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Effective degree of freedom for near-field plane-based XL-MIMO with tri-polarization

Key words: XL-MIMO; Near-field communication; Effective degree of freedom; Polarization effect; Performance analysis

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Motivation

1. To fully explore the benefits of XL-MIMO technology, the performance limit analysis for XL-MIMO systems is vital. Several works have studied the DoF for near-field XL-MIMO systems.

2. In practice, 2D plane based XL-MIMO systems are extensively researched and advocated. The uniform planar array (UPA)-based system with the discrete array aperture and the 2D continuous aperture (CAP) plane based system with the continuous array aperture are regarded as two promising plane-based XL-MIMO hardware designs. It is crucial to assess the effective DoF (EDoF) performance of these designs and explore their respective performance limits.

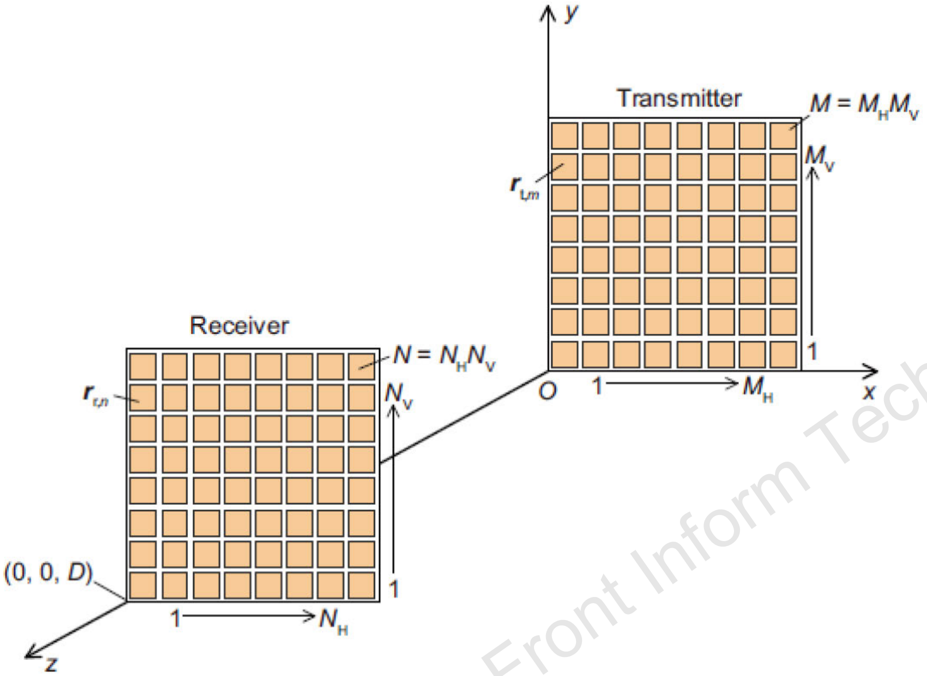
Main idea

1. We analyze the EDoF performance of both UPA-based and 2D CAP plane based XL-MIMO systems with both the scalar and dyadic Green channels.

2. For UPA-based XL-MIMO, we evaluate the EDoF performance by leveraging the discrete channel matrices for both the scalar Green and the dyadic Green channels.

3. Moreover, we propose a novel EDoF performance analysis framework specifically for the 2D CAP plane systems over the dyadic Green channel, with the aid of asymptotic analysis for the EDoF performance analysis framework for the UPA system.

Framework



$$G\left(\boldsymbol{r}_{\mathrm{r}}, \boldsymbol{r}_{\mathrm{t}}\right)=\frac{1}{4\pi} \frac{\exp \left(-\mathrm{j} \kappa_0\left\|\boldsymbol{r}_{\mathrm{r}}-\boldsymbol{r}_{\mathrm{t}}\right\|\right)}{\left\|\boldsymbol{r}_{\mathrm{r}}-\boldsymbol{r}_{\mathrm{t}}\right\|}$$

$$G_{nm}=G\left(\boldsymbol{r}_{\mathrm{r}, n}, \boldsymbol{r}_{\mathrm{t}, m}\right)=\frac{1}{4\pi} \frac{\exp \left(-\mathrm{j} \kappa_0 d_{nm}\right)}{d_{nm}}$$

$$\boldsymbol{G}\left(\boldsymbol{r}_{\mathrm{r}}, \boldsymbol{r}_{\mathrm{t}}\right)=\left(\boldsymbol{I}_3+\frac{\nabla_{\boldsymbol{r}_{\mathrm{r}}} \nabla_{\boldsymbol{r}_{\mathrm{r}}}^{\mathrm{H}}}{\kappa_0^2}\right) G\left(\boldsymbol{r}_{\mathrm{r}}, \boldsymbol{r}_{\mathrm{t}}\right)$$

$$\boldsymbol{G}(\boldsymbol{r}_{\mathrm{r}, n}, \boldsymbol{r}_{\mathrm{t}, m})=\frac{1}{4\pi}\left(\boldsymbol{I}_3+\frac{\nabla_{\boldsymbol{r}_{\mathrm{r}, n}} \nabla_{\boldsymbol{r}_{\mathrm{r}, n}}^{\mathrm{H}}}{\kappa_0^2}\right) G(\boldsymbol{r}_{\mathrm{r}, n}, \boldsymbol{r}_{\mathrm{t}, m})$$

Illustration of the investigated XL-MIMO system

Green’s function based channel models

Method

1. For UPA-based XL-MIMO, we evaluate the EDoF performance by leveraging the discrete channel matrices for both the scalar Green and the dyadic Green channels.

$$\boxed{\varepsilon_{\mathrm{S}} = \frac{\mathrm{tr}^2\left(\boldsymbol{R}_{\mathrm{S}}\right)}{\left\|\boldsymbol{R}_{\mathrm{S}}\right\|_{\mathrm{F}}^2}} \qquad \boxed{\varepsilon_{\mathrm{D}} = \frac{\mathrm{tr}^2\left(\boldsymbol{R}_{\mathrm{D}}\right)}{\left\|\boldsymbol{R}_{\mathrm{D}}\right\|_{\mathrm{F}}^2}}$$

Here $\boldsymbol{R}_{\mathrm{S}} = \boldsymbol{H}_{\mathrm{S}}^{\mathrm{H}}\boldsymbol{H}_{\mathrm{S}} \in \mathbb{C}^{M\times M}$ and $\boldsymbol{R}_{\mathrm{D}} = \boldsymbol{H}_{\mathrm{D}}^{\mathrm{H}}\boldsymbol{H}_{\mathrm{D}} \in \mathbb{C}^{3M\times 3M}$ denote the correlation matrices for the scalar Green function based channel and dyadic Green function based channel, respectively.

Method

2. For the 2D CAP plane-based XL-MIMO system with scalar Green channels, we apply the asymptotic analysis for the EDoF performance analysis framework for the UPA system to derive its EDoF analysis framework. We define the auto-correlation kernel:

$$\boxed{K(\boldsymbol{r}_{\mathrm{t}}, \boldsymbol{r}_{\mathrm{t}'}) = \int_{S_{\mathrm{R}}} G^*\left(\boldsymbol{r}_{\mathrm{r}}, \boldsymbol{r}_{\mathrm{t}}\right) G\left(\boldsymbol{r}_{\mathrm{r}}, \boldsymbol{r}_{\mathrm{t}'}\right) \mathrm{d}\boldsymbol{r}_{\mathrm{r}}}$$

and then apply the asymptotic analysis to derive the EDoF for the 2D CAP plane-based XL-MIMO system with scalar Green channels:

$$\boxed{\Psi_{\mathrm{S}} = \frac{\left(\int_{S_{\mathrm{T}}} \int_{S_{\mathrm{R}}} \left|G\left(\boldsymbol{r}_{\mathrm{r}}, \boldsymbol{r}_{\mathrm{t}}\right)\right|^2 \mathrm{d}\boldsymbol{r}_{\mathrm{r}} \mathrm{d}\boldsymbol{r}_{\mathrm{t}}\right)^2}{\int_{S_{\mathrm{T}}} \int_{S_{\mathrm{T}}} \left|K(\boldsymbol{r}_{\mathrm{t}}, \boldsymbol{r}_{\mathrm{t}'})\right|^2 \mathrm{d}\boldsymbol{r}_{\mathrm{t}} \mathrm{d}\boldsymbol{r}_{\mathrm{t}'}}}$$

$$\boxed{\begin{cases} [\boldsymbol{R}_{\mathrm{S}}]_{m_1 m_2} \rightarrow \frac{N_{\mathrm{H}} N_{\mathrm{V}}}{L_{\mathrm{r,H}} L_{\mathrm{r,V}}} K(\boldsymbol{r}_{\mathrm{t}}, \boldsymbol{r}_{\mathrm{t}'}), \\ \mathrm{tr}\left(\boldsymbol{R}_{\mathrm{S}}\right) \rightarrow \frac{N_{\mathrm{H}} N_{\mathrm{V}} M_{\mathrm{H}} M_{\mathrm{V}}}{L_{\mathrm{r,H}} L_{\mathrm{r,V}} L_{\mathrm{t,H}} L_{\mathrm{t,V}}} \int_{S_{\mathrm{T}}} \int_{S_{\mathrm{R}}} \left|G\left(\boldsymbol{r}_{\mathrm{r}}, \boldsymbol{r}_{\mathrm{t}}\right)\right|^2 \mathrm{d}\boldsymbol{r}_{\mathrm{r}} \mathrm{d}\boldsymbol{r}_{\mathrm{t}}, \\ \|\boldsymbol{R}_{\mathrm{S}}\|_{\mathrm{F}}^2 \rightarrow \frac{(N_{\mathrm{H}} N_{\mathrm{V}} M_{\mathrm{H}} M_{\mathrm{V}})^2}{(L_{\mathrm{r,H}} L_{\mathrm{r,V}} L_{\mathrm{t,H}} L_{\mathrm{t,V}})^2} \int_{S_{\mathrm{T}}} \int_{S_{\mathrm{T}}} \left|K(\boldsymbol{r}_{\mathrm{t}}, \boldsymbol{r}_{\mathrm{t}'})\right|^2 \mathrm{d}\boldsymbol{r}_{\mathrm{t}} \mathrm{d}\boldsymbol{r}_{\mathrm{t}'}. \end{cases}}$$

$$\boxed{\begin{cases} \mathrm{d}\boldsymbol{r}_{\mathrm{r}} = \mathrm{d}y_{\mathrm{r}} \mathrm{d}z_{\mathrm{r}} \rightarrow \frac{L_{\mathrm{r,H}} L_{\mathrm{r,V}}}{N_{\mathrm{H}} N_{\mathrm{V}}}, \\ \mathrm{d}\boldsymbol{r}_{\mathrm{t}} = \mathrm{d}y_{\mathrm{t}} \mathrm{d}z_{\mathrm{t}} \rightarrow \frac{L_{\mathrm{t,H}} L_{\mathrm{t,V}}}{M_{\mathrm{H}} M_{\mathrm{V}}}, \\ \mathrm{d}\boldsymbol{r}_{\mathrm{t}'} = \mathrm{d}y_{\mathrm{t}'} \mathrm{d}z_{\mathrm{t}'} \rightarrow \frac{L_{\mathrm{t,H}} L_{\mathrm{t,V}}}{M_{\mathrm{H}} M_{\mathrm{V}}}. \end{cases}}$$

Method

3. For the 2D CAP plane-based XL-MIMO system with dyadic Green channels, we define the polarized auto-correlation kernel function:

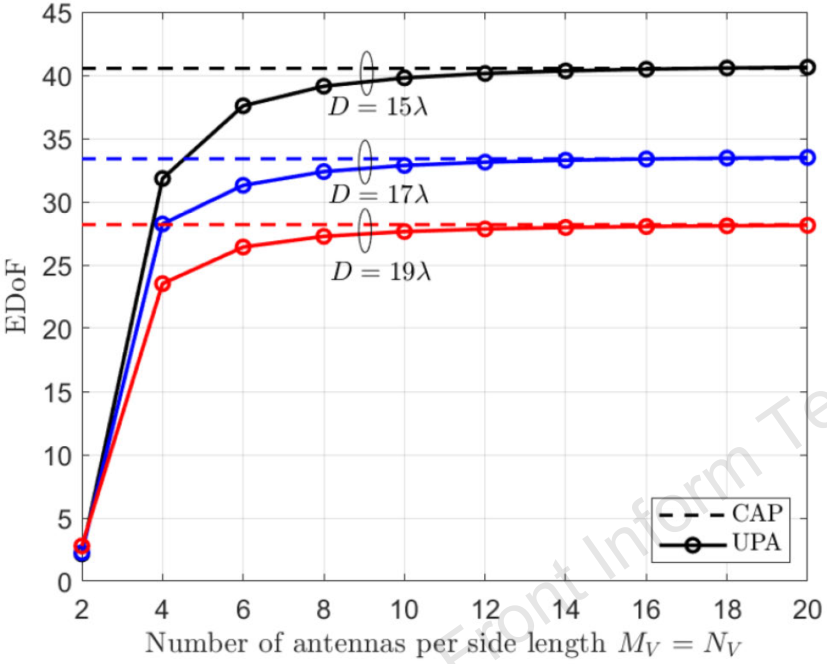
$$\bar{K}(\boldsymbol{r}_{\mathrm{t}}, \boldsymbol{r}_{\mathrm{t}'}, p, q)=\sum_{i=1}^{3} \int_{S_{\mathrm{R}}} \left[G^{ip}(\boldsymbol{r}_{\mathrm{r}}, \boldsymbol{r}_{\mathrm{t}})\right]^{*} G^{iq}(\boldsymbol{r}_{\mathrm{r}}, \boldsymbol{r}_{\mathrm{t}'})\mathrm{d}\boldsymbol{r}_{\mathrm{r}}$$

and then apply the asymptotic analysis to derive the EDoF for the 2D CAP plane-based XL-MIMO system with scalar Green channels:

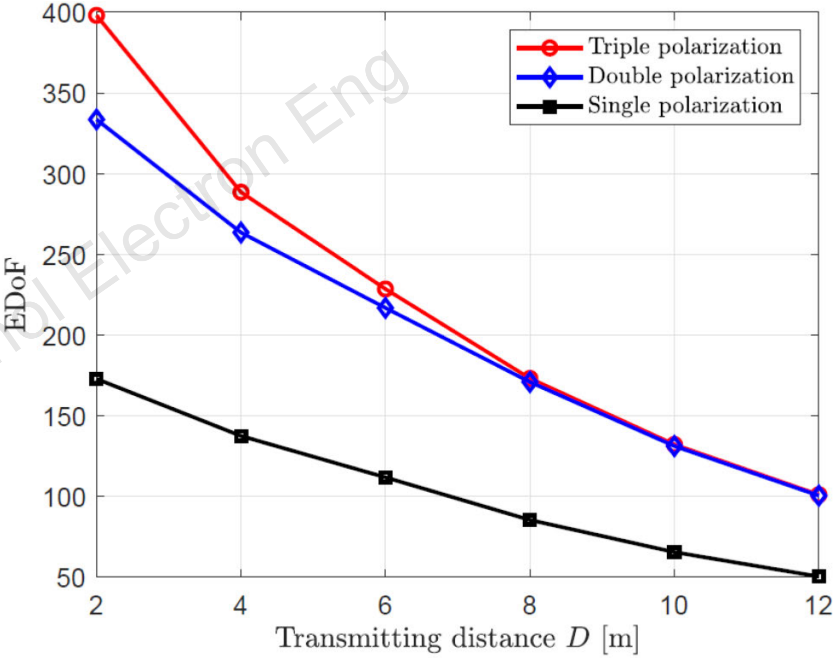
$$\Psi_{\mathrm{D}}=\frac{\left(\sum_{i=1}^{3} \sum_{p=1}^{3} \int_{S_{\mathrm{T}}} \int_{S_{\mathrm{R}}} \left|G^{ip}(\boldsymbol{r}_{\mathrm{r}}, \boldsymbol{r}_{\mathrm{t}})\right|^{2} \mathrm{d}\boldsymbol{r}_{\mathrm{r}} \mathrm{d}\boldsymbol{r}_{\mathrm{t}}\right)^{2}}{\sum_{p=1}^{3} \sum_{q=1}^{3} \int_{S_{\mathrm{T}}} \int_{S_{\mathrm{T}}} \left|\bar{K}(\boldsymbol{r}_{\mathrm{t}}, \boldsymbol{r}_{\mathrm{t}'}, p, q)\right|^{2} \mathrm{d}\boldsymbol{r}_{\mathrm{t}} \mathrm{d}\boldsymbol{r}_{\mathrm{t}'}}$$

$$\begin{cases} \operatorname{tr}(\boldsymbol{R}_{\mathrm{D}}) = \sum_{c=1}^{3M} [\boldsymbol{R}_{\mathrm{D}}]_{cc} = \sum_{p=1}^{3} \sum_{i=1}^{3} \sum_{a=1}^{M} \sum_{n=1}^{N} \left|G_{na}^{ip}\right|^{2}, \\ \|\boldsymbol{R}_{\mathrm{D}}\|_{\mathrm{F}}^{2} = \sum_{c=1}^{3M} \sum_{d=1}^{3M} \left|[\boldsymbol{R}_{\mathrm{D}}]_{cd}\right|^{2} = \sum_{p=1}^{3} \sum_{q=1}^{3} \sum_{a=1}^{M} \sum_{b=1}^{M} \left|\sum_{i=1}^{3} \sum_{n=1}^{N} \left(G_{na}^{ip}\right)^{*} G_{nb}^{iq}\right|^{2}. \end{cases}$$

Major results



EDoF performance for the UPA system and the 2D CAP plane system over the dyadic Green channel



EDoF performance for the 2D CAP plane system over the dyadic Green channel with single, double, or triple polarization

Conclusions

1. In this study, we carried out the EDoF performance analysis for the UPA and the 2D CAP systems. More importantly, the scalar and dyadic Green near-field channels were considered. First, we derived the EDoF performance for the UPA system by using discrete channel matrices based on either the scalar or dyadic Green function.

2. For the 2D CAP plane system, asymptotic analysis was applied to construct the EDoF performance analysis framework based on the scalar or dyadic Green channel. For the numerical results, we presented a comparative analysis of the EDoF performance between the UPA-based and 2D CAP plane based XL-MIMO systems.

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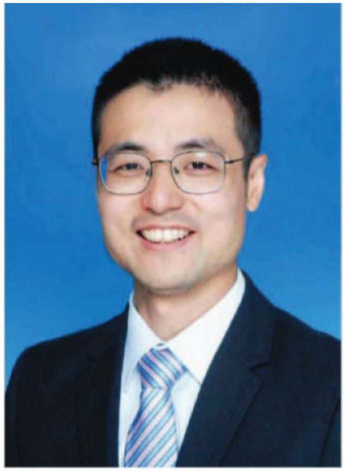

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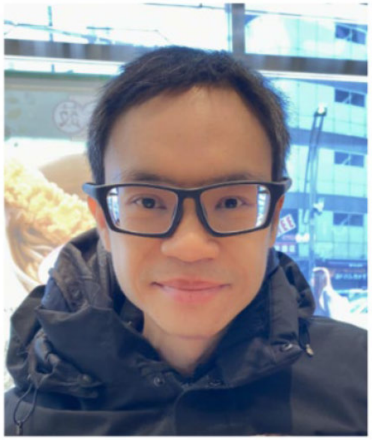

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