Joint Codebook Design for Multi-Cell NOMA

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1 - Motivation & Contribution

- In cellular systems, intercell interference is present between close base stations.
- For spreading-based NOMA or OMA, intercell interference causes full collision of the spreading sequences in the code-domain.
- We propose to reduce intercell interference by employing jointly designed codebooks.
- The criterion for the design is to minimize the maximum cross-correlation between the codebooks.

2 - System Model

- For a NOMA system with spreading length N, number of users M, the received signal at the base station is

$$\mathbf{y} = \sum_{m=1}^{M} h_m \sqrt{P_m} \mathbf{s}_m x_m + \mathbf{n}\,, \tag{1}$$

where

- $x_m \in \mathbb{C}$ ... transmit symbol,
- $\mathbf{s}_m \in \mathbb{C}^{N\times 1}$ ... unit-norm signature,
- $\sqrt{P_m} \in \mathbb{R}^{+}$ ... transmit power,
- $h_m \in \mathbb{C}$ ... fading coefficient,
- $\mathbf{n} \in \mathbb{C}^{N\times 1}$ ... noise.

- Intercell interference adds extra terms to (1) from the other cells.
- The base stations are unaware of the transmit powers of the interfering users from the interfering cells.
- From the code-domain perspective, the performance depends on the codebook of signatures defined as

$$\mathbf{S} \in \mathbb{C}^{N\times M} = \begin{bmatrix}\mathbf{s}_1 & \mathbf{s}_2 & \dots & \mathbf{s}_M\end{bmatrix}. \tag{2}$$

3 - Codebook Design Problem

- Instead of reusing the codebook in each cell, we assign different codebooks that are jointly designed.
- To keep the intracell interference unaffected, the codebooks need to have identical Gramians, i.e.,

$$\mathbf{S}_1^H\mathbf{S}_1 = \mathbf{S}_2^H\mathbf{S}_2 = \dots = \mathbf{S}_K^H\mathbf{S}_K\,. \tag{3}$$

- We attempt to get close to orthogonality according to some metric $\|\mathbf{S}_1^H\mathbf{S}_2\|$.
- Consider the element-wise maximum norm

$$\|\mathbf{A}\|_{\max} = \max_{k,l} |[\mathbf{A}]_{kl}|\,, \tag{4}$$

Applying it to our problem, we obtain

$$\begin{aligned}\|\mathbf{S}_1^H\mathbf{S}_2\|_{\max} &= \max_{k,l} |[\mathbf{S}_1^H\mathbf{S}_2]_{kl}| \\ &= \max_{\mathbf{a}\in\mathbf{S}_1,\,\mathbf{b}\in\mathbf{S}_2} |\mathbf{a}^H\mathbf{b}|\,.\end{aligned} \tag{5}$$

- This is a robust approach that minimizes the maximum cross-correlation between the codebooks.

4 - Alternating Projection

- Find codebooks $\mathbf{S}_1, \mathbf{S}_2, \dots, \mathbf{S}_K$ such that

$$\begin{aligned}\mathbf{S}_i^H\mathbf{S}_i &= \mathbf{S}^H\mathbf{S}\,, && \text{for every } i\,, \\ \|\mathbf{S}_i^H\mathbf{S}_j\|_{\max} &\leq \mu\,, && \text{for every } i \neq j\,.\end{aligned} \tag{6}$$

- Let $\mathbf{\Sigma} = \begin{bmatrix}\mathbf{S}_1 & \mathbf{S}_2 & \dots & \mathbf{S}_K\end{bmatrix}$. The Gramian of the codebooks is given by

$$\mathbf{G} = \mathbf{\Sigma}^H\mathbf{\Sigma} = \begin{bmatrix}\mathbf{S}_1^H\mathbf{S}_1 & \mathbf{S}_1^H\mathbf{S}_2 & \cdots & \mathbf{S}_1^H\mathbf{S}_K \\ \mathbf{S}_2^H\mathbf{S}_1 & \mathbf{S}_2^H\mathbf{S}_2 & \cdots & \mathbf{S}_2^H\mathbf{S}_K \\ \vdots & \cdots & \ddots & \vdots \\ \mathbf{S}_K^H\mathbf{S}_1 & \mathbf{S}_K^H\mathbf{S}_2 & \cdots & \mathbf{S}_K^H\mathbf{S}_K\end{bmatrix}. \tag{7}$$

- The properties of the Gramian matrix $\mathbf{G}$ from (6) can be divided into a structural constraints set

$$\begin{aligned}\mathcal{H} = \{\mathbf{H} \in \mathbb{C}^{MK\times MK} : \mathbf{H} = \mathbf{H}^H, \\ \mathbf{H}_{ii} = \mathbf{S}^H\mathbf{S},\ \|\mathbf{H}_{ij}\|_{\max} \leq \mu, \forall\, i \neq j\}\,,\end{aligned} \tag{8}$$

and a spectral constraints set

$$\begin{aligned}\mathcal{G} = \{\mathbf{G} \in \mathbb{C}^{MK\times MK} : \mathbf{G} \succcurlyeq 0,\ \mathrm{rank}(\mathbf{G}) = N, \\ \mathrm{trace}(\mathbf{G}) = MK\}\,.\end{aligned} \tag{9}$$

We use the alternating projection algorithm to find a matrix $\mathbf{G}$ satisfying both constraint sets.

- The algorithm operates by iteratively solving a nearest matrix problem to each constraint set.

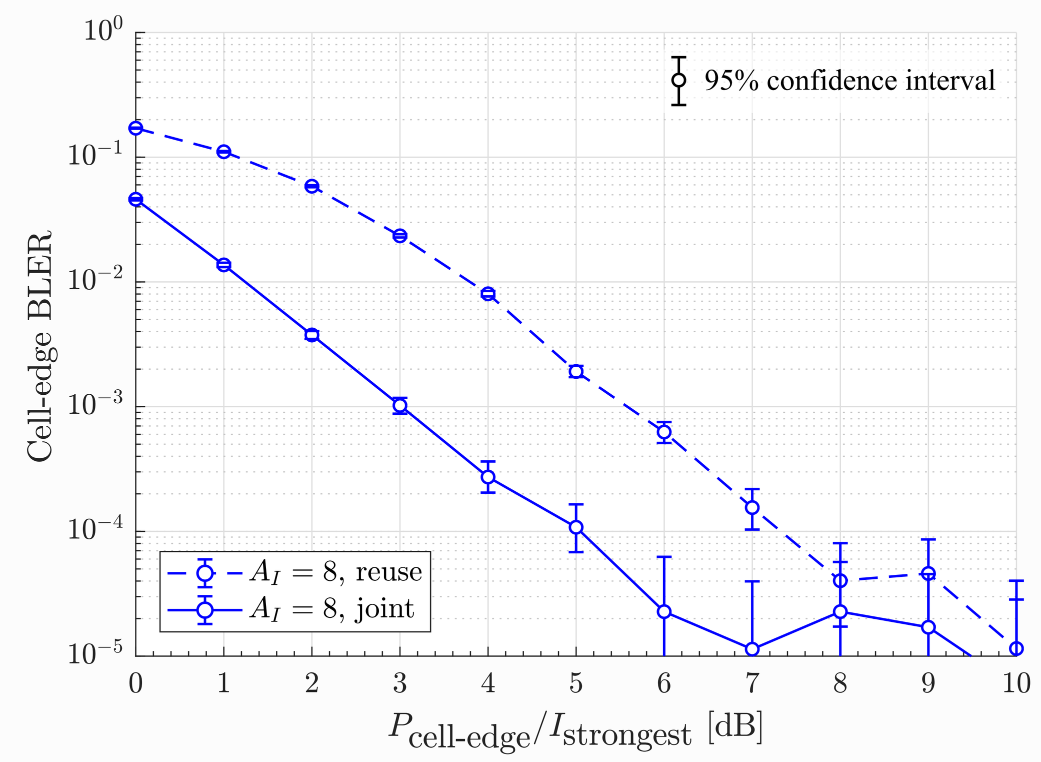
5 - Simulation Scenario

- Two cells with spreading length $N = 8$, for both NOMA and OMA systems.
- For the NOMA system, a base 8×24 codebook is used. The lowest μ found was 0.52.
- For the OMA system, a base 8×8 unitary codebook is used. The lowest μ found was 0.3536.
- The SNR of the users in the primary cell is uniformly distributed in $[4, 20]$ dB.
- The SNR of the cell-edge user is fixed to 4 dB.
- The SNR of the users from the interfering cell at the primary base station is uniformly distributed in $[-12, 4] - P_{\text{cell-edge}}/I_{\text{strongest}}$ dB.

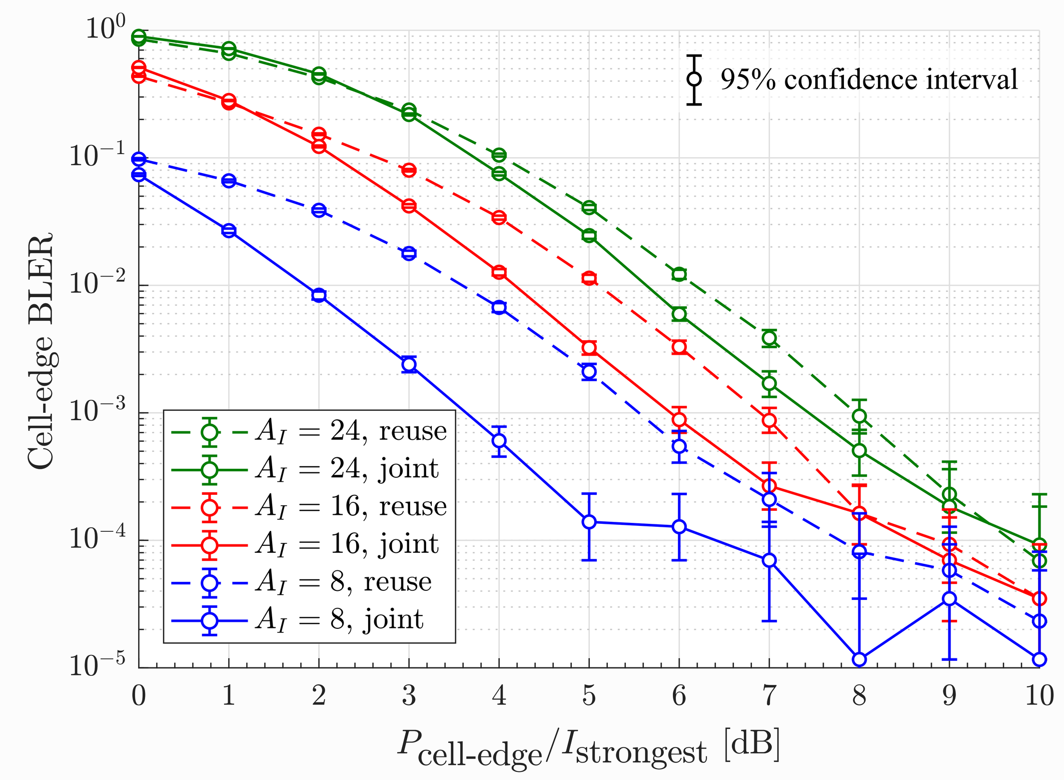
Parameter	Value
Spreading length	8
Number of users for NOMA	8, 16, 24
Number of users for OMA	8
Modulation	4-QAM
Channel coding	Turbo, code rate 1/3
Channel model	Flat fading
Channel estimation	Ideal
Multiuser Detector	CWL-MMSE-SIC

6 - Cell-Edge Performance

- The figures below show the performance of the cell-edge user for two strategies
  - Reuse; in which the base codebook is reused in each cell.
  - Joint; in which joint codebooks are used.
- A_P and A_I are the number of active users in the primary cell and interfering cell, respectively.



Performance of the OMA cell-edge user for $A_P = 8$ (100%), and $A_I = 8$ (100%).



Performance of the NOMA cell-edge user for $A_P = 24$ (300%), and $A_I = 8, 16, 24$ (100, 200, 300%).

Summary

- We propose a method for reducing intercell interference in NOMA and OMA systems by using jointly designed codebooks.
- The criterion for the codebook design is to minimize the maximum cross-correlation between the codebooks.
- The performance of the cell-edge user is evaluated, in which a considerable gain is obtained.

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