IEEE GLOBECOM®
IEEE Global Communications Conference
4-8 December 2023 // Kuala Lumpur, Malaysia
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Near-Field 2D Hierarchical Beam Training for Extremely Large-Scale MIMO

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Dec 07, 2023

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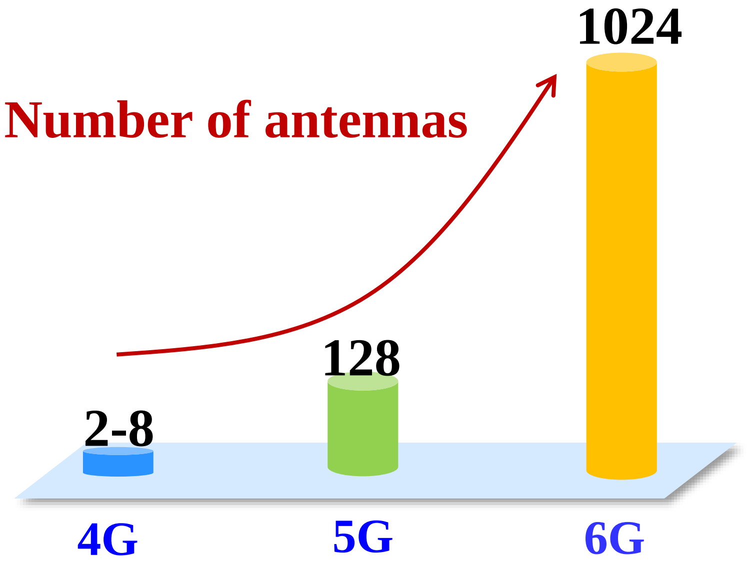
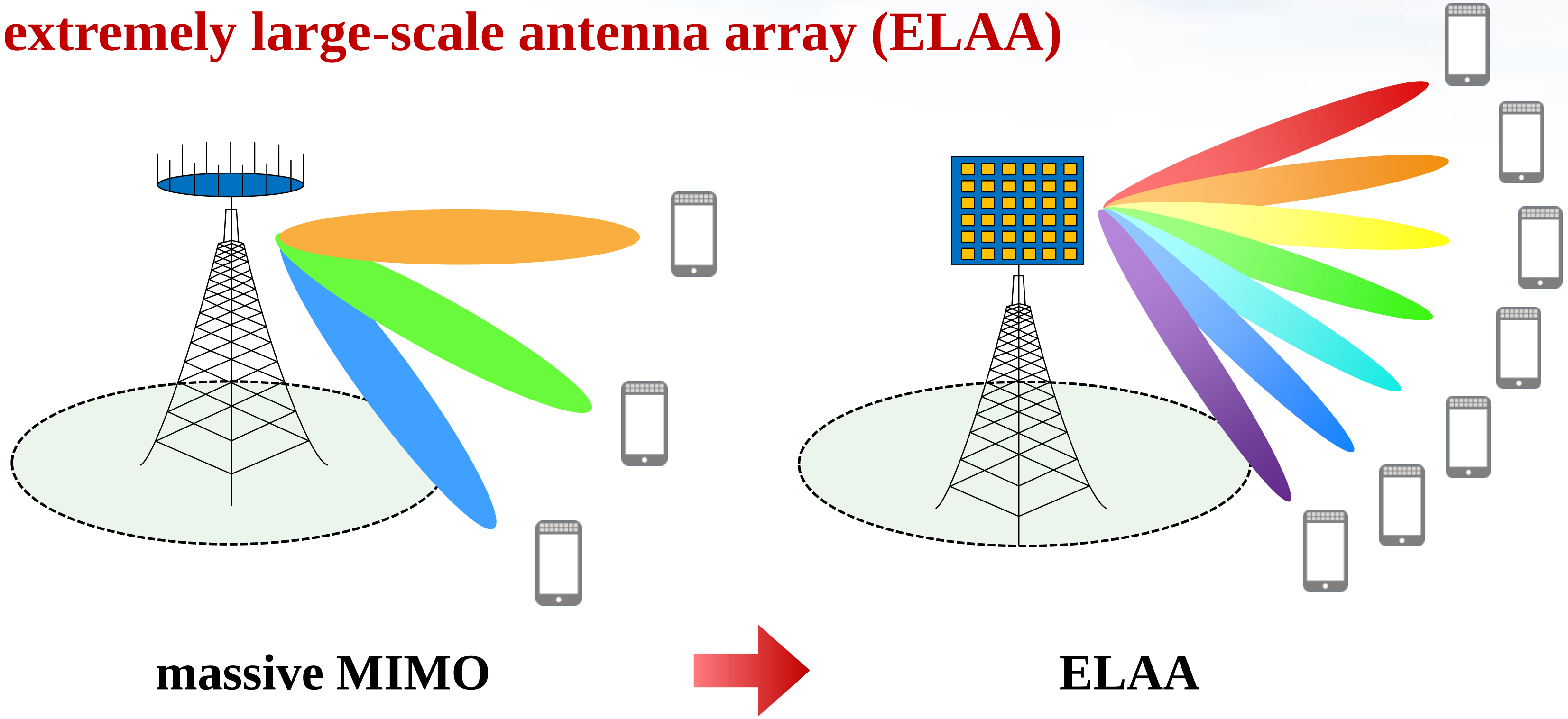
Extremely Large-Scale Antenna Array

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

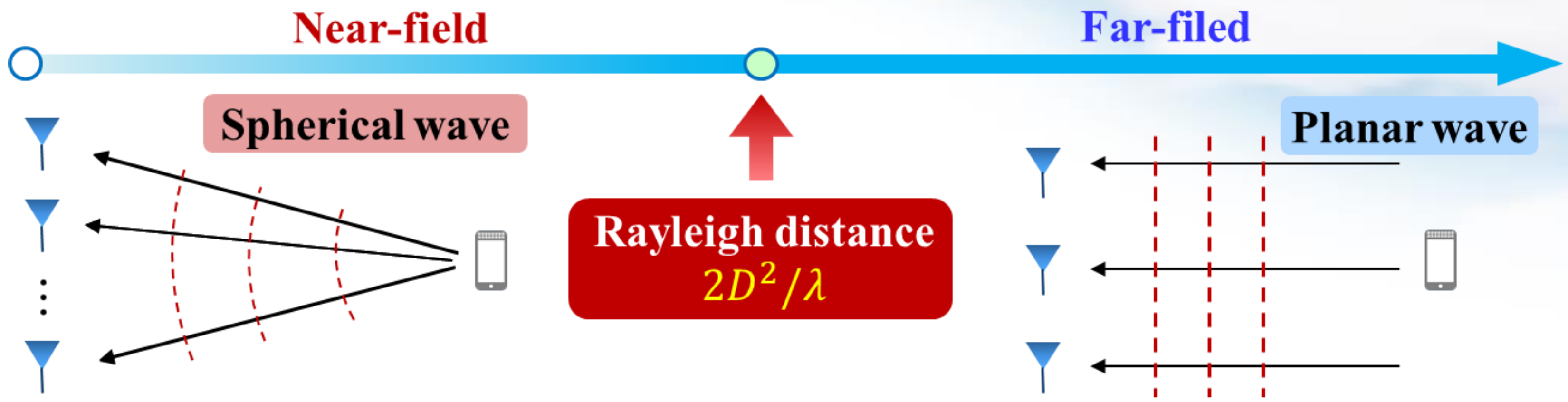




[1] W. Jiang, B. Han, M. A. Habibi and H. D. Schotten, "The Road Towards 6G: A Comprehensive Survey," *IEEE Open J. Commun. Soc.*, vol. 2, pp. 334-366, Feb. 2021.

Near-Field for ELAA

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



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

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	/	/

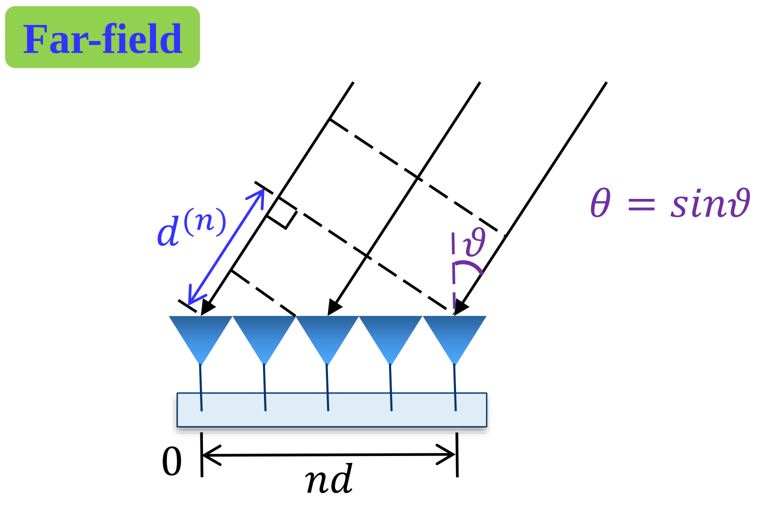
Evolution from massive MIMO to extremely large-scale array results in the near-field propagation

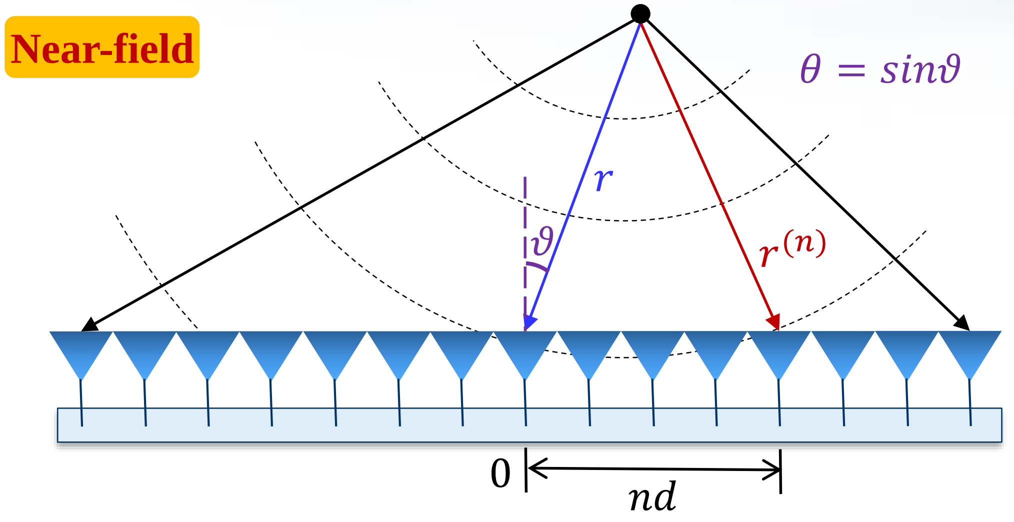
[1] A. Pizzo, L. Sanguinetti, and T. L. Marzetta, "Fourier plane-wave series expansion for holographic MIMO communications," *IEEE Trans. Wireless Commun.*, vol. 21, no. 9, pp. 6890-6905, Sep. 2022.

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

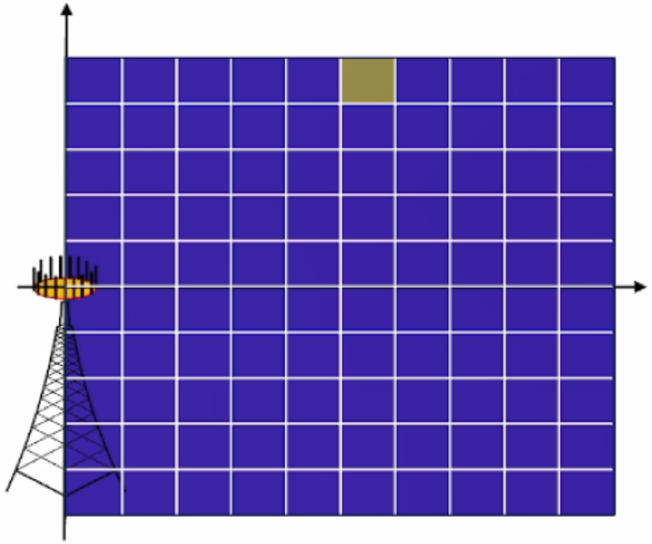
Distance: $r^{(n)} = \sqrt{r^2 + n^2d^2 - 2ndr\theta}$ **Non-linear**

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:** $M = 2N + 1$

The Challenge of Near-Field Beam Training

- **Beam training is an essential method is acquire the channel state information (CSI)**
- **However, since the near-field codebook requires extra grids on the distance domain, its codebook size is much larger than that of the far-field codebook**



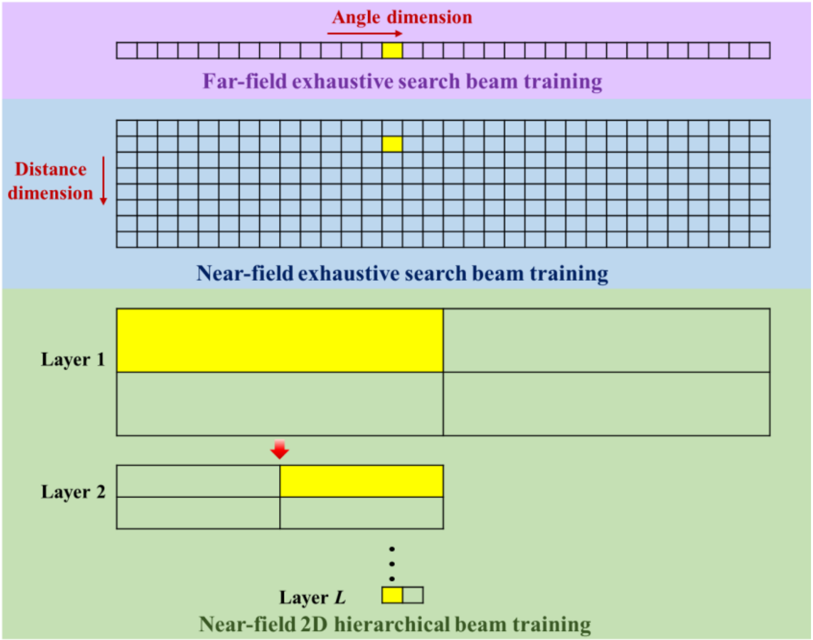
Exhaustive search

Parameters	Far-field codebook	Near-field codebook
Number of antennas	512	512
Carriers	100 GHz	100 GHz
Number of angle grids	512	512
Number of distance grids	1	20
Codebook size	512	10240

The overhead of near-field exhaustive beam training is unaffordable

Near-Field Hierarchical Beam Training

- Low-resolution beam covers a wider range of angle and distance, and each layer of codebook narrows the search range gradually
- Perform binary search on **both angle and distance** simultaneously



Comparisons of beam training schemes

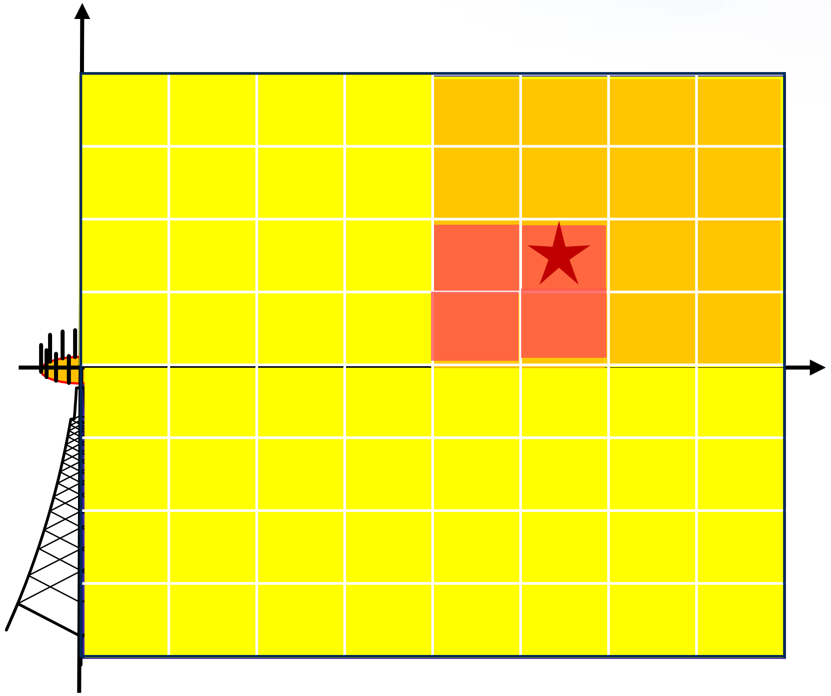


Illustration of near-field hierarchical beam training

N: number of angle grids
S: number of distance grids

	Complexity
near-field	$\mathcal{O}(NS)$
far-field	$\mathcal{O}(\log(N) + \log(S))$

Near-Field Multi-Resolution Codeword Design

- The aim to design a codeword $\mathbf{v}$ is to approach the ideal beam pattern after beamforming with $\mathbf{v}$

codeword needed to be designed

ideal beam pattern

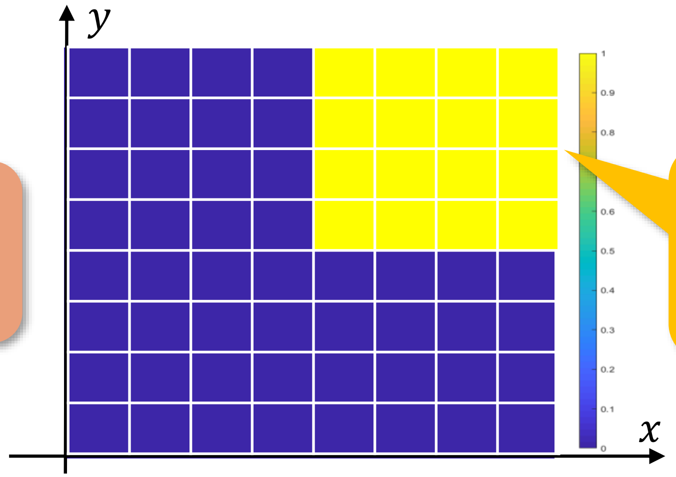
$$\min_{\mathbf{v}, f(\theta, r)} \|\mathbf{A}^H \mathbf{v} - \mathbf{g}\|_2^2 \qquad \mathbf{A} \triangleq \sqrt{N}\left[\mathbf{a}(\theta_1, r_1), \cdots, \mathbf{a}(\theta_N, r_{S_N})\right]$$

$$\text{s.t.} \quad \|\mathbf{v}\|_2 = 1;$$

$$[\mathbf{g}]_{\theta, r} = |G(\theta, r)| \, e^{jf(\theta, r)}$$

additional phase: increase design freedom

ideal beam pattern



Target coverage $B_{\theta,r}$

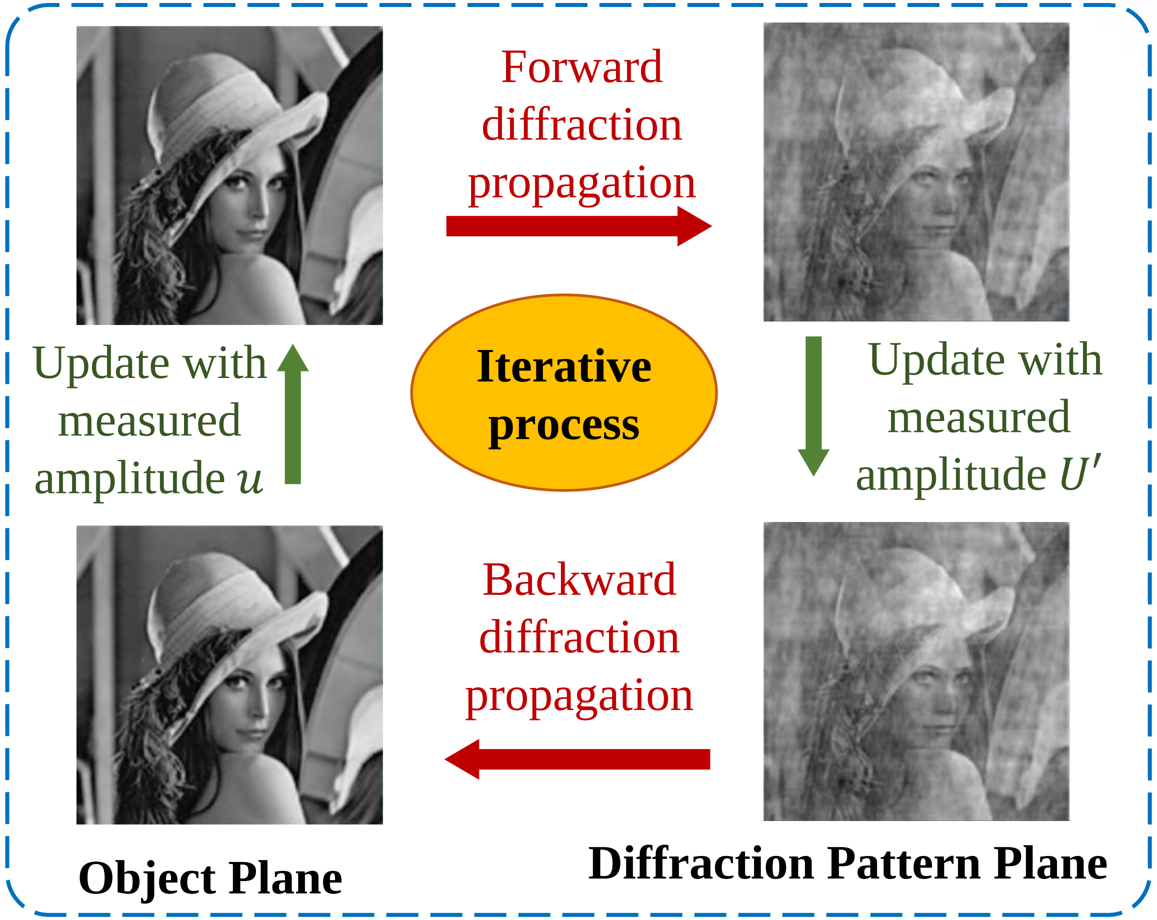
$$|G(\theta, r)| = \begin{cases} \sqrt{C}, & (\theta, r) \in B_{\theta,r} \\ 0, & (\theta, r) \notin B_{\theta,r} \end{cases}$$

beamforming gains in target coverage are flattened

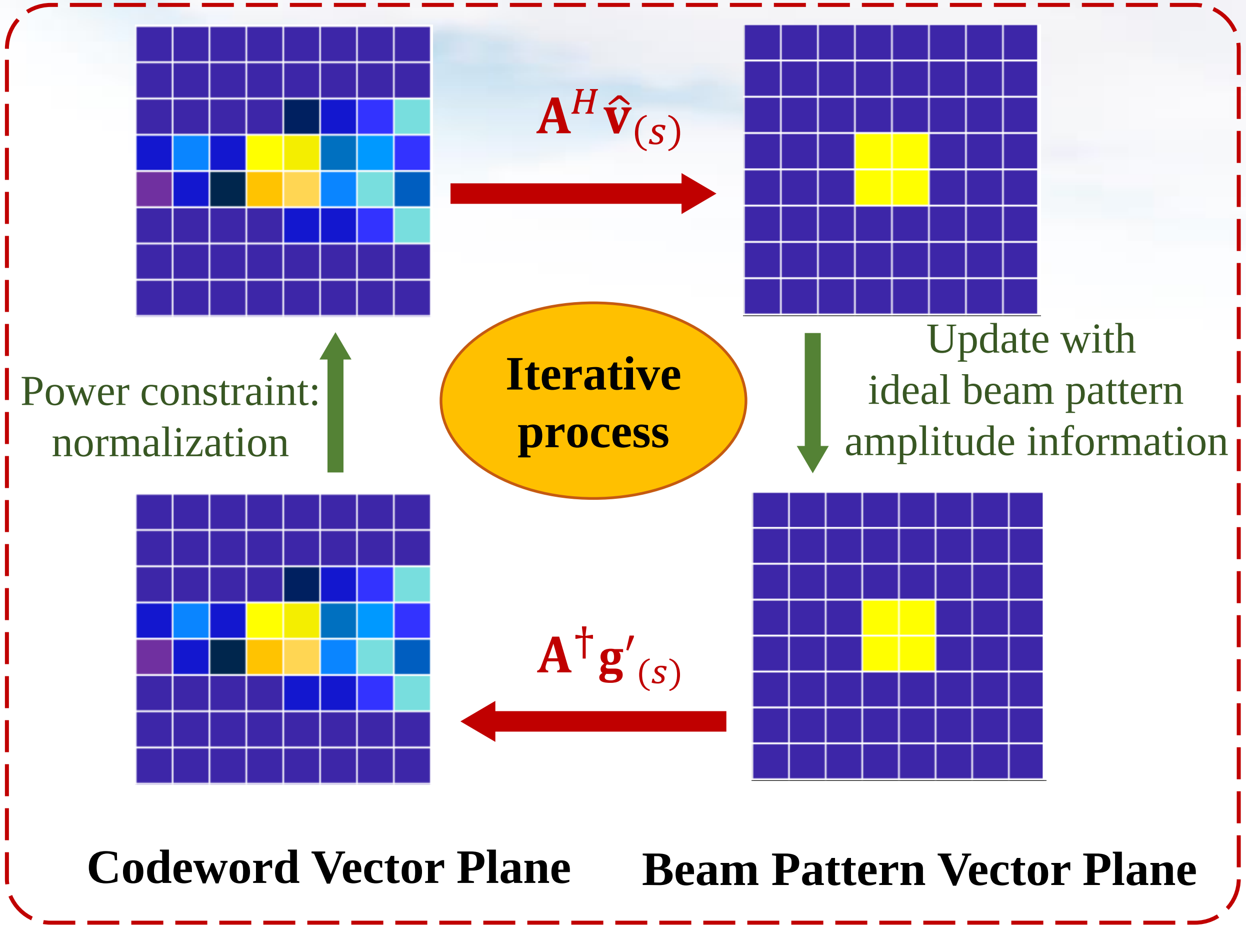
beamforming gains outside target coverage are zero

GS（Gerchberg-Saxton）Algorithm

- **Phase recovery in holographic imaging ≜ designing near-field multi-resolution codewords**



(a) GS algorithm in iterative phase retrieval problem.



(b) GS algorithm in codeword design.

Simulation Results: Beam Pattern

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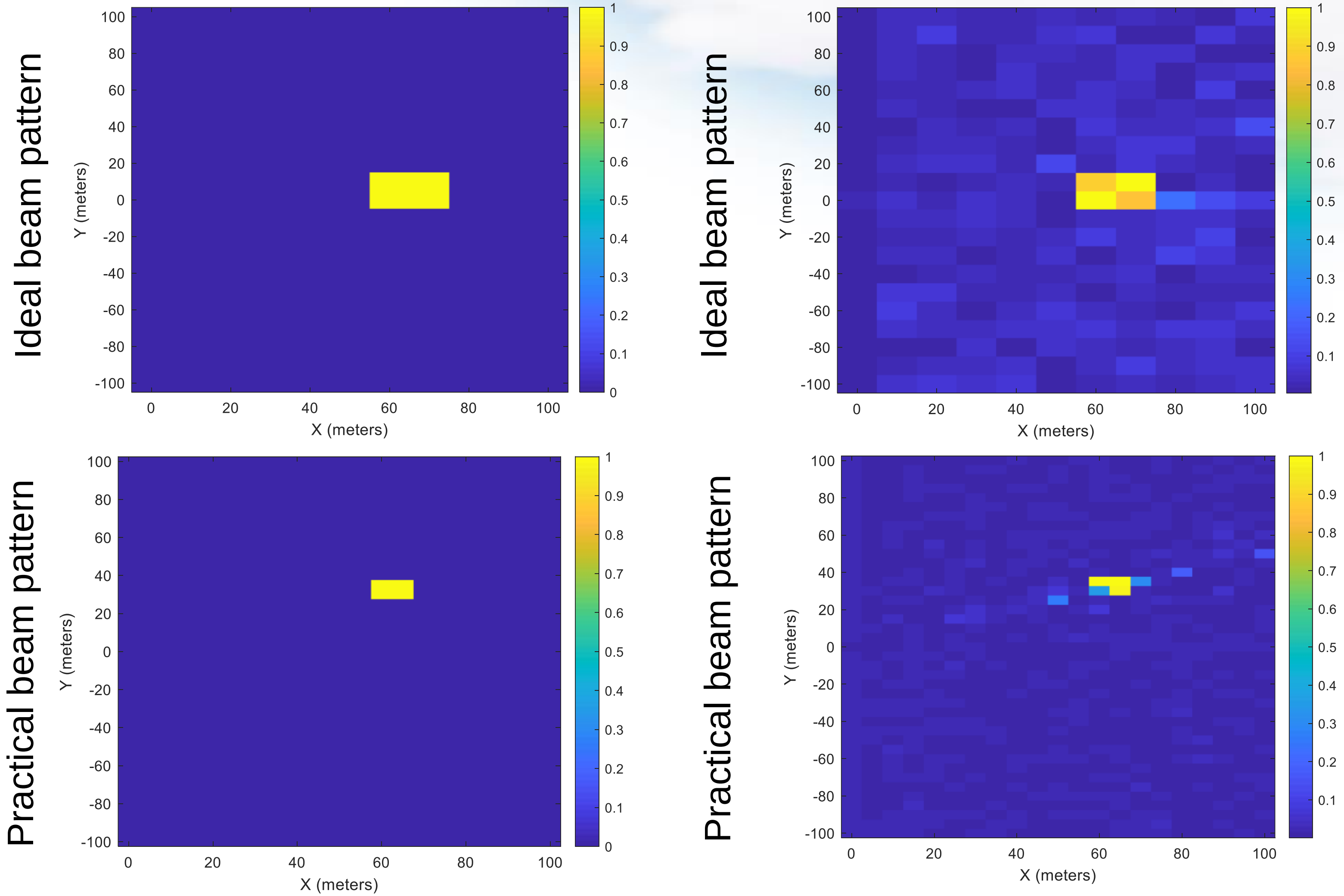
- **The practical beam pattern approach the ideal beam pattern**

Low-resolution beam: cover wider range

High-resolution beam: cover wider range



Simulation Results: Achievable Rate

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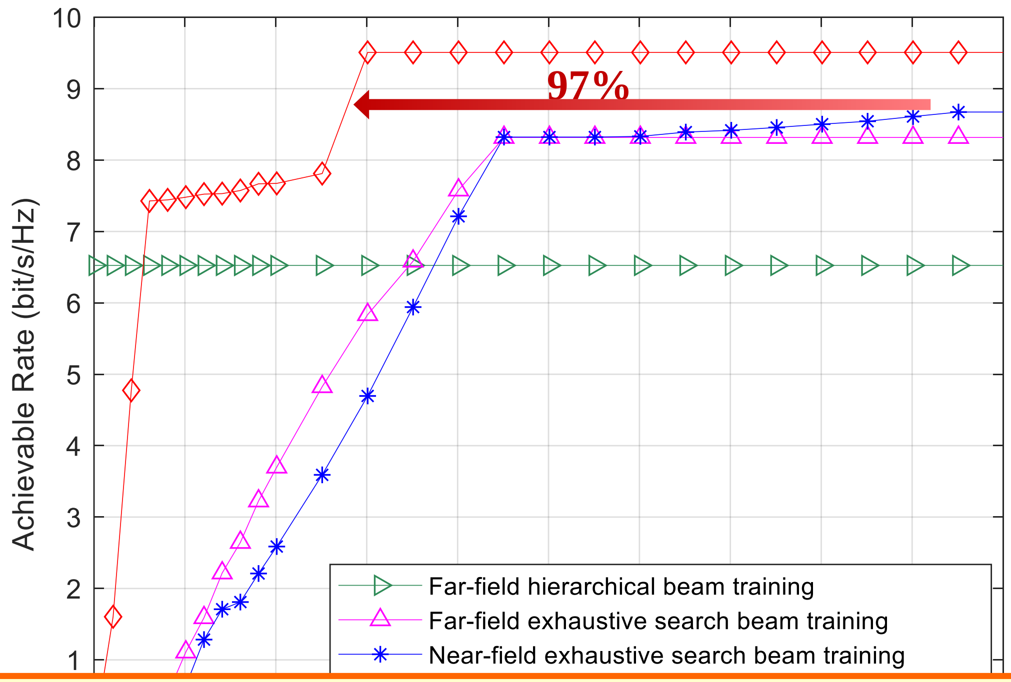
- **The proposed scheme provides a tradeoff between the performance and overhead**



Scheme	Overhead
Near-field exhaustive search beam training	8192
Proposed near-field 2D hierarchical beam training	268

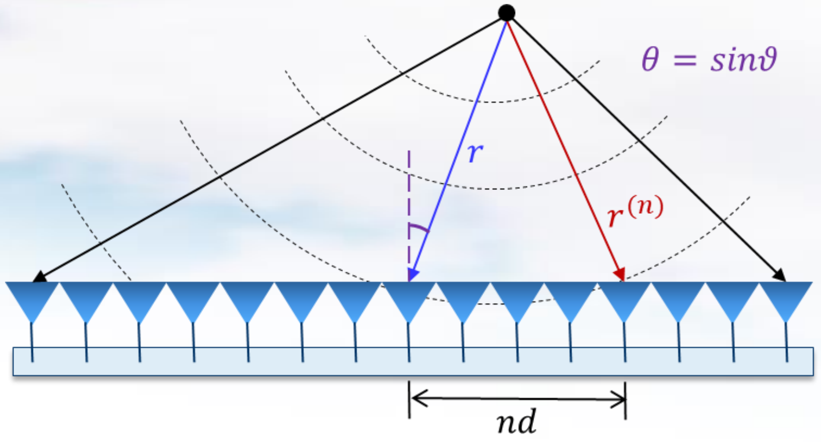
Parameters	Value
Number of antennas	512
Carrier	60GHz
Number of angle grids	512

[1] Y. Lu, Z. Zhang and L. Dai, "Near-Field 2D Hierarchical Beam Training for Extremely Large-Scale MIMO," ***in Proc. 2023 IEEE Global Commun. Conf. (IEEE GLOBECOM'23)***, Kuala Lumpur, Malaysia, Dec. 2023.

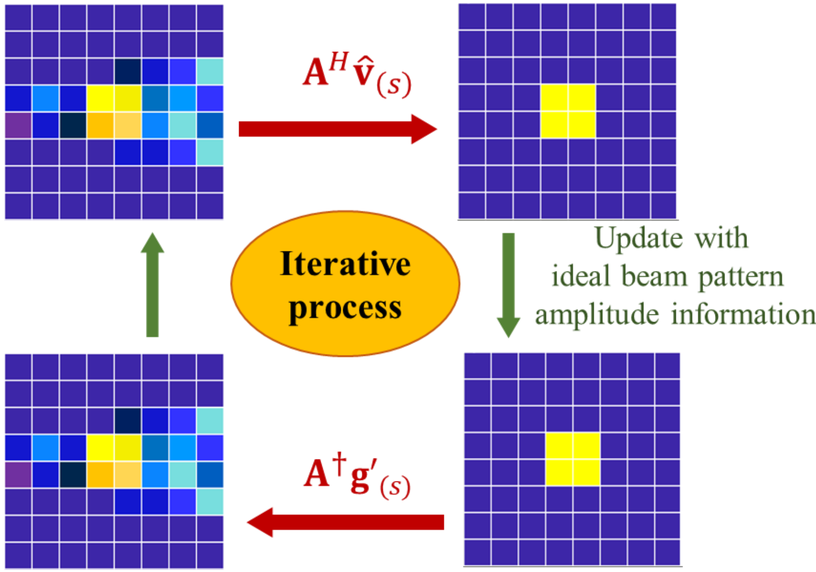
[2] Y. Lu, Z. Zhang and L. Dai, "Hierarchical Beam Training for Extremely Large-Scale MIMO: From Far-Field to Near-Field," ***IEEE Trans. Commun.***, 2023. (Major Revision)

Summary

- **Background**
  - ➢ **ELAA results in near-field propagation**
  - ➢ **Near-field beam training needs extra grids in distance-domain**



- **Solutions**
  - ➢ **2D hierarchical beam training: perform the binary search on both angle and distance simultaneously**
  - ➢ **Low-resolution near-field beam design: Holographic imaging inspired method**



- **Results**
  - ➢ **Reduce the overhead by 97% compared to near-field exhaustive search beam training**

Near-Field 2D Hierarchical Beam Training for Extremely Large-Scale MIMO

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Abstract

Extremely large-scale MIMO (XL-MIMO) is a promising technique for future 6G. The sharp increase of the number of antennas causes the electromagnetic propagation to change **from far-field to near-field**. Due to the near-field effect, the exhaustive near-field beam training at all angles and distances requires **very high overhead**. In this paper, we propose a near-field **two dimension (2D) hierarchical beam training** scheme to reduce the overhead without need of extra hardware circuits. Specifically, we first formulate the multi-resolution near-field codewords design problem covering different angle and distance coverages. Next, **inspired by phase retrieval problems** in digital holography imaging technology, we propose a Gerchberg-Saxton (GS)-based algorithm to acquire the theoretical codeword by considering the ideal fully digital architecture. Based on the theoretical codeword, an alternating optimization algorithm is then proposed to acquire the practical codeword by considering the hybrid digital-analog architecture. Finally, with the help of multi-resolution codebooks, we propose a near-field 2D hierarchical beam training scheme to significantly reduce the training overhead.

Near-field communications

The electromagnetic field can be divided into two regions, i.e., the far-field region and the near-field region as shown in Fig.1. The boundary between these two regions is the **Rayleigh distance**, i.e., $Z = 2D^2/\lambda$, which is proportional to the square of the array aperture and inversely proportional to the wavelength. As the antenna number dramatically increases in XL-MIMO systems, the near-field range will expand by orders of magnitude, which can be up to several hundreds of meters.

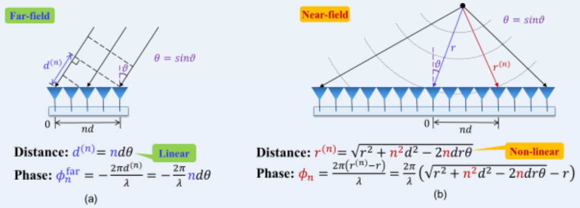

Fig. 1 Two electromagnetic fields.

Near-field 2D beam training

To realize spatial multiplexing gain by reliable beamforming, beam training should be conducted to search the optimal beamforming vector, i.e., codeword, in the predefined codebook. For the near-field beam training, the array response vector of the near-field channel is not only related to the angles but also to distances. Thus, to capture the physical angle as well as distance information of the channel paths, a polar-domain codebook should be utilized instead of DFT codebook. Accordingly, the size of the polar-domain codebook is the product of the antenna number at BS and the number of sampled distances. Since only one angle and one distance can be measured in each time slot, the exhaustive search method for near-field beam training has a **very high overhead** as shown in Table I.

Table I. Comparisons of codebooks

Parameters	Far-field codebook	Near-field codebook
Number of antennas	512	512
Carriers	100 GHz	100 GHz
Number of angle grids	512	512
Number of distance grids	1	20
Codebook size	512	10240

In order to obtain the tradeoff between the near-field beam training overhead and the performance, one of the method is to apply a hierarchical near-field codebook, which consists of **multi-resolution** sub-codebooks. The sizes of sub-codebooks are determined by the angle sample step and distance sample step of the codebook. Specifically, as the increase of the angle sample step and distance sample step, the corresponding codeword has a lower resolution, and the size of the corresponding sub-codebook becomes smaller. These sub-codebooks are applied to conduct near-field 2-dimension (2D) hierarchical beam training. Compared with far-field scenario, the near-field 2D hierarchical beam training need to reduce the search range of angle and distance at the same time as shown in Fig. 2.

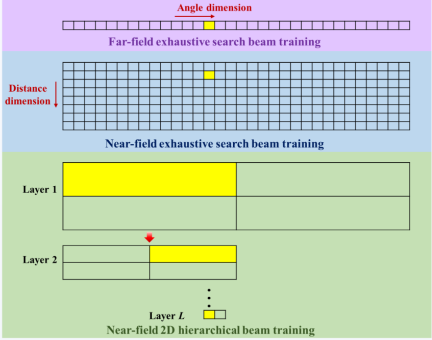

Fig. 2 Comparisons between beam training schemes.

Holography imaging inspired codeword design

The key to implementing 2D hierarchical beam training is to design **multi-resolution near-field codeword**, especially for the low resolution codeword. The aim of the design a codeword is to make the beamforming gains obtained by the codeword $\mathbf{v}$ can be as close to the beamforming gains in ideal beam pattern as possible.

$$\min_{\mathbf{v}, f(\theta,r)} \|\mathbf{A}^H\mathbf{v} - \mathbf{g}\|_2^2$$

$$\text{s.t.} \quad \|\mathbf{v}\|_2 = 1; \quad \mathbf{A} \triangleq \sqrt{N}[\mathbf{a}(\theta_1,r_1),\cdots,\mathbf{a}(\theta_N,r_{S_N})]$$

$$[\mathbf{g}]_{\theta,r} = |G(\theta,r)|e^{jf(\theta,r)}$$

additional phase: increase design freedom

In the minimization problem, A is a matrix composed of near-field array response vectors determined by different angles and distances. The codeword has power constraint, and the ideal beam pattern $\mathbf{g}$ has modulus constraint, that is, the beamforming gain within the target coverage range is flat, while the gain outside the target coverage range is 0. The phase of $\mathbf{g}$ does not have an impact on the gain, so we introduced an additional phase in the design to improve the design freedom.

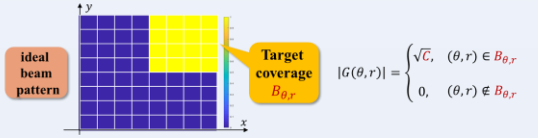

Fig. 3 Ideal beam pattern

In optical systems, the amplitude information is easy to measured, while the direct recording of the phase information is not allowed. Thus, in order to realize the imaging of the original object, one of the most important problem is conducting phase retrieval. With help of the measured amplitude, some signal processing algorithms offer an alternative methods for recovering the phase of optical images without requiring sophisticated device.
Reviewing the theoretical codeword design problem, it is obvious that the problem is similar to the phase retrieval in digital holography imaging, where the phase information $f(\theta,r)$ of the ideal beam pattern vector should be designed while by amplitude information of ideal beam pattern vector is fixed.

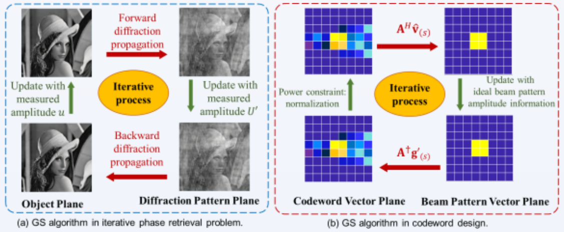

Fig. 4 Comparisons of the original and improved GS algorithm

Results and conclusions

Simulation result shows that the proposed scheme can achieve sub-optimal performance without restriction to the hardware cost and wideband condition. The proposed method is able to reduce the overhead by 97% compared to near-field exhaustive search beam training.

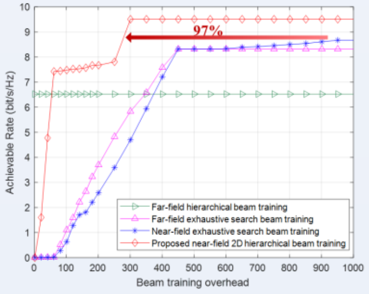

Fig. 5 Achievable sum-rate performance comparison

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