Distance-Aware Precoding for Near-Field Capacity Improvement in XL-MIMO

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Outline

- Background
- System Model
- Proposed Precoding Architecture
- Simulation Results
- Conclusions
Key Performance Indicators (KPI) of 6G

- The involving from 5G to 6G will further fuse the **digital worlds** and **real worlds**
- To support emerging applications, KPIs in 6G should be much superior to those in 5G

[Image of Extended Reality, Digital Replica, Holographic Video, Intelligent Transport]

**Peak data rate**
- 1Tbps

**Spectral efficiency**
- 20 Gbps
- 100 b/s/Hz
- 100 users/m²
- 1 user/m²
- 2 ms
- 500μs

**Coverage**
- 90%

**Low latency**
- 5G
- 7%
- 6G

**Spectral efficiency is expected to achieve 10 times increase**

[1] ITU FG-NET-2030, “Network 2030-A Blueprint of Technology, Applications and Market Drivers towards the Year 2030 and Beyond,” https://www.itu.int/en/ITUT/focusgroups/net2030/Documents/White_Paper.pdf, document ITU-T FG-NET-2030, ITU, Geneva, Switzerland, May 2019.
Extremely Large Antenna Arrays (ELAA)

- 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 **ultra-massive MIMO (UM-MIMO)** and **cell-free massive MIMO (CF-MIMO)**

[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.
EM Propagation: Near-field vs. Far-field

- Electromagnetic (EM) propagation can be divided into far-field and near-field regions
  - Boundary of these regions is the Rayleigh distance
  - In far-field, EM propagation can be approximately modeled by the planar wave
  - In near-field, EM propagation has to be accurately modeled by the spherical wave

![Diagram showing EM Propagation: Near-field vs. Far-field]

It has a critical difference of the EM characteristics between the near-field and far-field

[1] M. Cui, Z. Wu, Y. Lu, X. Wei, and L. Dai, “Near-field communications for 6G: Fundamentals, challenges, potentials, and future directions,” arXiv preprint arXiv:2203.16318, Mar. 2022.
Challenges of Near-Field Communications

- **Challenges**
  - **Channel estimation**: near-field angle-domain channels suffer from a severe energy spreading problem.
  - **Beam forming**: beamforming vectors are related to both angles and distances.

[Image: showing far-field sparse vs near-field non-sparse channels]

Overcoming near-field effect \(\rightarrow\) Exploiting near-field effect

[1] M. Cui and L. Dai, “Channel estimation for extremely large-scale MIMO: Far-field or near-field?,” *IEEE Trans. Commun.*, vol. 70, no. 4, pp. 2663-2677, Apr. 2022.
[2] N. J. Myers and R. W. Heath, “InFocus: a spatial coding technique to mitigate misfocus in near-field LoS beamforming,” *IEEE Trans. Wireless Commun.*, vol. 21, pp. 2193-2209, April 2022.
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Near-Field ELAA Communication System

- **System Model**
  - Consider a single-user ELAA communication system with hybrid precoding
  \[ y = HF_s + n = HF_A F_D s + n \]

- **Expression of sum rate**
  \[ R = \max_{F, W} \log_2 \left| I + H W F F^H H^H W^H \right| \]

  **Upper bound with digital**
  \[ R \leq \sum_{i=1}^{\min(N_t, N_r)} \log_2 \left( 1 + \frac{p_i}{\sigma_n^2} \lambda_i^2(H) \right) \]

  Where \( p_i = \left( \frac{1}{\mu} - \frac{\sigma_n^2}{\lambda_i^2(H)} \right)^+ \rightarrow 0 (\lambda_i \rightarrow 0) \)

**Capacity can be enhanced as the number of large singular values increases**
Based on planar wave assumptions, **degrees of freedom (DoF)** are limited in line-of-sight (LoS) far-field channel.

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

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

\[
\mathbf{a}(\phi) = \frac{1}{\sqrt{N}} [1, e^{j\frac{2\pi}{\lambda}dsin\phi}, \ldots, e^{j(2N)\frac{2\pi}{\lambda}dsin\phi}]^T
\]

\[
\mathbf{H}_{\text{LoS}} = \alpha_{\text{LoS}} \mathbf{a}_r(\theta_{\text{LoS}}^r) \mathbf{a}_t^H(\theta_{\text{LoS}}^t)
\]

**Far-field steering vector**

**The rank-one LoS channel can only support one data stream**

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[1] O. Ayach, S. Rajagopal, S. Abu-Surra, Z. Pi, and R. W. Heath, “Spatially sparse precoding in millimeter wave MIMO systems,” *IEEE Trans. Wireless Commun.*, vol. 13, no. 3, pp. 1499–1513, Jan. 2014.
From Rank-one Channel to Highly-Ranked Channel

- The rank-one far-field LoS channel is not valid any more in the near-field region
- Based on spherical waves, the near-field LoS channel becomes highly ranked

\[
\text{Phase: } \phi_n = \frac{2\pi(r^{(n)} - r)}{\lambda} = \frac{2\pi}{\lambda} \left( \sqrt{r^2 - 2nd\theta + n^2d^2} - r \right)
\]

\[r > \text{RD} \approx \frac{2\pi}{\lambda} nd\theta\]

Not valid in near-field region

**Near-field LoS channel**

\[
H_{\text{LoS}} = \begin{bmatrix}
\alpha_{1,1}e^{-j2\pi r_{1,1}/\lambda} & \ldots & \alpha_{1,N_2}e^{-j2\pi r_{1,N_2}/\lambda} \\
\vdots & \ddots & \vdots \\
1e^{-j2\pi r_{N_2,1}/\lambda} & \ldots & 1e^{-j2\pi r_{N_2,N_1}/\lambda}
\end{bmatrix}
\]

Significantly increased rank
DoFs Analysis in the Near-Field Region

- DoFs analysis of the near-field LoS channel
  - Inspired by the research of optics, the channel can be analyzed with continuous waves

\[ \sigma^2 x = H^H H x \]

Eigenproblem

\[ \nu \psi(r_T) = \int_{S_T} K(r_T', r_T) \psi(r_T') dr_T' \]

Convolution of Green Function

\[ K(r_T', r_T) = \int_{S_R} G^*(r_R, r_T') G(r_R, r_T) dr_R \]

Near-field Green function

\[ G(r, r_1) = \frac{\exp(-jk |r - r_1|)}{4\pi |r - r_1|} \]
DoFs Analysis in the Near-Field Region

DoFs analysis of the near-field LoS channel

- Inspired by the research of optics, the channel can be analyzed with continuous waves

\[
\nu \psi(r_T) = \int_{S_T} K(r_T', r_T) \psi(r_T') dr_{T'}
\]

\[
= \int_{S_T} \int_{S_R} \exp(jk |r_R - r_T|) \exp(-jk |r_R - r_{T'}|) \frac{1}{(4\pi)^2 |r_R - r_T||r_R - r_{T'}|} dr_R \psi(r_{T'}) dr_{T'}
\]

Singular values

Eigenproblem

\[
\nu_n \psi_n(c_y, \xi_T) = \int_{-1}^{1} \frac{\sin[c_y (\xi_T - \xi_{T'})]}{\pi(\xi_T - \xi_{T'})} \psi_n(c_y, \xi_{T'}) d\xi_{T'}
\]

Degrees of freedom

\[
N_{\text{DoF}} \approx \frac{2}{\pi} c_y \frac{D_l D_r \cos \theta \cos \phi}{\lambda r}
\]

- Proportion to aperture
- Inversely proportion to distance

Near-field approximation

\[
\sqrt{1 + x} \approx 1 + \frac{1}{2} x - \frac{1}{8} x^2
\]
Increased DoFs for Near-Field LoS Channel

- DoFs analysis of the near-field LoS channel
  - Accurate estimation of singular values with PSWFs
    \[ \nu_n \psi_n(c_y, \xi_T) = \int_{-1}^{1} \frac{\sin[c_y(\xi_T - \xi_T')] \psi_n(c_y, \xi_T') \psi_n(c_y, \xi_T')d\xi_T']}{\pi(\xi_T - \xi_T')} \]

- Simulation
  - Parallel positioned
  - Large-scale fading is neglected
  - \( f = 30 \text{ GHz} \)
  - \( N_t = N_r = 256 \)
  - \( d = \lambda / 2 = 5 \text{ mm} \)
**Limitation of hybrid precoding architecture**

- However, **limited by the small number of RF chains**, the classical hybrid precoding can **not efficiently utilize the increased DoFs to enhance the capacity**

| Precoding          | Region     | Spatial DoFs | RF chains                                   | Spectral Efficiency   |
|--------------------|------------|--------------|---------------------------------------------|-----------------------|
| Hybrid Precoding   | Far-Field  | Low          | RF Chains ≈ DoFs                            | Near Optimal          |
|                    | Near-Field | High         | RF Chains ≪ Distance-Related DoFs           | Far From Optimal      |

**How to efficiently utilize the significantly increased DoFs in near field**
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Distance-Aware Precoding Architecture

- Based on the distance-related DoFs in the near-field region, the distance-aware precoding architecture is proposed.
- The number of activated RF chains can be configured to match the increased DoFs in the near-field region.

Hybrid Precoding

Distance-Aware Precoding for Near-Field Capacity Improvement in XL-MIMO
Distance-Aware Precoding Algorithm

- Spectral efficiency maximization problem

$$\max_{F_A, F_S, F_D} \left\{ R = \log_2 \left( \frac{1}{\sigma_n^2} \mathbf{I} + \mathbf{H} \mathbf{F}_A \mathbf{F}_S \mathbf{F}_D \mathbf{F}_D^H \mathbf{F}_S^H \mathbf{F}_A^H \mathbf{H}^H \right) \right\}$$

subject to:

- $C_1 : \| \mathbf{F}_A \mathbf{F}_S \mathbf{F}_D \|_F^2 \leq P_{\text{tot}}$
- $C_2 : \mathbf{F}_A \in F$
- $C_3 : (\mathbf{F}_S)_{ij} \in \{0, 1\}, \forall i, j$
- $C_4 : \text{diag}(\mathbf{F}_S \mathbf{F}_S^H) = \mathbf{1}_{N_s}$

- Optimization Process
  - Stage 1: Determine the optimal number of RF chains $N_s$
  - Stage 2: Determine the selection matrix $F_S$
  - Stage 3: Obtain the analog precoder $F_A$ and digital precoder $F_D$
Distance-Aware Precoding Algorithm

Stage 1: Optimization of RF chains $N_s$

Similar to the classical hybrid precoding scheme, the purpose is to design the number of RF chains to match the valid spatial DoFs

$$N_s^{opt} = \#\{ p_i \mid p_i > 0 \}$$

Stage 2: Optimization of selection matrix $F_S$

$$R = \log_2 \left( I + \frac{1}{\sigma_n^2} \mathbf{H}_A F_S F_D \mathbf{F}_D^H \mathbf{F}_S^H \mathbf{F}_A^H \mathbf{H}_H \right)$$

$$R = \sum_{i=1}^{N_s} \log_2 \left( 1 + \frac{\lambda_i^2 (\mathbf{H}_A F_S) p_i}{\sigma_n^2} \right)$$

$$\leq N_s \log_2 \left( 1 + \frac{1}{N_s} \sum_{i=1}^{N_s} \frac{\lambda_i^2 (\mathbf{H}_A F_S) p_i}{\sigma_n^2} \right)$$

$$\max_{\mathbf{F}_A, \mathbf{F}_S} \sum_{i=1}^{N_s} \lambda_i^2 (\mathbf{H}_S \mathbf{F}_A \mathbf{F}_S) \approx \sum_{i=1}^{N_s} \lambda_i (\mathbf{H}_S^H \mathbf{H}_S)$$

Classify the channel by column and maximize the sum of largest singular value

$$S_1 \quad S_2 \quad \cdots$$
Distance-Aware Precoding Algorithm

- Summary of the proposed optimization process for $F_S$
  - To optimize the selection matrix $F_S$, it is equivalent to **partition the subarrays** which maximizes the **sum of the largest singular values**

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### Algorithm 2: Near-Field Subarray Partitioning Algorithm

**Input:** Channel $H$, $N_a$, $N_{bound}$ and $N_c$.

**Output:** $S_1, S_2, \ldots, S_N$.

1. $R = H^H H$, $S_{set} = \emptyset$, $n_{group} = \left\lceil \frac{N_a}{2} \right\rceil$.
2. Initialize $S_i = \{i \cdot n_{group}\}$, $S_{sel} \leftarrow S_{set} \cup \{i \cdot n_{group}\}$, for $i = 1, 2, \ldots, N_c$.

3. **for** $k = 1 : N_c - N_a$ do
   4. $\{i_k, j_k\} = \underset{\{i \in S_{sel}\} \cap \{j \in S_{set}\}}{\arg\max} ||R||_{i,j}$
   5. $\tilde{\lambda} = \arg\max \tilde{\lambda}_1(R, S_{c} \cup \{j_k\}) - \tilde{\lambda}_1(R, S_{c})$
   6. $S_{sel} \leftarrow S_{sel} \cup j_k$, $S_{c} \leftarrow S_{c} \setminus j_k, S_{c} \leftarrow S_{c} \setminus j_k$

7. **if** $|S_c| \geq N_{bound}$ **then**
   8. $\tilde{m} = \arg\min_{m \in S_r} \sum_{n \in S_c} |R_{m,n}|$
   9. $\tilde{\lambda} = \arg\max \tilde{\lambda}_1(R, S_r \cup \{j\}) - \tilde{\lambda}_1(R, S_r)$
   10. $S_c \leftarrow S_c \setminus \tilde{m}, S_r \leftarrow S_r \setminus \tilde{m}$

11. **end if**
12. **end for**

13. **for** $l = 1 : N_a$ do
   14. $\tilde{m} = \arg\min_{m \in S_c} \sum_{n \in S_l} |R_{m,n}|$
   15. $\tilde{\lambda} = \arg\max \tilde{\lambda}_1(R, S_r \cup \{j\}) - \tilde{\lambda}_1(R, S_r)$
   16. $S_c \leftarrow S_c \setminus \tilde{m}, S_r \leftarrow S_r \setminus \tilde{m}$

17. **end for**
18. **return** $S_1, S_2, \ldots, S_N$.

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- **Initialization**: initialize all sets with uniformly distributed antennas
- **Greedy searching**: add the antennas that maximizes the singular value
- **Limit the subarray**: Remove the antenna with the least contribution
- **Eliminate the influence of manual initialization**: check all the sets to remove the least contributor
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Simulation Results

- In the distance-aware precoding architecture, the number of RF chains can be flexibly adjusted to match the spatial DoFs.
- The spectral efficiency can be significantly enhanced in the near-field region.

Simulation Results

50% improvement spectral efficiency

Parameters | Values
---|---
Carrier | 100 GHz
BS antennas | 256
MS antennas | 256
SNR | 30 dB

[1] X. Gao, L. Dai, S. Han, C.-L. I, and R. W. Heath, “Energy-efficient hybrid analog and digital precoding for mmwave MIMO systems with large antenna arrays,” *IEEE J. Sel. Areas Commun.*, vol. 34, no. 4, pp. 998–1009, Apr. 2016.

[2] X. Yu, J. Z. J. Shen, and K. B. Letaief, “Alternating minimization algorithms for hybrid precoding in millimeter wave MIMO systems,” *IEEE J. Sel. Areas Commun.*, vol. 10, no. 3, pp. 485–500, Apr. 2016.
The proposed scheme also **outperforms** the existing hybrid precoding schemes in terms of **energy efficiency** in the near-field region.

### Simulation Results

| Parameters     | Values   |
|----------------|----------|
| Carrier        | 100 GHz  |
| BS antennas    | 256      |
| MS antennas    | 256      |
| SNR            | 30 dB    |

[1] X. Gao, L. Dai, S. Han, C.-L. I, and R. W. Heath, “Energy-efficient hybrid analog and digital precoding for mmwave MIMO systems with large antenna arrays,” *IEEE J. Sel. Areas Commun.*, vol. 34, no. 4, pp.998–1009, Apr. 2016.

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Conclusions

- **DoFs analysis in the near-field region**
  - Different from the rank-one far-field LoS channel, the near-field LoS channel becomes highly-ranked
  - The DoFs significantly increase in the near-field region, which can enhance the channel capacity

- **Distance-Aware Precoding (DAP) architecture**
  - To efficiently utilize the increased DoFs in the near-field region, the DAP architecture is proposed with adjustable RF chains and selection network
  - Corresponding precoding algorithm is also proposed with optimized data streams $N_s$ and selection network $F_S$
  - Simulation results verify the superiorities on both spectral and energy efficiency
Thank you!

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