Location Division Multiple Access for Near-Field Communications

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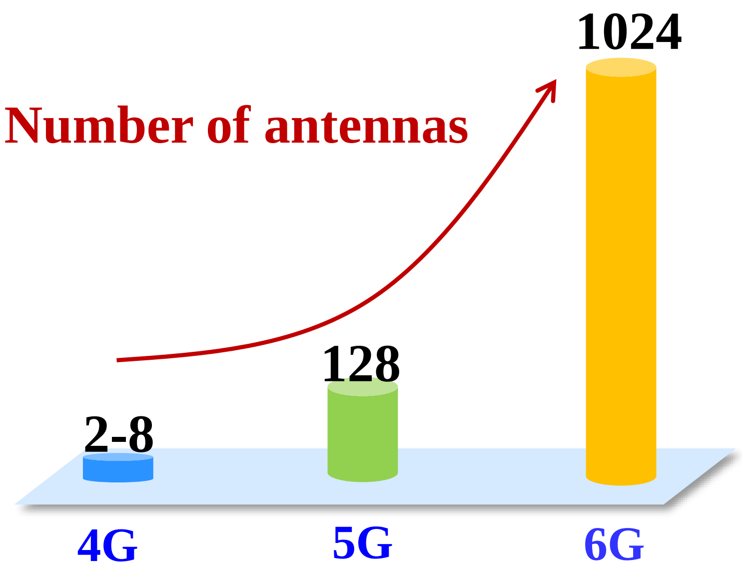
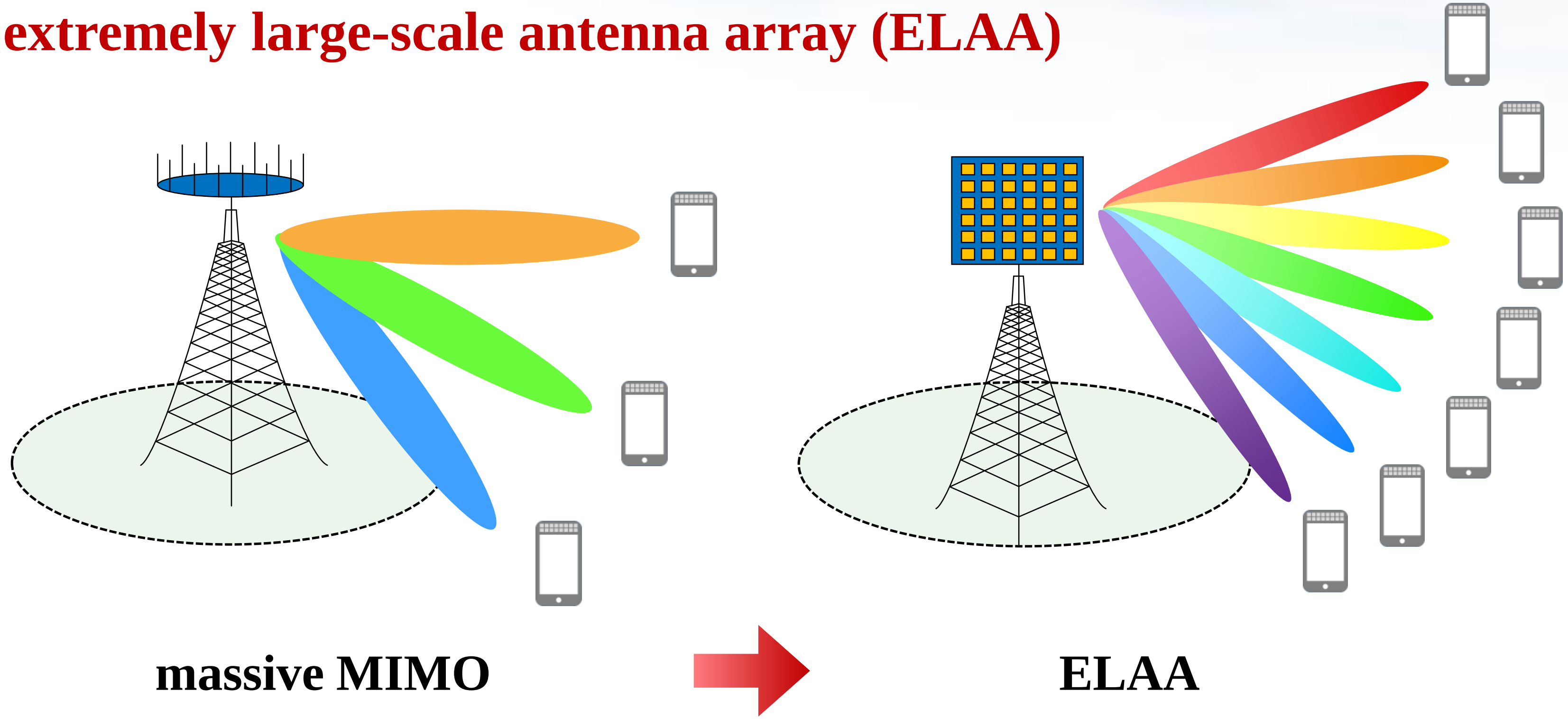
Z. Wu and L. Dai, "Location division multiple access for near-field communications," in *Proc. IEEE Int. Conf. Commun. (IEEE ICC'22)*, Rome, Italy, May, 2023.

Extremely Large-Scale Antenna Array

- 6G is expected to achieve 10 times higher spectral efficiency compared with 5G
- The higher spectral efficiency can be achieved 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**

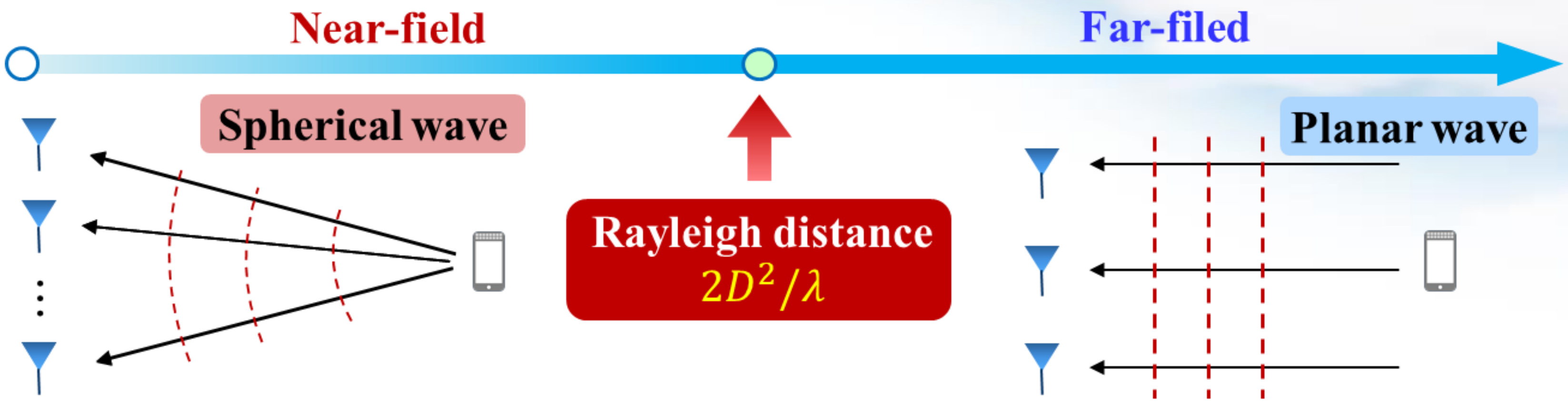


Table I. Near-field region [m] (data from [1])

	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	/	/

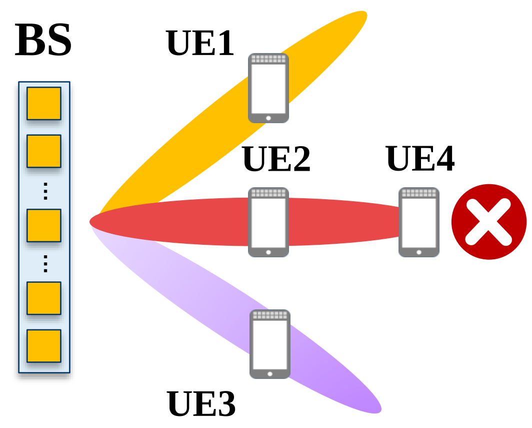
ELAA with 2304 antennas@28GHz, Rayleigh distance is 25 m, Tsinghua [2]

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

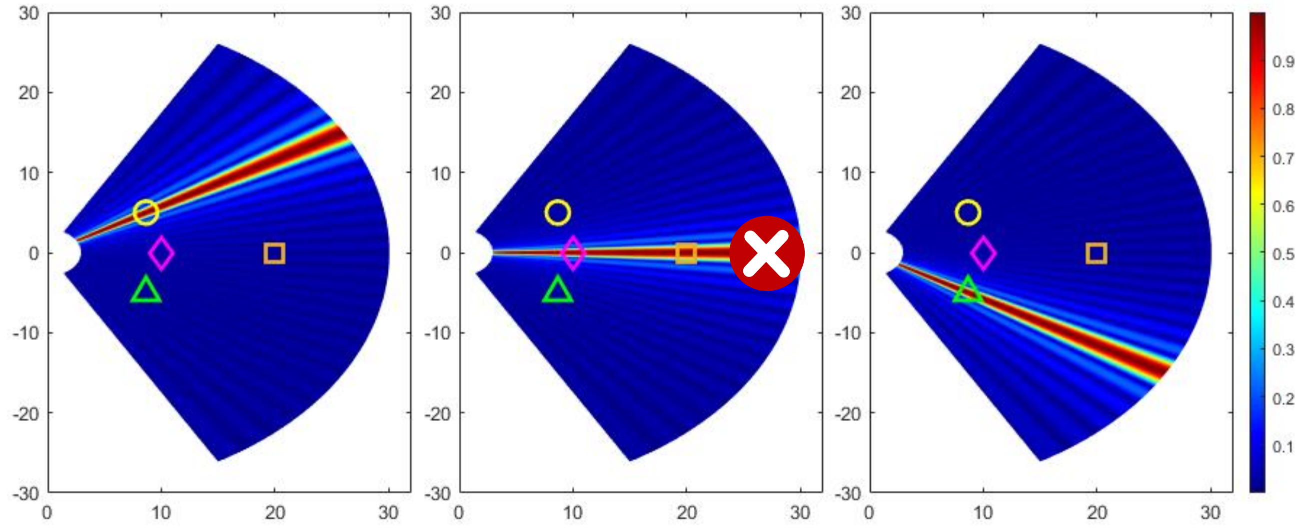
[1] A. Pizzo, L. Sanguinetti, and T. L. Marzetta, "Fourier plane-wave series expansion for holographic MIMO communications," *IEEE Trans. Wireless Commun.*, vol. 21, no. 9, pp. 6890-6905, Sep. 2022.
[2] M. Cui, Z. Wu, Y. Chen, S. Xu, F. Yang, and **L. Dai**, "Demo: Low-power communications based on RIS and AI for 6G," in *Proc. IEEE Int. Conf. Commun. (IEEE ICC'22)*, Seoul, SouthKorea, May 2022. (**IEEE ICC 2022 Outstanding Demo Award**) .

Challenge of SDMA

- **Spatial division multiple access (SDMA) is employed by massive MIMO to multiplex data streams to different users for improving spectral efficiency**
- **In massive MIMO systems, far-field beamsteering vectors only focus on specific angles, which enables the multiple access for users at different angles**



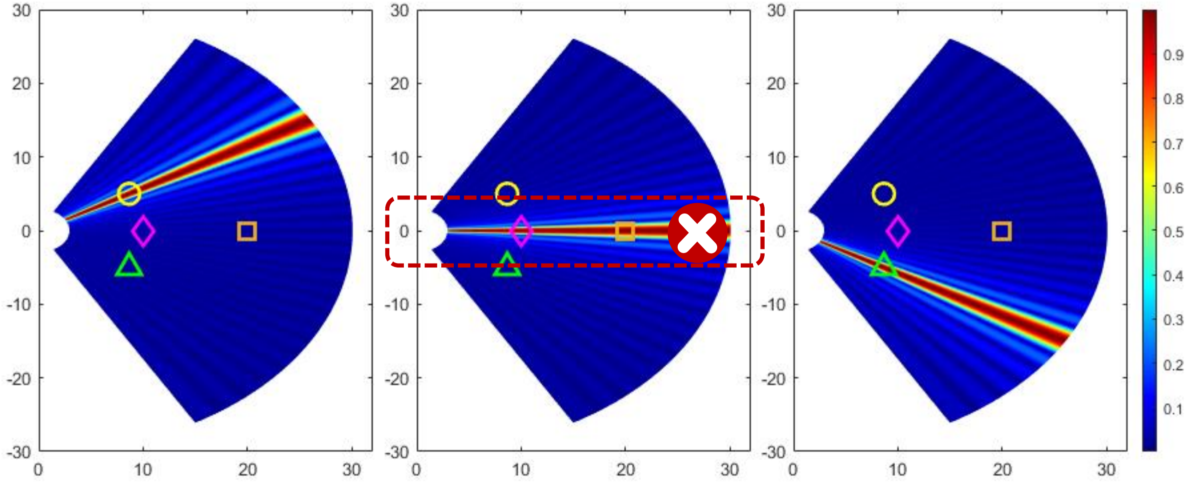
SDMA for far-field communications



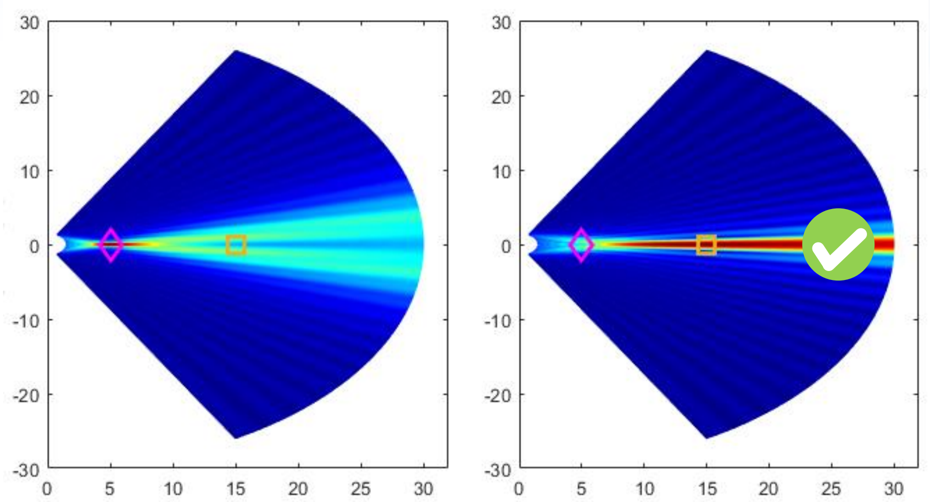
Users at the same angle cannot be simultaneously served by massive MIMO with SDMA

Mitigated Interference with Beamfocusing

- **Far-field beamsteering** vectors focus on specific spatial **angle**
- **Near-field beamfocusing** is capable to focus on specific **location**[1], which could be leveraged to mitigate **inter-user interferences**



Far-field beamsteering



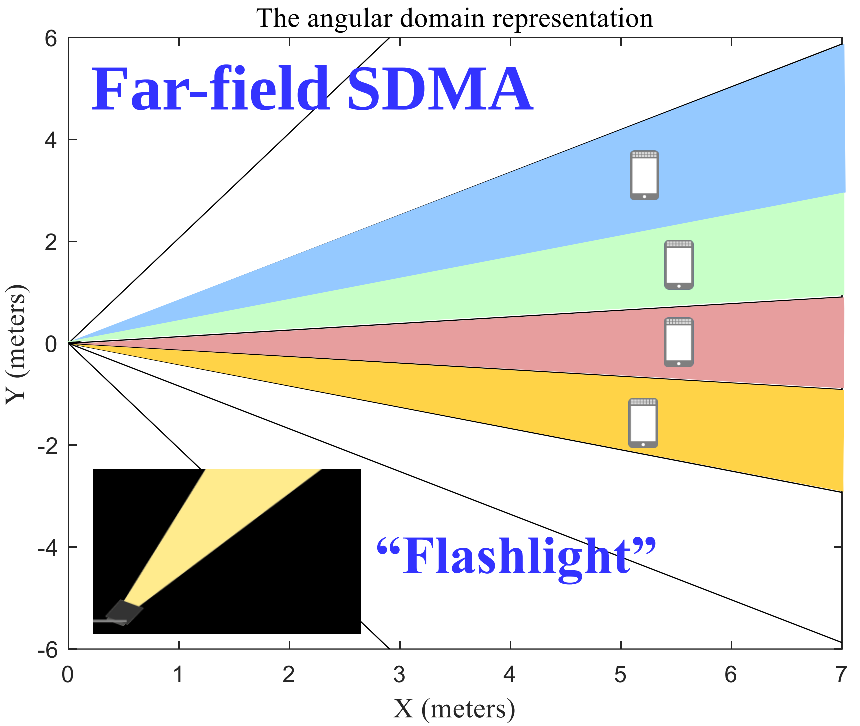
Near-field beamfocusing

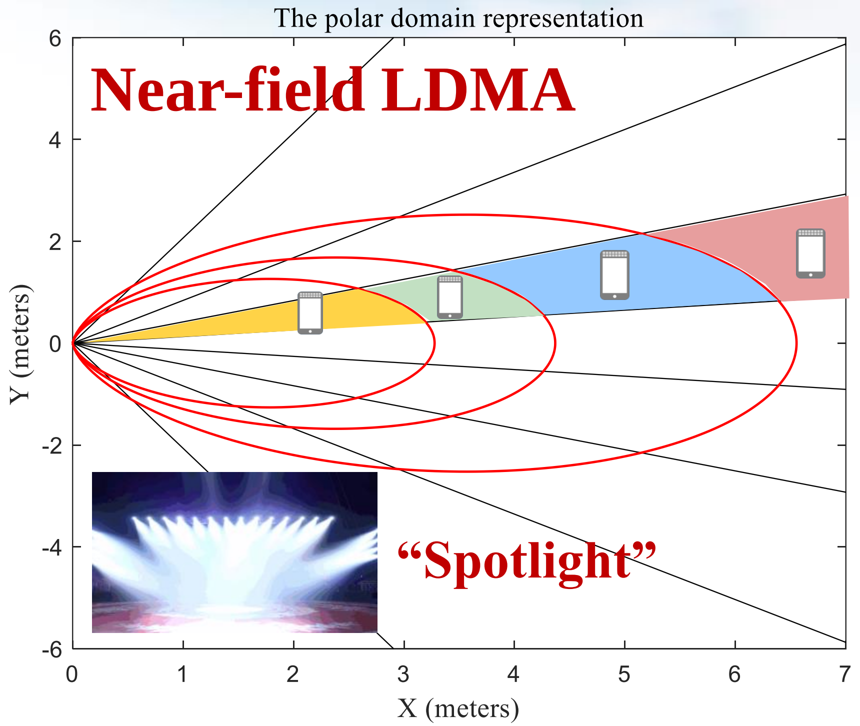
Near-field beamfocusing has the potential to serve users at the same spatial angle

[1] H. Zhang, N. Shlezinger, F. Guidi, D. Dardari, M. F. Imani and Y. C. Eldar, "Beam focusing for near-field multiuser MIMO communications," *IEEE Trans. Wireless Commun.*, vol. 21, no. 9, pp. 7476-7490, Sept. 2022.

Multiple Access in Near-Field: SDMA or LDMA?

- **Far-field SDMA: Users at different angles can be served by orthogonal far-field beams**
- **Near-field location division multiple access (LDMA): Users at different locations can be simultaneously served due to property of near-field beam focusing**





Compared with far-field SDMA, near-field LDMA provides a new possibility for capacity improvement

[1] Z. Wu and L. Dai, "Location division multiple access for near-field communications," in *Proc. IEEE Int. Conf. Commun. (IEEE ICC'22)*, Rome, Italy, May, 2023.

Far-Field vs. Near-Field

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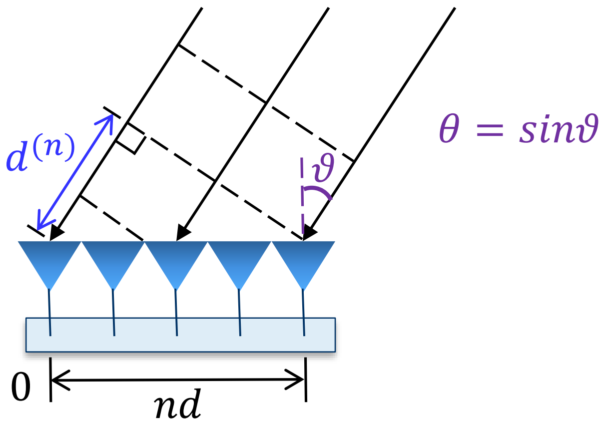
- **Far-field: the EM waves impinging on the antenna array can be approximately modeled as planar waves, where the phase of the EM wave is a linear function of the antenna index**
- **Near-field: the EM waves have to be accurately modeled as spherical waves, where the phase of the EM wave is a non-linear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

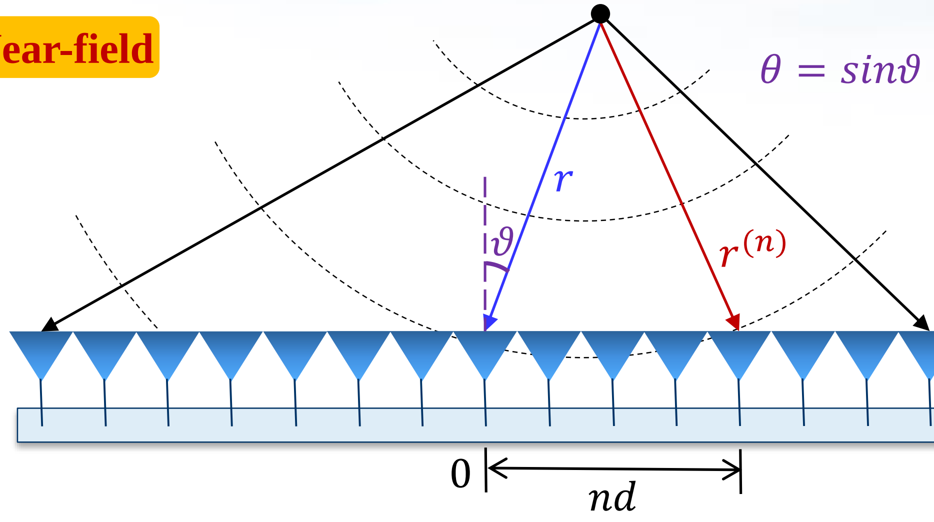
Far-field



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

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

Near-field



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

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

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

Near-Field LoS Channel Model

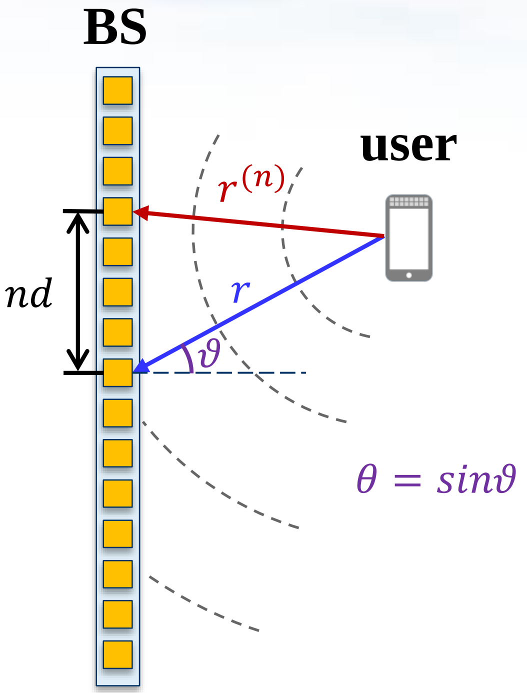
- **Base station (BS) antenna number $M = 2N + 1$, antenna spacing $d = \lambda/2$, array aperture $D = (M-1)d$, the location of the n-th antenna is $(0, nd)$, where $n \in [-N, \cdots, 0, \cdots, N]$**
- **The channel between the n-th antenna and the user located at $(r\cos\vartheta, r\sin\vartheta)$ is**

$$h_n = \tilde{g}_n e^{-j\frac{2\pi}{\lambda}r^{(n)}} = g_n e^{-j\frac{2\pi}{\lambda}\left(r^{(n)}-r\right)}$$

Complex gain ($\tilde{g}_n$)

$g_n = \tilde{g}_n e^{j\frac{2\pi}{\lambda}r}$

Near-field phase ϕ_n ($\frac{2\pi}{\lambda}\left(r^{(n)}-r\right)$)



- **Generally, the complex gains are very similar when $r > 1.2D$**

$$g_{-N} \approx \cdots \approx g_0 \approx \cdots \approx g_N \approx g$$

- **Therefore, the LoS channel is**

$$\boldsymbol{h} = [h_{-N}, \cdots, h_0, \cdots, h_N]^T = g\left[e^{-j\frac{2\pi}{\lambda}\left(r^{(-N)}-r\right)}, \cdots, e^{-j\frac{2\pi}{\lambda}\left(r^{(N)}-r\right)}\right]^T$$

$$= g\boldsymbol{a}(r, \theta)$$

Near-field array response vector ($\boldsymbol{a}(r, \theta)$)

[1] E. Björnson, Ö. T. Demir, and L. Sanguinetti, "A primer on near-field beamforming for arrays and reconfigurable intelligent surfaces," in *Proc. 2021 55th Asilomar Conference on Signals, Systems, and Computers*, pp. 105-112, Oct. 2021.

Beamfocusing of Near-Field Beams

Lemma 1: The normalized array gain achieved by $\boldsymbol{w} = \boldsymbol{a}^*(\bar{r}, \theta)$ at any user location (r, θ) is obtained through Fresnel approximation as

$$f(r, \bar{r}, \theta) = |\boldsymbol{a}^H(\bar{r}, \theta)\boldsymbol{a}(r, \theta)| \frac{1}{M}\left|\sum_{n=-N}^{N} e^{jk\left(\bar{r}^{(n)} - r^{(n)}\right)}\right| \approx |G(\beta)| = \left|\frac{C(\beta) + jS(\beta)}{\beta}\right|$$

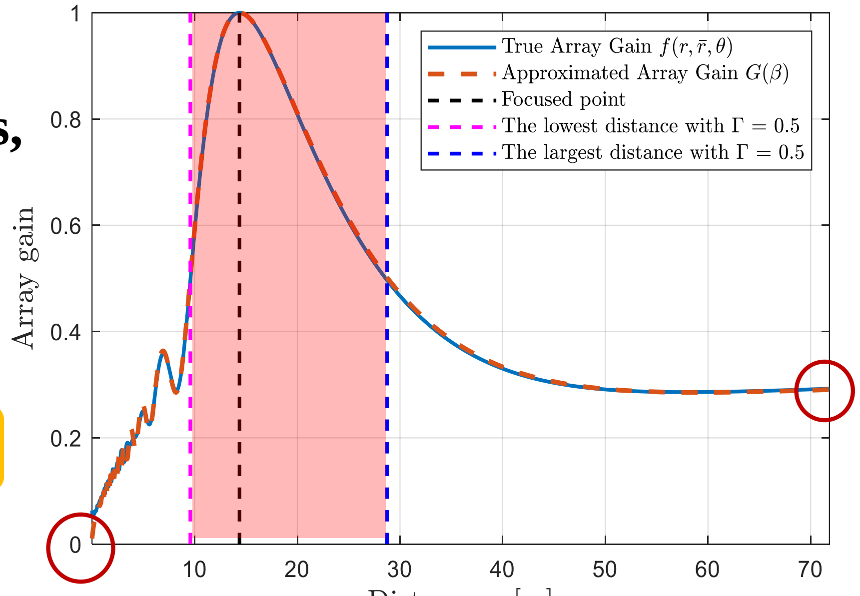
where $\beta = \sqrt{\frac{M^2 d^2 (1-\theta^2)}{2\lambda}\left|\frac{1}{r} - \frac{1}{\bar{r}}\right|}$, $C(\beta) = \int_0^\beta \cos\left(\frac{\pi}{2}t^2\right)\mathrm{d}t$ **and** $S(\beta) = \int_0^\beta \sin\left(\frac{\pi}{2}t^2\right)\mathrm{d}t$ **are Fresnel functions.**

- **Beamfocusing property of near-field beams**
  - **Similar to the beam-width in angular domain of far-field beams, near-field beams possess depth-of-focus[1] in distance domain**

3dB range: $r \in \left[\frac{\bar{r}D^2(1-\theta^2)}{D^2(1-\theta^2) + 2\lambda\beta_\Gamma^2\bar{r}}, \frac{\bar{r}D^2(1-\theta^2)}{D^2(1-\theta^2) - 2\lambda\beta_\Gamma^2\bar{r}}\right]$

$G(\beta_\Gamma) = 0.5$

3dB depth-of-focus: $r_d = \frac{4\lambda\beta_\Gamma^2\bar{r}^2 D^2(1-\theta^2)}{D^4(1-\theta^2)^2 - 4\lambda^2\beta_\Gamma^4\bar{r}^2}$



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Asymptotic Orthogonality in Distance

- **Far-field orthogonality in angular domain**

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

  Correlation: $f^{\text{far}} = |\mathbf{a}^H(\theta_1)\mathbf{a}(\theta_2)| = \frac{1}{N}\left|\frac{\sin(\frac{1}{2}Nkd(\sin\theta_1 - \sin\theta_2))}{\sin(\frac{1}{2}kd(\sin\theta_1 - \sin\theta_2))}\right|$

  As $N \to \infty$, interference from different angles $I^{\text{far}} \to 0$ $(\theta_1 \neq \theta_2)$

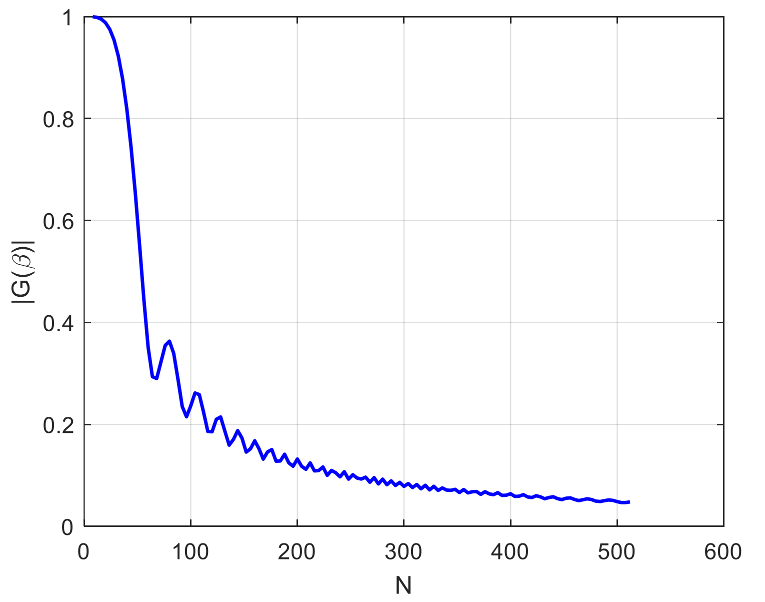
- **Lemma 2: Near-field orthogonality in distance domain**

  Phase: $\phi_n^{\text{near}}(\theta) = -\frac{2\pi}{\lambda} n d \theta + \frac{1-\theta^2}{\lambda r}\pi n^2 d^2$

  Correlation: $f^{\text{near}} = |\mathbf{a}^H(\theta, r_1)\mathbf{a}(\theta, r_2)| \approx |G(\beta)| = \left|\frac{C(\beta)+jS(\beta)}{\beta}\right|$

  where $\beta = \sqrt{\frac{N^2 d^2 (1-\theta^2)}{2\lambda}\left|\frac{1}{r} - \frac{1}{\bar{r}}\right|}$

  As $N \to \infty$, interference from different distances $I^{\text{near}} \to 0$ $(\forall \theta, r_1 \neq r_2)$



General Form of Asymptotic Orthogonality

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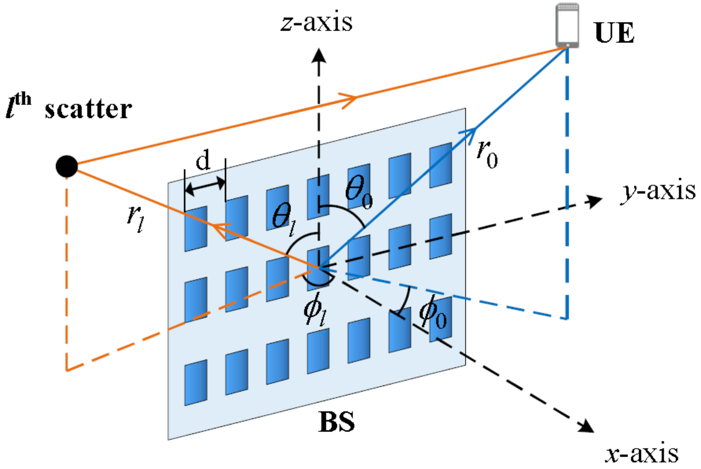
- **Corollary 2: Near-field beam focusing vectors on different angles or distances are asymptotically orthogonal with the increasing number of antennas**

$$\lim_{N\to+\infty} |\mathbf{a}^H(r_l,\theta_l)\mathbf{a}(r_m,\theta_m)| = 0, \qquad \text{for } r_l \neq r_m \text{ or } \theta_l \neq \theta_m$$



- **Lemma 3: Orthogonality of UPA in the distance domain**

Phase: $\phi_n^{\text{near}}(\theta,\phi) = -n_1 d\cos(\theta) - n_2 d\sin\theta\sin\phi + \frac{n_1^2 d^2}{2r}(1-\cos\theta)$

$$+\frac{n_2^2 d^2}{2r}(1-\sin^2\theta\sin^2\phi) - \frac{n_1 n_2 d^2\cos\theta\sin\theta\sin\phi}{r}$$

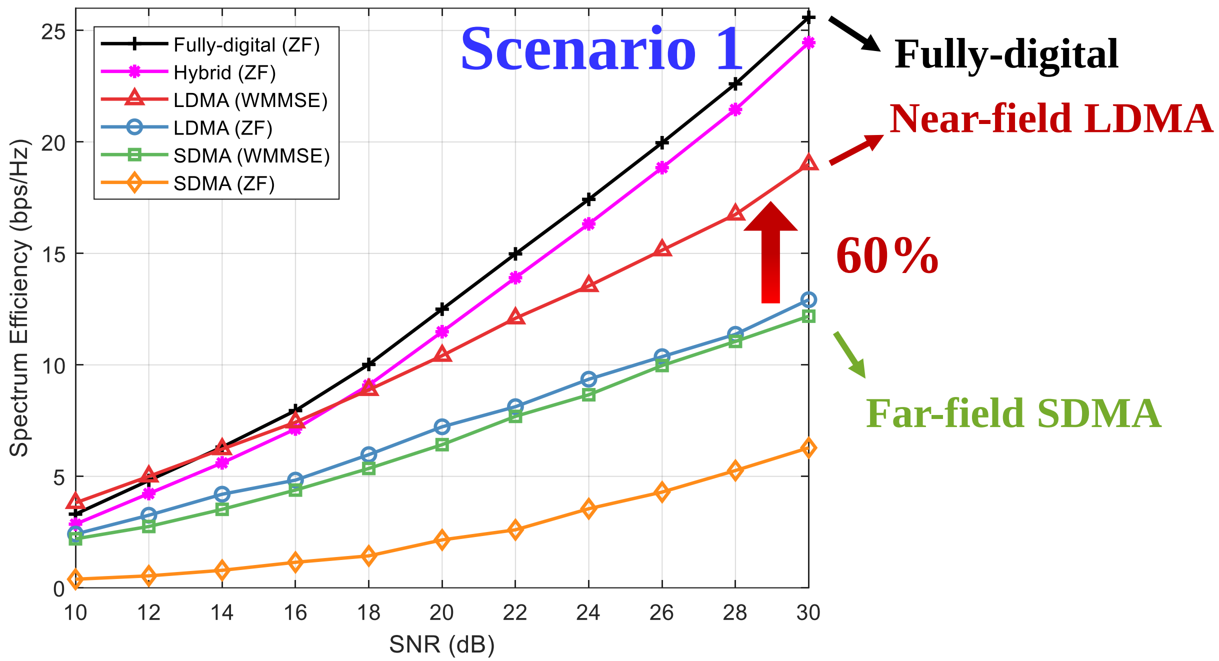
Correlation: $f^{\text{near}} = |\mathbf{a}^H(\theta,\phi,r_1)\mathbf{a}(\theta,\phi,r_2)|$

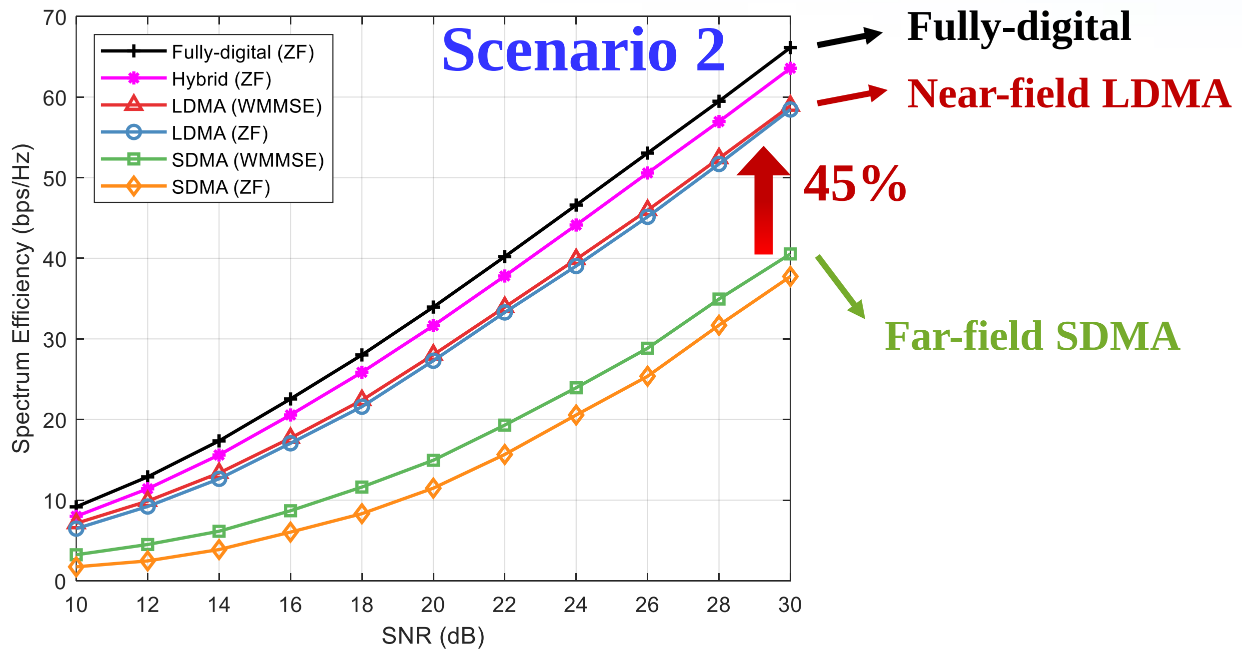
As N_1 or $N_2 \to \infty$, interference from different distances $f \to 0$ $(r_1 \neq r_2)$

Simulation Results for LDMA

- Scenario 1: Users are **linearly distributed** along the same direction
- Scenario 2: Users are **uniformly distributed** within a cell

BS Antennas	UE Antennas	Frequency	UE Numbers	Elevation/ Azimuth Angle Range	Distance Range
256	1	30 GHz	20	$[-\pi/2, \pi/2]$	[4m, 100m]





[1] Z. Wu and L. Dai, "Location division multiple access for near-field communications," in *Proc. IEEE Int. Conf. Commun. (IEEE ICC'22)*, Rome, Italy, May, 2023.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