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Mixed LoS/NLoS Near-Field Channel Estimation for Extremely Large-Scale MIMO Systems

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Extremely Large-Scale Antenna Array

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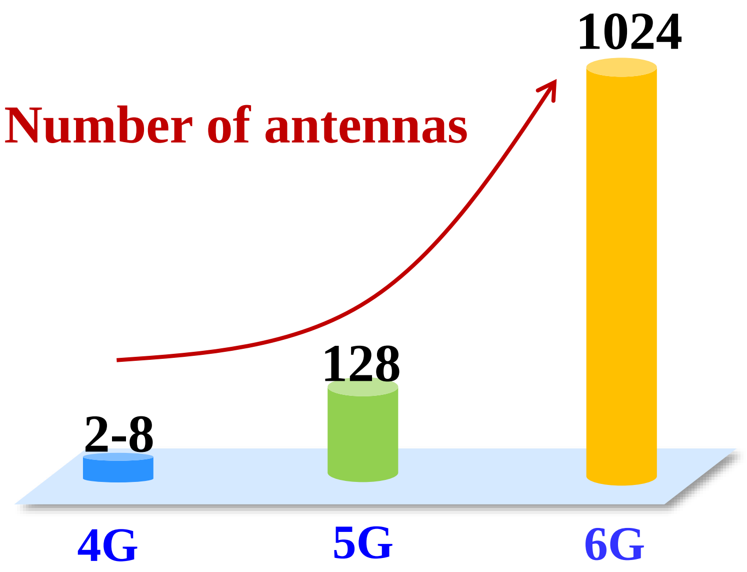
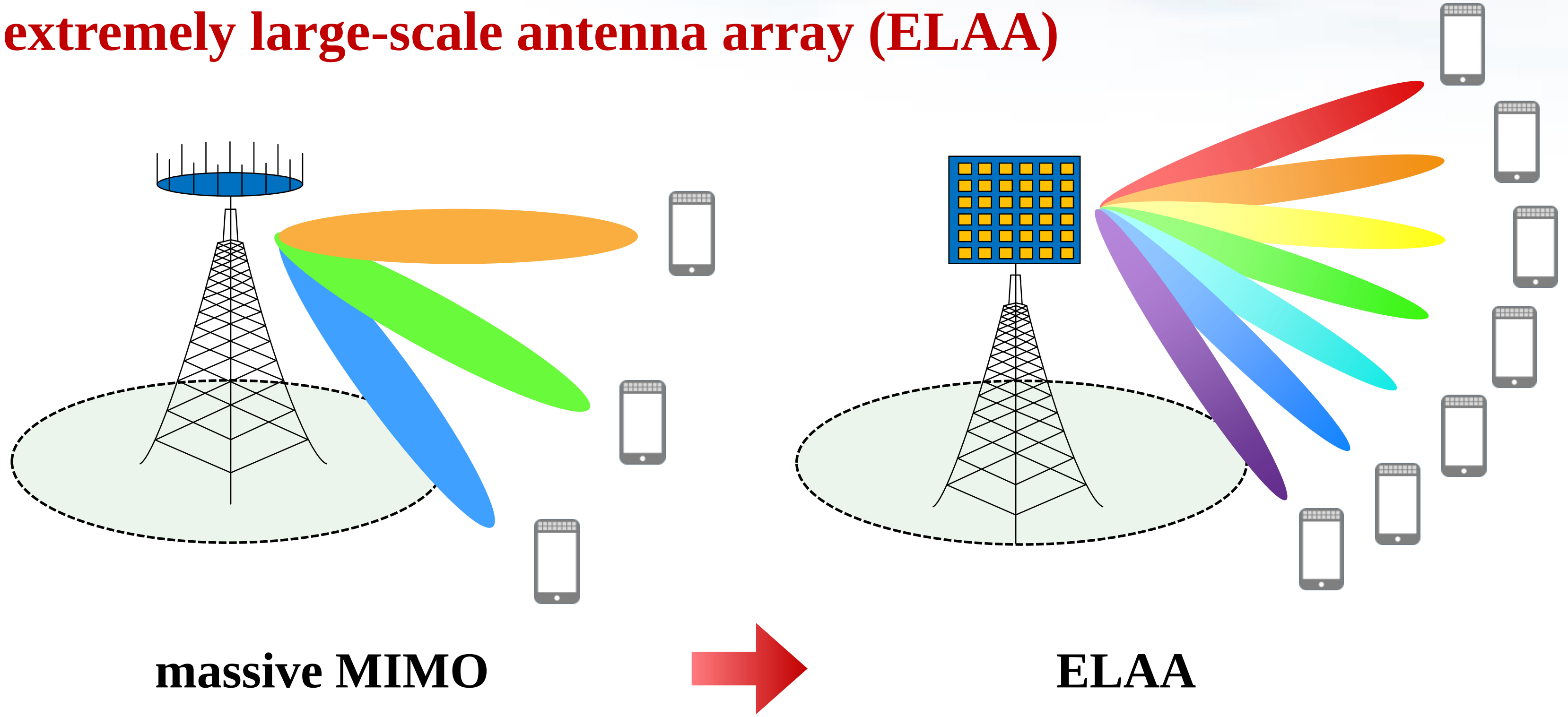
- 6G is expected to achieve 10 times higher spectral efficiency compared with 5G
- The higher spectral efficiency can be achieved by exploiting spatial multiplexing, which requires significantly increased number of antennas
  - 4G: 2-8 antennas → 5G: 64-256 antennas
  - 6G: 1024+ antennas with extremely large-scale antenna array (ELAA)





[1] W. Jiang, B. Han, M. A. Habibi and H. D. Schotten, "The Road Towards 6G: A Comprehensive Survey," *IEEE Open J. Commun. Soc.*, vol. 2, pp. 334-366, Feb. 2021.

Near-Field for ELAA

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- Electromagnetic propagation can be divided into far-field and radiative near-field region

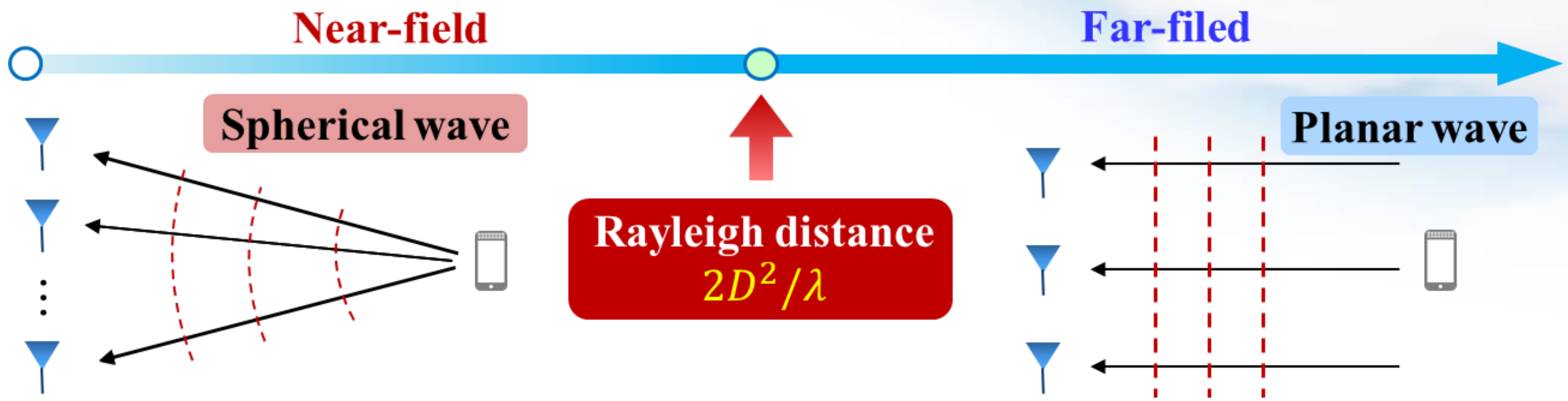


Table I. Near-field region [m] (data from [1])

	0.1 m	0.5 m	1 m	3 m
3 GHz	0.21	5	20	180
28 GHz	1.9	47	187	/
142 GHz	9.0	237	/	/

ELAA with 2304 antennas@28GHz, Rayleigh distance is 25 m, Tsinghua [2]

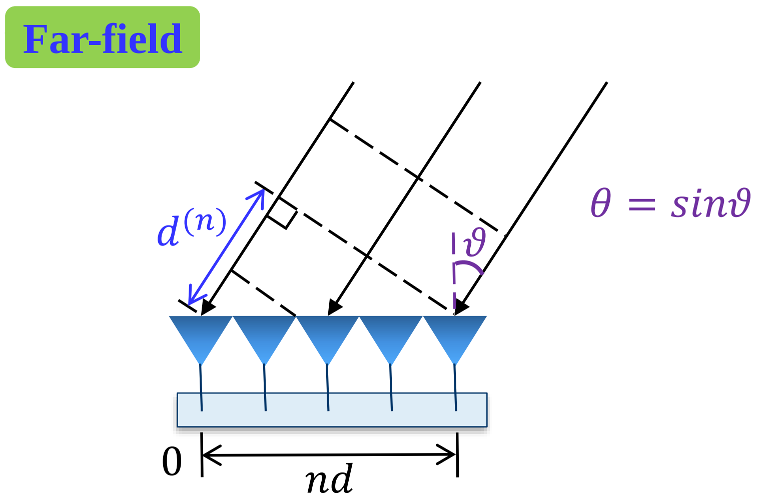
Evolution from massive MIMO to extremely large-scale array results in the near-field propagation

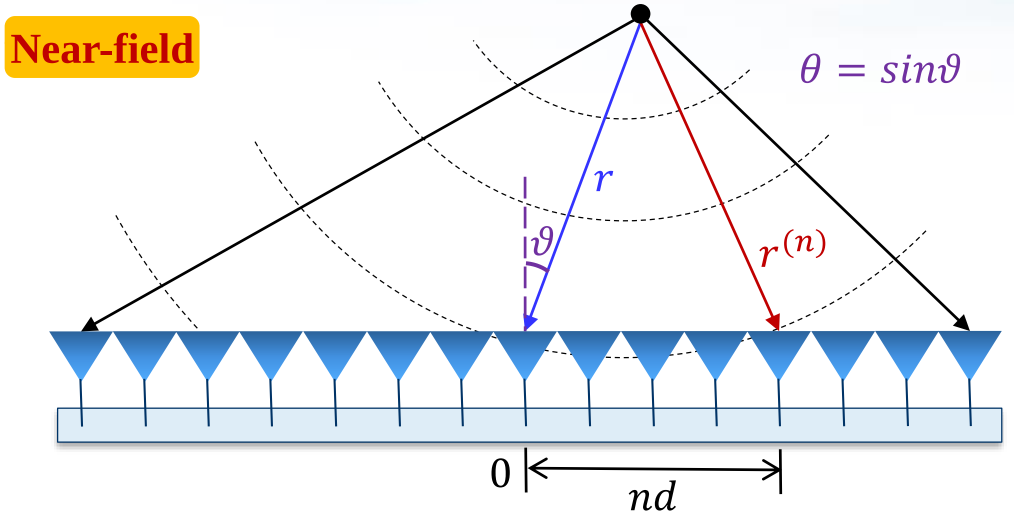
[1] A. Pizzo, L. Sanguinetti, and T. L. Marzetta, "Fourier plane-wave series expansion for holographic MIMO communications," *IEEE Trans. Wireless Commun.*, vol. 21, no. 9, pp. 6890-6905, Sep. 2022.

[2] M. Cui, Z. Wu, Y. Chen, S. Xu, F. Yang, and L. Dai, "Demo: Low-power communications based on RIS and AI for 6G," in *Proc. IEEE Int. Conf. Commun. (IEEE ICC'22)*, Seoul, SouthKorea, May 2022. (**IEEE ICC 2022 Outstanding Demo Award**) .

Far-Field vs. Near-Field

- **Far-field: the EM waves impinging on the antenna array can be approximately modeled as planar waves, where the phase of the EM wave is a linear function of the antenna index**
- **Near-field: the EM waves have to be accurately modeled as spherical waves, where the phase of the EM wave is a non-linear function of the antenna index**





Distance: $d^{(n)} = nd\theta$ **Linear**

Phase: $\phi_n^{\text{far}} = -\frac{2\pi d^{(n)}}{\lambda} = -\frac{2\pi}{\lambda} nd\theta$

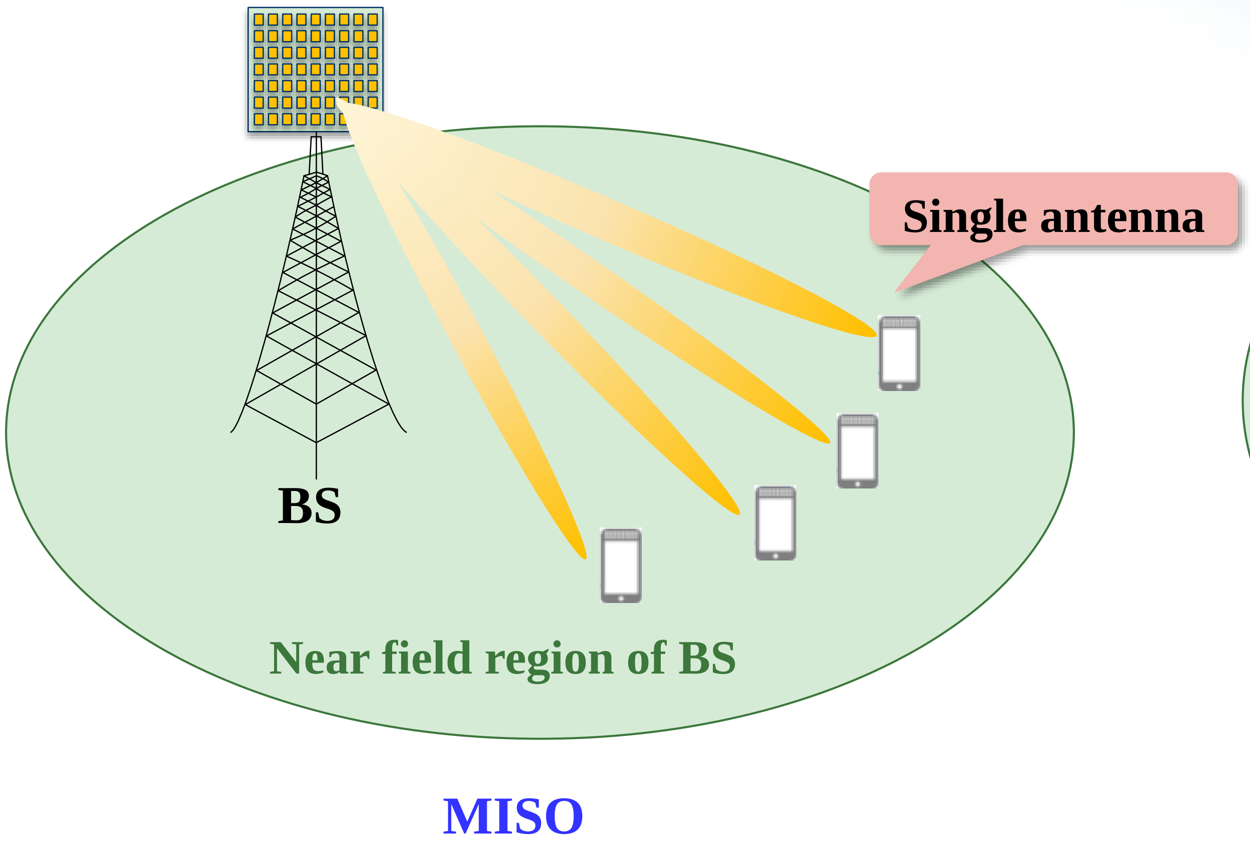
Distance: $r^{(n)} = \sqrt{r^2 + n^2d^2 - 2ndr\theta}$ **Non-linear**

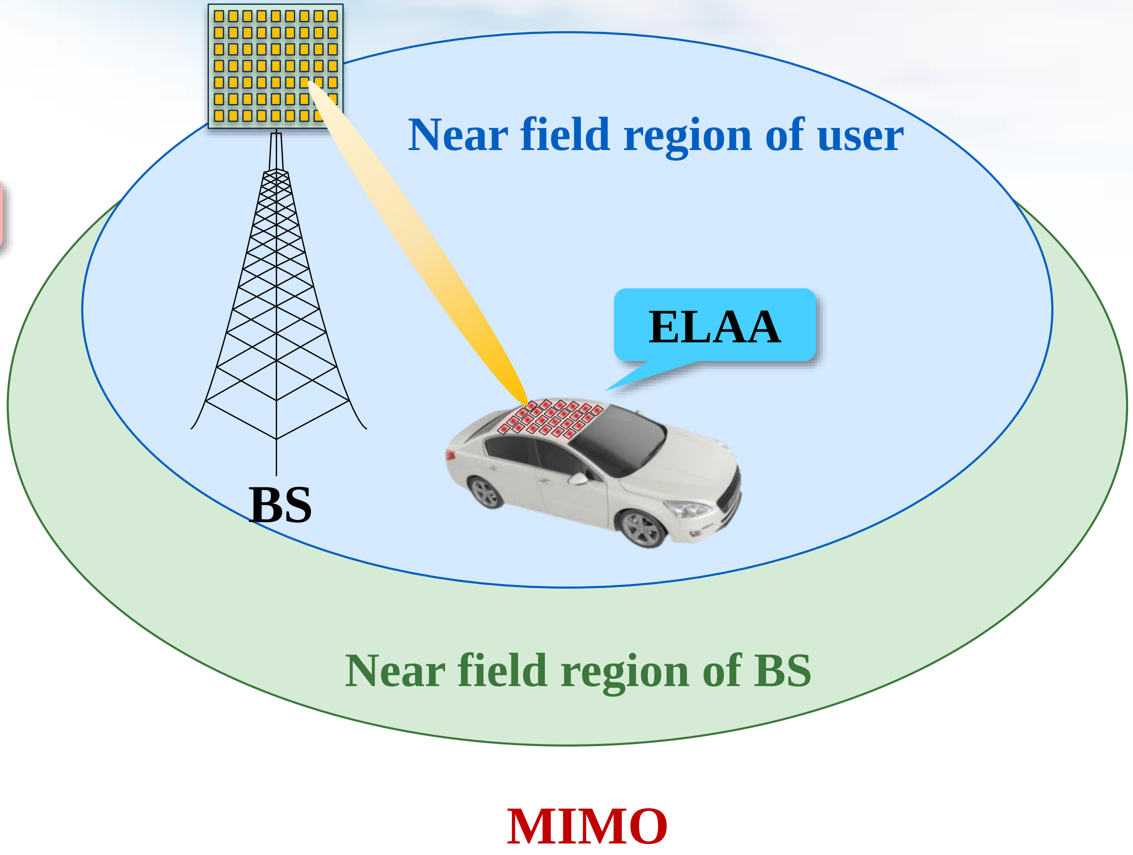
Phase: $\phi_n = \frac{2\pi\left(r^{(n)} - r\right)}{\lambda} = \frac{2\pi}{\lambda}\left(\sqrt{r^2 + n^2d^2 - 2ndr\theta} - r\right)$

Antenna index: $n \in [-N, \cdots, 0, \cdots, N]$ **Antenna number:** $M = 2N + 1$

Near-Field: From MISO to MIMO

- **MISO**: Only the BS is equipped with **extremely large-scale antenna array (ELAA)**
- **MIMO**: Both the BS and the user are equipped with **ELAA**

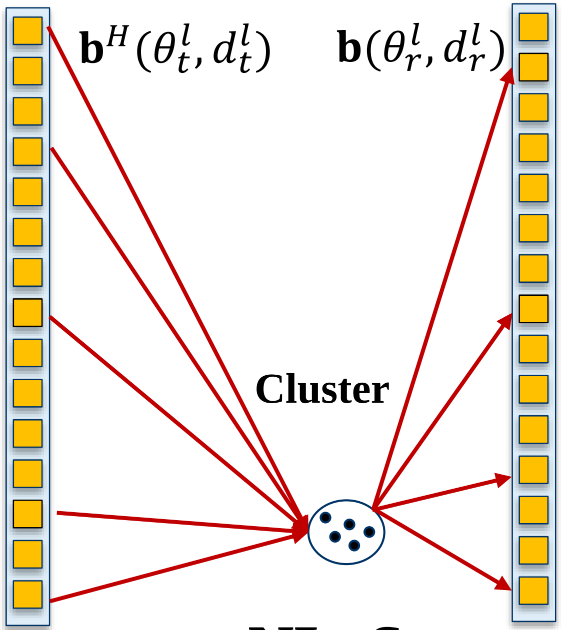




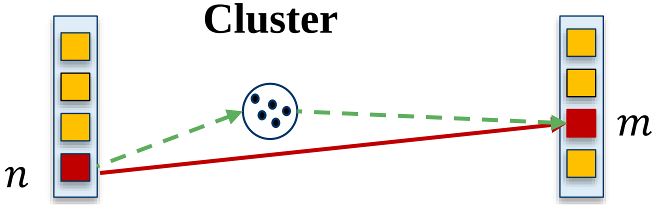
Near-Field MIMO Channel Model

- **Similar to far-field MIMO channel model, the existing near-field MIMO channel model is based on the near-field array response vector**

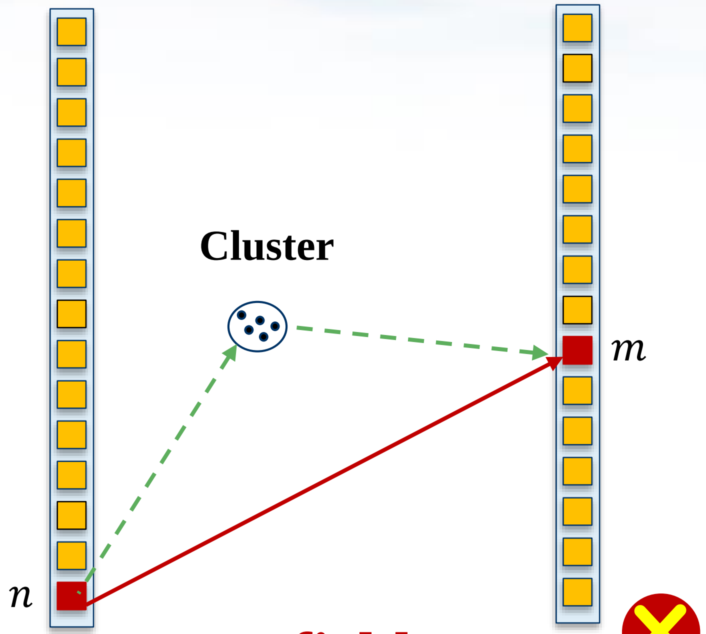
$$\mathbf{H}_{\text{near-field}} = \sqrt{\frac{N_1 N_2}{L}} \sum_{l=1}^{L} g_l \mathbf{b}(\theta_r^l, d_r^l)\, \mathbf{b}^H(\theta_t^l, d_t^l)$$



NLoS



Far-field LoS



Near-field LoS

The existing model cannot accurately describe the characteristic of near-field LoS path

Near-Field MIMO Channel Model

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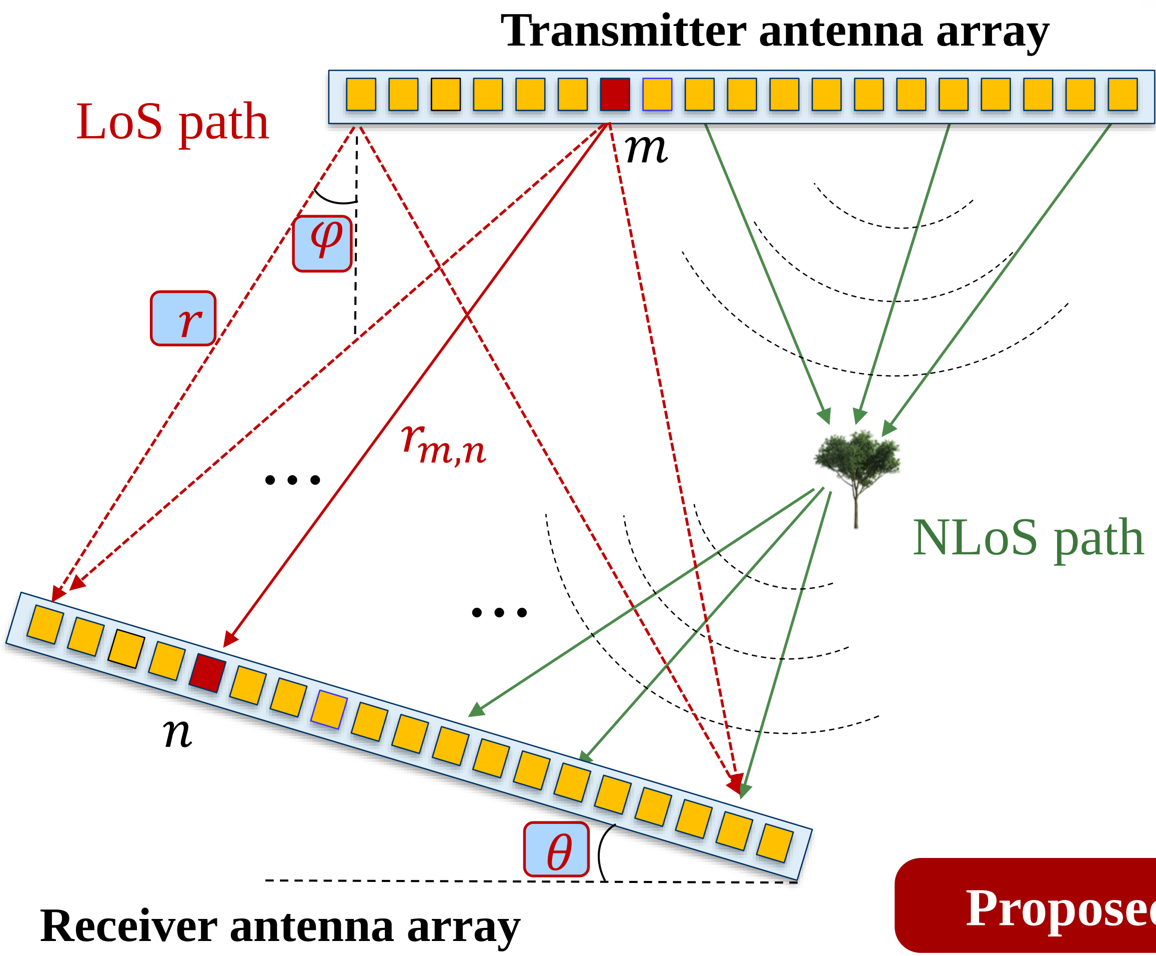
- **The LoS and NLoS paths are modeled separately**



LoS: Free space propagation assumption

$$\mathbf{H}_{\mathrm{LoS},(m,n)} = \frac{e^{-j2\pi r_{m,n}/\lambda}}{r_{m,n}}$$

$$r_{m,n} = \sqrt{r^2 + (md)^2 + (nd)^2 - 2rmd\cos(\theta+\varphi) + 2rnd\cos(\theta) - 2mnr^2\cos(\varphi)}$$

$$\mathbf{H}_{\mathrm{LoS}}(r,\theta,\varphi) = \begin{bmatrix} \frac{e^{-j2\pi r_{1,1}/\lambda}}{r_{1,1}} & \cdots & \frac{e^{-j2\pi r_{1,N}/\lambda}}{r_{1,N}} \\ \vdots & \ddots & \vdots \\ \frac{e^{-j2\pi r_{M,1}/\lambda}}{r_{M,1}} & \cdots & \frac{e^{-j2\pi r_{M,N}/\lambda}}{r_{M,N}} \end{bmatrix}$$

NLoS: Based on array steering vector

$$\mathbf{H}_{\mathrm{NLoS}} = \sum_{l=1}^{L} g_l \boldsymbol{a}(\theta_r^l, r_r^l)\, \mathbf{b}^H(\theta_t^l, r_t^l)$$

Proposed near-field MIMO channel model: $\mathbf{H} = \mathbf{H}_{\mathrm{LoS}} + \mathbf{H}_{\mathrm{NLoS}}$

Near-Field MIMO Rayleigh Distance

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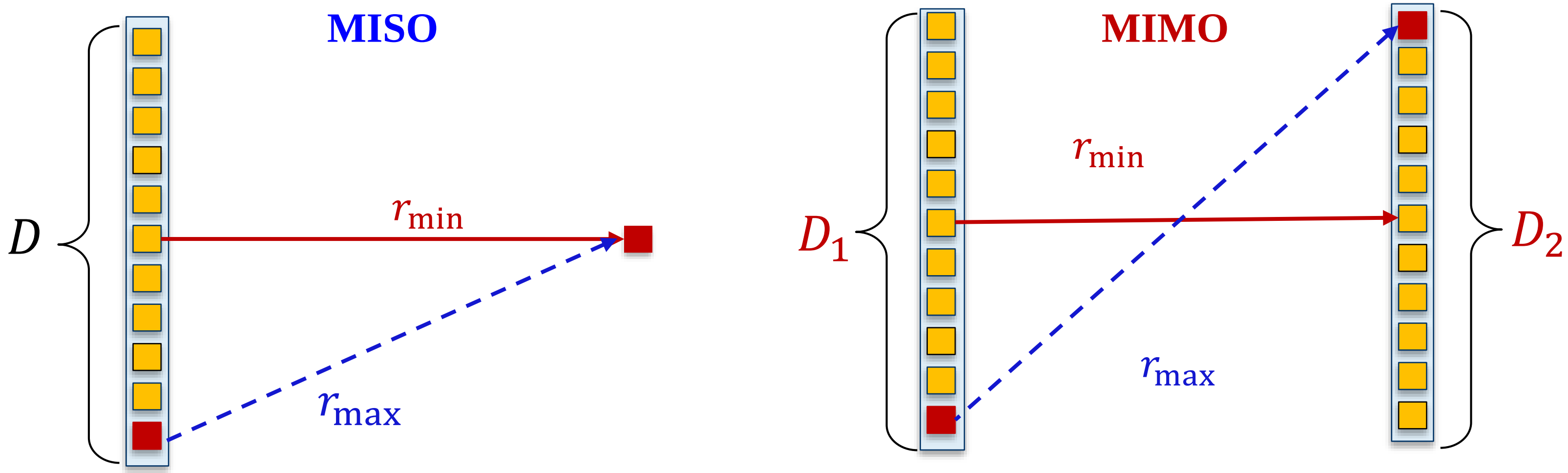
- **Rayleigh Distance: The transceiver distance when the maximum difference between spherical wave and plane wave is ($\pi/8$)**
  - **Classical MISO Rayleigh Distance:** $R_1 = 2D^2/\lambda$ (Array aperture)
  - **Proposed MIMO Rayleigh Distance:** (Sum of transmitter and receiver array apertures)

$$R_2 = 2(D_1 + D_2)^2/\lambda$$



MIMO-RD is larger than MISO-RD

Near-Field MIMO Channel Estimation

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- **The proposed channel estimation scheme based on near-field MIMO channel model**

Received pilot **Transmitted pilot** **Noise**

$$\mathbf{Y}_{N_2\times M} = \mathbf{H}_{N_2\times N_1}\mathbf{P}_{N_1\times M} + \mathbf{N}_{N_2\times M}$$

$$\mathbf{H}_{LOS} + \mathbf{H}_{NLOS}$$

Maximum likelihood

$$\min_{r,\theta,\varphi} \|\mathbf{Y} - \mathbf{H}_{\mathrm{LoS}}(r,\theta,\varphi)\mathbf{P}\|^2$$

$$\mathrm{s.t.}\quad (r,\theta,\varphi) \in \Xi$$

$$\Xi = \{(r,\theta,\varphi)|$$
$$1/r = 1/r_{max}, 1/r_{max} + 1/\Delta r, \cdots, 1/r_{min};$$
$$\theta = \theta_{min}, \theta_{min} + \Delta\theta, \cdots, \theta_{max};$$
$$\varphi = \varphi_{min}, \varphi_{min} + \Delta\varphi, \cdots, \varphi_{max}\}$$

Utilize polar-domain sparsity

Remove $\hat{\mathbf{H}}_{\mathrm{LoS}}$ component:

$$\mathbf{Y}_{\mathrm{NLoS}} = \mathbf{Y} - \hat{\mathbf{H}}_{\mathrm{LoS}}\mathbf{P}$$

Estimate $\mathbf{H}_{\mathrm{NLoS}}$ with $\mathbf{Y}_{\mathrm{NLoS}}$ and $\mathbf{P}$:

$$\mathbf{Y}_{\mathrm{NLoS}} = \mathbf{H}_{\mathrm{NLoS}}\mathbf{P} + \mathbf{N}$$

Vectorize the equation and formulate as sparse signal reconstruction problem with sparse channel $\mathbf{h}^P_{NLOS}$

$$\mathbf{y}_{NLOS} = \mathbf{A}\mathbf{h}^P_{NLOS} + \mathbf{n}$$

Simulation Results

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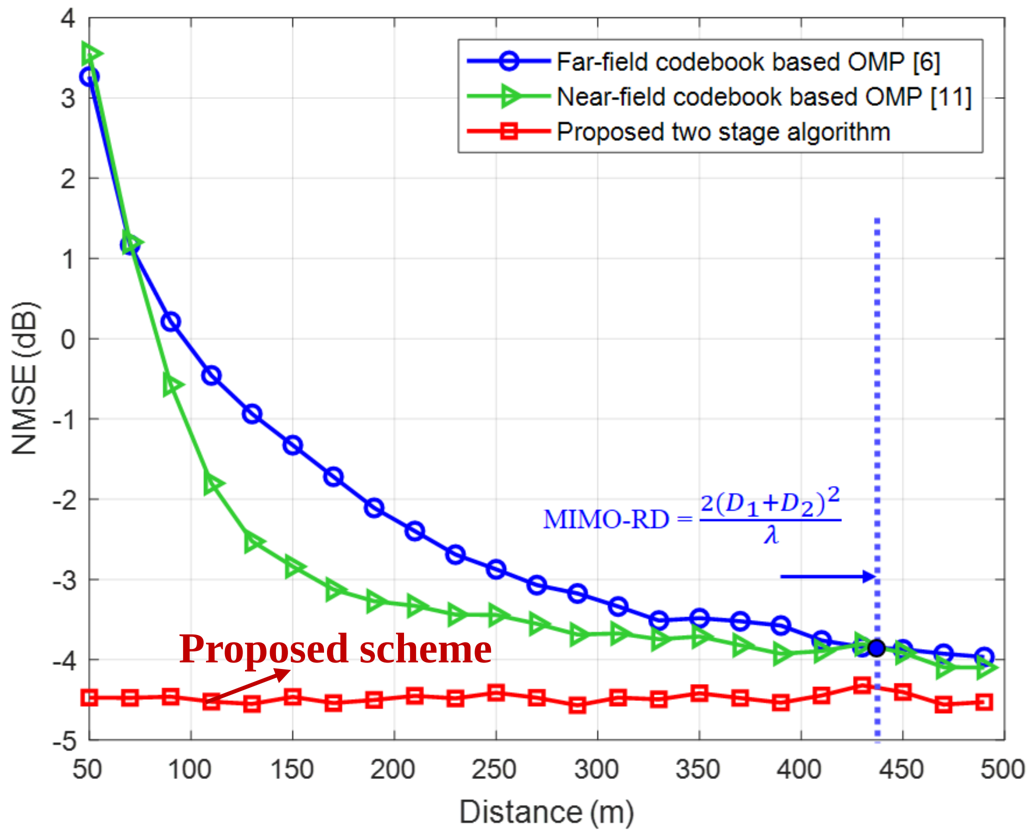
- **The proposed schemes can accurately estimate the near-field MIMO channel.**



Parameters	Value
Carrier	10 GHz
Element number of transmitter antenna array	128
Element number of receiver antenna array	64
Number of NLoS Paths	5
SNR	5 dB
Pilot compression ratio	0.5

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