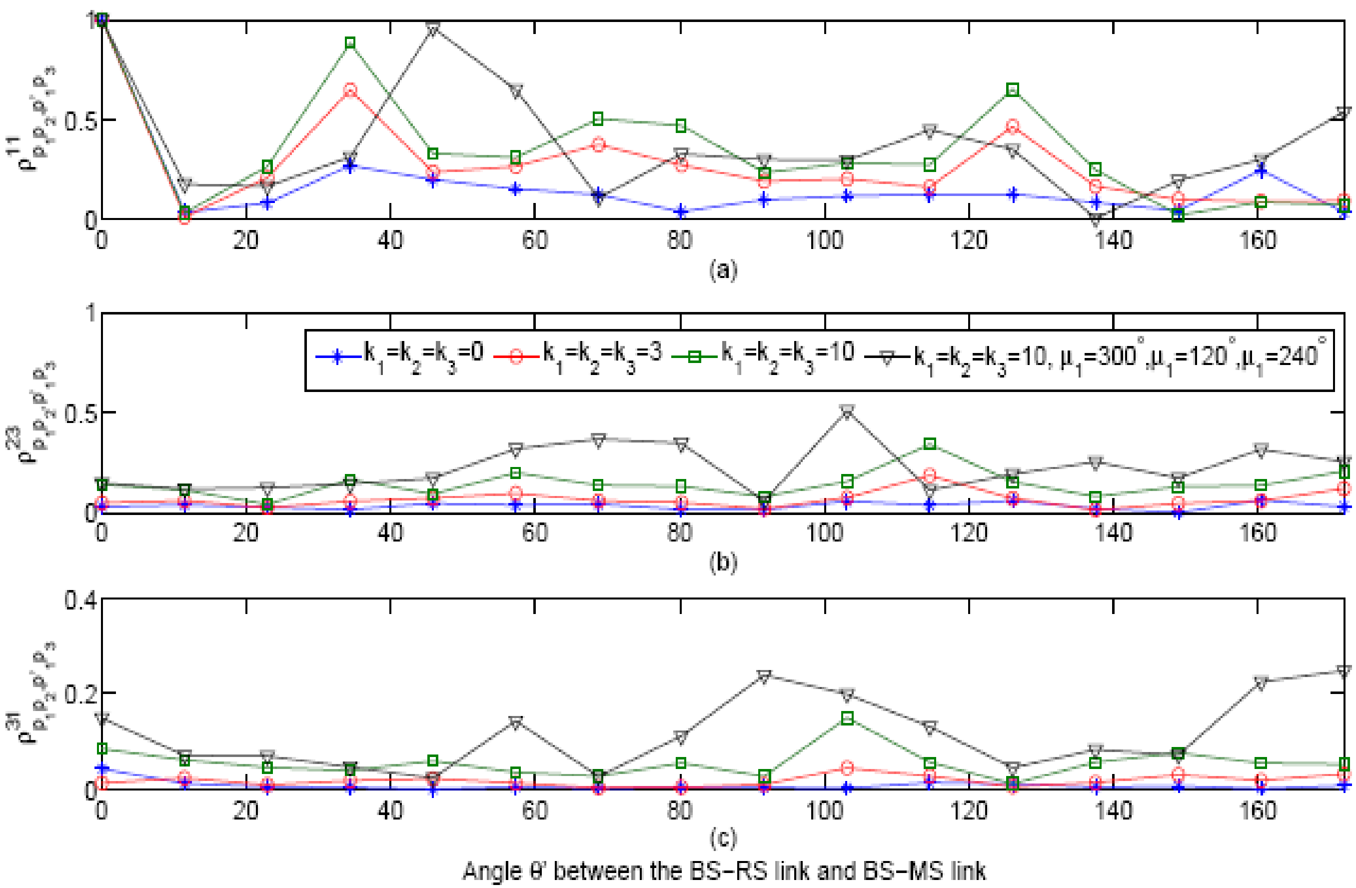
# Spatial Correlation Properties of Scattered Components

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



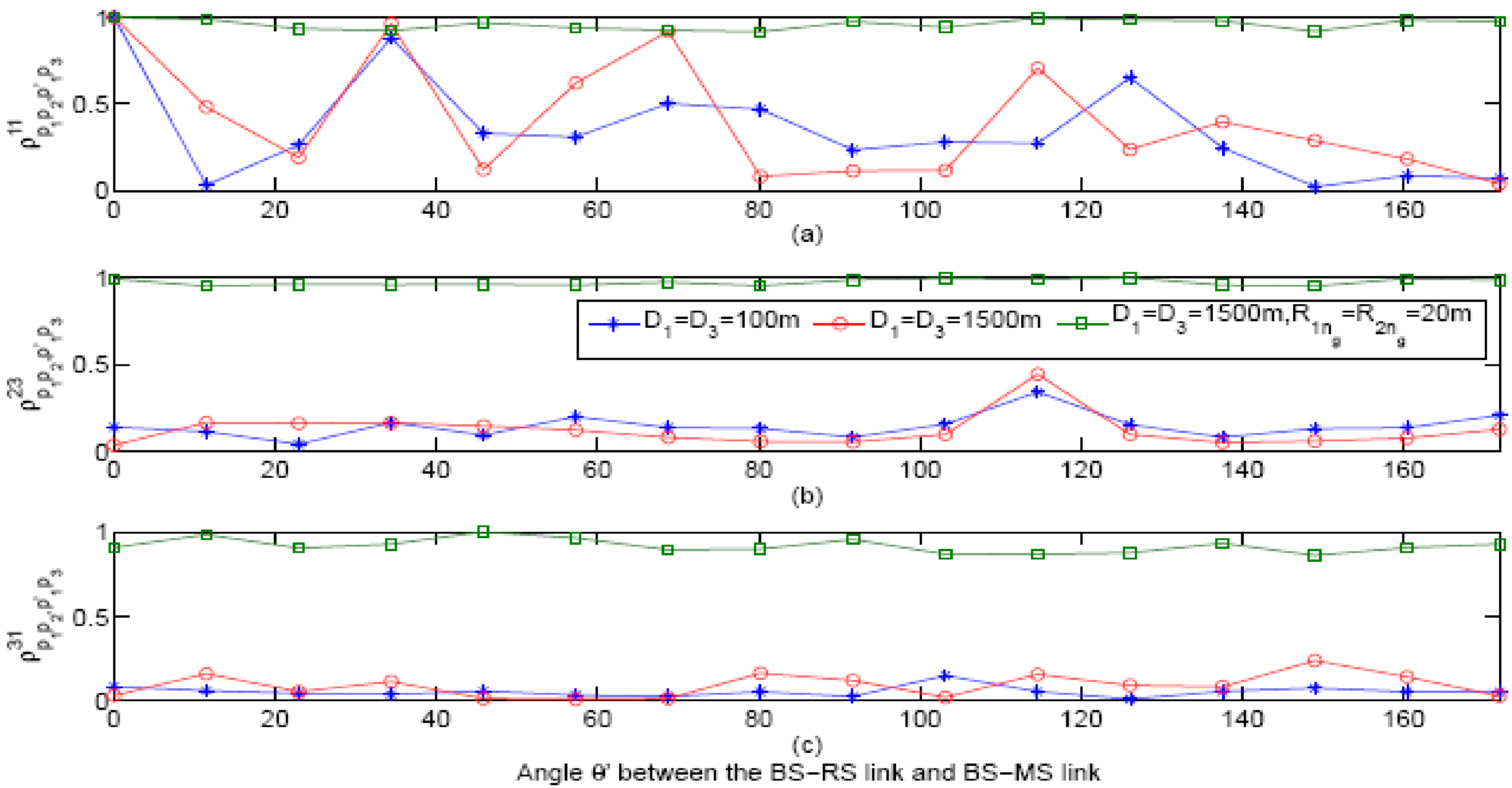
# Impact of Environment Parameters on Spatial Correlation Properties (I)

- The increase of the environment parameter $k_g$ will enhance the spatial correlation.



# Impact of Environment Parameters on Spatial Correlation Properties (II)

- Local scattering area with smaller size leads to higher spatial correlation.



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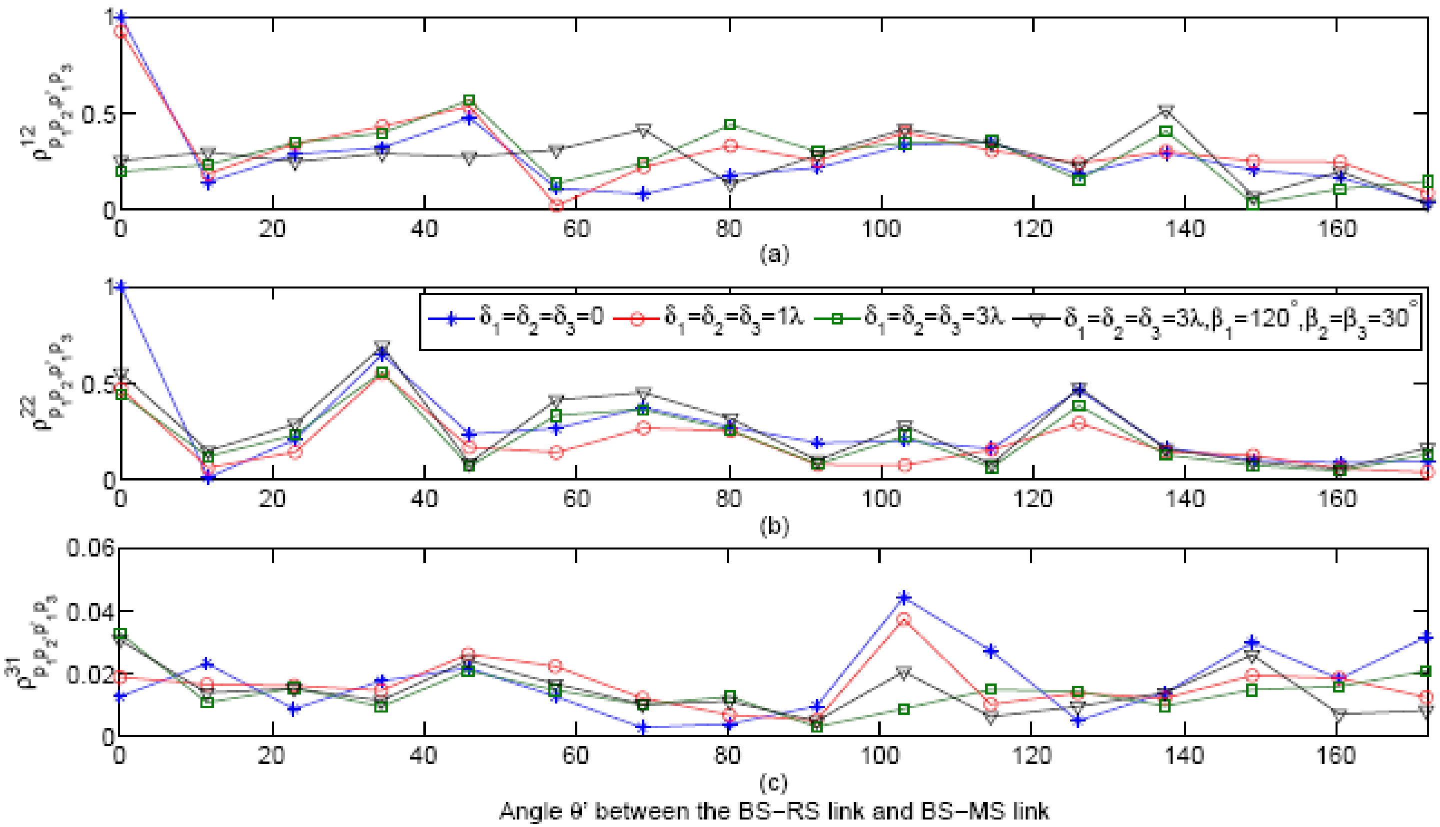
# Impact of Antenna Parameters on Spatial Correlation Properties

- 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: $\eta^{13}_{p_3p_2} = \eta^{13}_{p'_3p_1} = \eta^{21}_{p_3p_2} = \eta^{21}_{p'_3p_1} = \eta^{22}_{p_3p_2} = \eta^{22}_{p'_3p_1} = \eta^{31}_{p_3p_2} = \eta^{31}_{p'_3p_1} = 0$

  $D_1 = D_3 = 1500\text{m}$ $K_{p_3p_2} = K_{p'_3p_1} = 0$
- **Low local scattering density (LSD)**:
  - Energy-related parameters: $\eta^{11}_{p_3p_2} = \eta^{11}_{p'_3p_1} = \eta^{12}_{p_3p_2} = \eta^{12}_{p'_3p_1} = 0.2$ $\eta^{23}_{p_3p_2} = \eta^{23}_{p'_3p_1} = 0.6$
  - Environment parameters: $k_1 = k_2 = 10,$ $R_{1n_1} = R_{1n_2} = 5\text{m}$, $R_{2n_1} = R_{2n_2} = 20\text{m}$
- **High LSD:**
  - Energy-related parameters : $\eta^{11}_{p_3p_2} = \eta^{11}_{p'_3p_1} = \eta^{12}_{p_3p_2} = \eta^{12}_{p'_3p_1} = 0.05$ $\eta^{23}_{p_3p_2} = \eta^{23}_{p'_3p_1} = 0.9$
  - Environment parameters : $k_1 = k_2 = 1,$ $R_{1n_1} = R_{1n_2} = 5\text{m}$ $R_{2n_1} = R_{2n_2} = 200\text{m}$
- **Mixed LSD:**
  - Energy-related parameters : $\eta^{11}_{p'_3p_1} = \eta^{12}_{p'_3p_1} = 0.2,$ $\eta^{23}_{p'_3p_1} = 0.6,$ $\eta^{11}_{p_3p_2} = \eta^{12}_{p_3p_2} = 0.1$ $\eta^{23}_{p_3p_2} = 0.8$
  - Environment parameters : $k_1 = 10$ $k_2 = 2,$ $\mu_1 = 60^\circ,$ $\mu_2 = 120^\circ,$ $R_{1n_1} = R_{1n_2} = 5\text{m}$

    $R_{2n_1} = 20\text{m}$, $R_{2n_2} = 100\text{m}$

# Parameters of the Proposed Model for Indoor Scenario

**Indoor MS Cooperation Scenario**:

- **Low LSD**:
  - Energy-related parameters: $\eta^{11}_{p_3p_2} = \eta^{11}_{p'_3p_1} = \eta^{12}_{p_3p_2} = \eta^{12}_{p'_3p_1} = \eta^{13}_{p_3p_2} = \eta^{13}_{p'_3p_1} = 0.3$

    $K_{p_3p_2} = K_{p'_3p_1} = 3$, $\eta^{21}_{p_3p_2} = \eta^{21}_{p'_3p_1} = \eta^{22}_{p_3p_2} = \eta^{22}_{p'_3p_1} = \eta^{23}_{p_3p_2} = \eta^{23}_{p'_3p_1} = \eta^{31}_{p_3p_2} = \eta^{31}_{p'_3p_1} = 0.025$
  - Environment parameters: $k_1 = k_2 = k_3 = 10,\ R_{1n_1} = R_{1n_2} = R_{1n_3} = 2\text{m}$

    $R_{2n_1} = R_{2n_2} = R_{2n_3} = 8\text{m}$
- **High LSD:**
  - Energy-related parameters : $\eta^{11}_{p_3p_2} = \eta^{11}_{p'_3p_1} = \eta^{12}_{p_3p_2} = \eta^{12}_{p'_3p_1} = \eta^{13}_{p_3p_2} = \eta^{13}_{p'_3p_1} = 0.05$

    $K_{p_3p_2} = K_{p'_3p_1} = 0.1$ $\eta^{21}_{p_3p_2} = \eta^{21}_{p'_3p_1} = \eta^{22}_{p_3p_2} = \eta^{22}_{p'_3p_1} = \eta^{23}_{p_3p_2} = \eta^{23}_{p'_3p_1}$ $\eta^{31}_{p_3p_2} = \eta^{31}_{p'_3p_1} = 0.25$
  - Environment parameters : $k_1 = k_2 = k_3 = 1,\ R_{1n_1} = R_{1n_2} = R_{1n_3} = 2\text{m}$

    $R_{2n_1} = R_{2n_2} = R_{2n_3} = 25\text{m}$
- **Mixed LSD:**
  - Energy-related parameters : $\eta^{11}_{p'_3p_1} = \eta^{12}_{p'_3p_1} = \eta^{13}_{p'_3p_1} = 0.25$ $\eta^{11}_{p_3p_2} = \eta^{12}_{p_3p_2} = \eta^{13}_{p_3p_2} = 0.05$ $\eta^{31}_{p_3p_2} = 0.15$

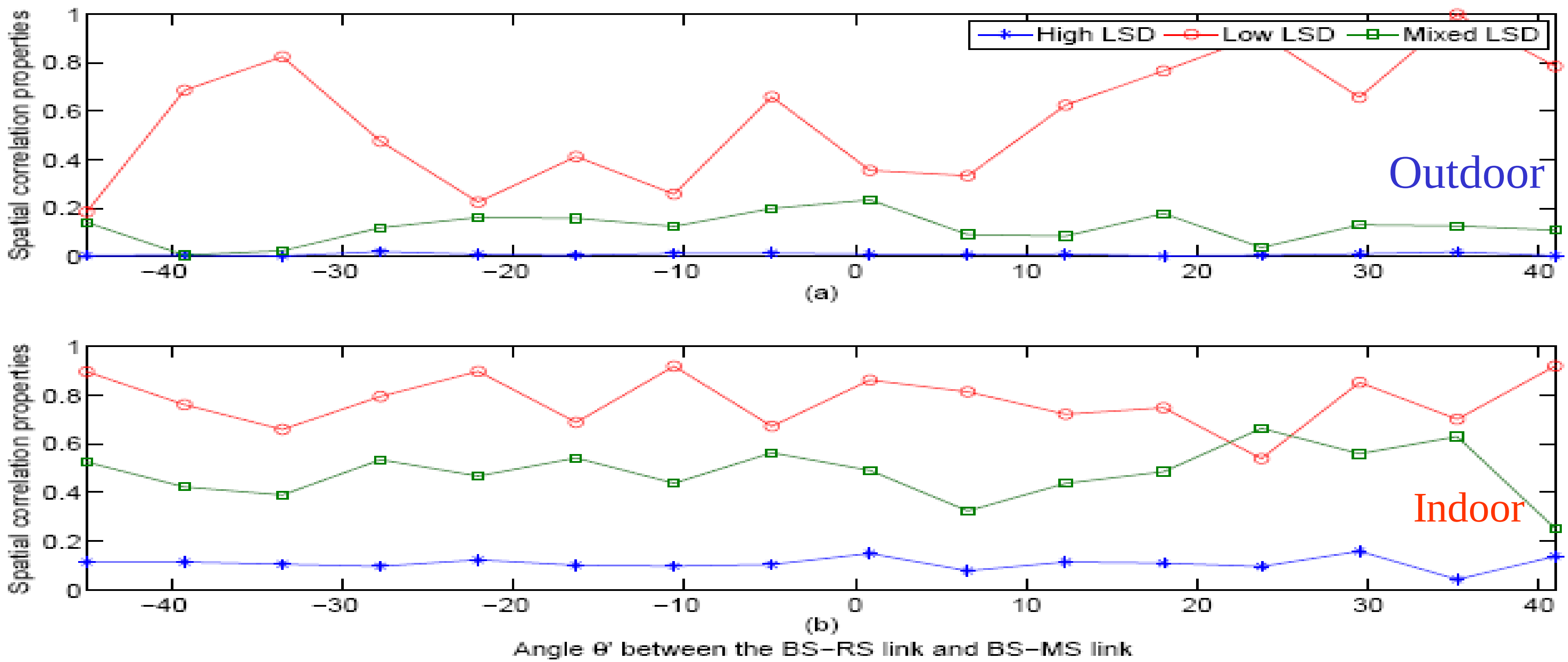
    $K_{p_3p_2} = 0.5,\ K_{p'_3p_1} = 2.5$ $\eta^{21}_{p_3p_2} = \eta^{23}_{p_3p_2} = 0.3$ $\eta^{22}_{p'_3p_1} = \eta^{23}_{p'_3p_1} = \eta^{31}_{p'_3p_1} = 0.05$ $\eta^{21}_{p'_3p_1} = \eta^{22}_{p_3p_2} = 0.1$
  - Environment parameters :

    $k_1 = 6,\ k_2 = 2,\ k_3 = 15,\ \mu_1 = 60°,\ \mu_2 = 120°,\ \mu_3 = 240°$

    $R_{1n_1} = R_{1n_2} = R_{1n_3} = 2\text{m},\ R_{2n_1} = 12\text{m}$ $R_{2n_2} = 20\text{m}$ $R_{2n_3} = 5\text{m}$

# 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.



# Outline

# V. Conclusions

- 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.

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- X. Cheng, **C.-X. Wang**, H. Wang, X. Gao, X.-H. You, D. Yuan, B. Ai, Q. Huo, L. Song, and B. Jiao, "Cooperative MIMO channel modeling and multi-link spatial correlation properties," *IEEE Journal on Selected Areas in Communications(JSAC)*, vol. 30, no. 2, Feb. 2012.
- **C.-X. Wang**, X. Hong, X. Ge, X. Cheng, G. Zhang, and J. S. Thompson, "Cooperative MIMO channel models: a survey," *IEEE Communications Magazine*, vol. 48, no. 2, pp. 80-87, Feb. 2010.
- **C.-X. Wang**, X. Cheng, and D. I. Laurenson, "Vehicle-to-vehicle channel modeling and measurements: recent advances and future challenges", *IEEE Communications Magazine*, vol. 47, no. 11, pp. 96-103, Nov. 2009.


Thank you for your attention!