



QoS-aware multi-user scheduling and power control for modular XL-MIMO communications*

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Abstract: This study addresses the challenges of near-field interference suppression and resource allocation in extremely large-scale multiple-input multiple-output (XL-MIMO) communication systems, particularly under dense-user scenarios. We propose a quality-of-service (QoS)-aware joint user scheduling and power control scheme. Leveraging the spherical wave (SW) characteristics of near field channels, a dual-domain interference suppression strategy is developed by analyzing the spatial correlation of beam focusing vectors in terms of both angular separation and distance constraints. Based on this, a spatial correlation-based scheduling (SCS) algorithm is designed. By integrating this user selection strategy with a dynamic power allocation mechanism, the proposed approach optimizes the sum spectral efficiency while ensuring the user QoS. This framework is further extended to modular XL-MIMO systems. We show how modular deployment can enhance spatial resolution and develop an adapted QoS-aware user scheduling algorithm, called modular SCS (SCS-mod), for this architecture. Simulation results validate that the proposed algorithms significantly outperform existing schemes in terms of sum spectral efficiency and the number of scheduled users, especially under high user density and high transmission power conditions.

Key words: Extremely large-scale multiple-input multiple-output (XL-MIMO); User scheduling; Power control; Near-field communication; Modular array; Interference suppression

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1 Introduction

Extremely large-scale multiple-input multiple-output (XL-MIMO) technology, characterized by the deployment of antenna arrays with extremely large

apertures (e.g., hundreds to thousands of elements), promises significant enhancement in spatial resolution and spectral efficiency for wireless communication systems (Dong and Zeng, 2022; Lu et al., 2024). Unlike conventional MIMO systems where users typically reside in the far field, users in XL-MIMO systems may be located in the radiative near-field region (Björnson et al., 2019; De Carvalho et al., 2020; Tang et al., 2024). This necessitates the use of a more accurate spherical wave (SW) channel model and enables beam focusing to enhance the desired signal strength (Lu and Zeng, 2022; Wu and Dai, 2023; Chen and Dai, 2024; Dong et al., 2024). Moreover, near-field

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beam focusing enables high-gain energy beams to be formed at specific locations through phase control. It also distinguishes users' spatial positions via distance-domain resolution. This offers new possibilities for multi-user multiplexing in scenarios with high user density (Dong and Zeng, 2022; Zheng et al., 2024). However, these near-field effects also complicate the inter-user interference (IUI) management. In the far field, user separation relies solely on angular differences, and interference suppression depends on the angular-domain orthogonality of steering vectors. In contrast, the beam focusing property in the near-field region introduces distance-domain resolution in addition to angular resolution, making the channel characteristics of near-field users depend on both angle and distance. This implies that two users with similar angles and distances exhibit strong spatial correlation (Wu and Dai, 2023; Lu et al., 2024), which further complicates near-field interference suppression. Consequently, conventional far-field interference suppression strategies relying solely on angular resolution are not directly applicable in the near field. Therefore, it is crucial to fully exploit the spatial degrees of freedom and beam focusing capabilities of XL-MIMO to achieve efficient scheduling and interference mitigation in dense-user scenarios (González-Coma et al., 2023; Lu et al., 2024; Yang et al., 2024; Zhang et al., 2024).

Conventional XL-MIMO features collocated antenna elements, providing higher array gain and a compact physical structure. This configuration offers strong performance benefits in scenarios where a large, contiguous aperture deployment is feasible (Wu and Dai, 2023; Lu et al., 2024). However, the requirement for a contiguous platform poses challenges for non-contiguous installations (Li et al., 2023). To address this challenge, modular XL-MIMO offers a practical solution for achieving very large apertures with enhanced deployment flexibility by deploying multiple spatially separated antenna modules (Li et al., 2022). In practice, these modules, each with a moderately sized uniform array, are arranged on a common platform but separated by relatively large distances, allowing for flexible integration into urban environments. For instance, they can be distributed across building facades or embedded within large indoor venues like airports and stadiums (Li et al., 2023, 2024). This flexibility is a key advantage over collocated arrays. Furthermore, modular XL-MIMO

significantly enhances spatial resolution, allowing for better user discrimination in the near field. The primary drawback, however, is that excessively large inter-module spacing brings grating lobes, leading to severe IUI (Li et al., 2022). Therefore, designing modular arrays requires careful consideration of the trade-off between deployment flexibility and system performance. In addition, by exploiting the extended inter-module spacing and the compact design within each module, the modular architecture reduces spatial correlation among user channels and provides a potential solution for mitigating near-field interference in dense-user scenarios (Jeon et al., 2021; Wang and Zeng, 2023).

In recent years, several studies have proposed various solutions to the user scheduling problem in XL-MIMO systems based on the SW model. For example, in millimeter wave (mmWave) system studies, Du et al. (2022) and Qu et al. (2022) proposed beam selection and user scheduling algorithms exploiting angular-domain sparsity, which effectively increase the number of served users under limited beam resources. However, due to the fundamental differences between narrow mmWave beams and wide near-field beam focusing on XL-MIMO, these methods are not directly applicable. González-Coma et al. (2021) proposed an equivalent distance-based strategy that prioritizes users with larger distance differences to reduce interference, thereby lowering complexity but ignoring angular-domain correlation, leading to limited interference suppression in dense-user scenarios. In contrast, De Souza et al. (2023) employed an exhaustive search method to find the optimal user group, achieving good performance but suffering from computational complexity that grows exponentially with the number of users, rendering it impractical for scenarios with a very large number of users. However, these existing methods may not fully exploit the nuanced spatial correlation characteristics inherent in near-field channels, potentially limiting their effectiveness in dense-user scenarios. Although modular architectures can inherently reduce inter-user channel correlation (Li et al., 2022, 2024), multi-user scheduling for such systems often still relies on algorithms designed for conventional arrays. Consequently, the full potential of modularity, particularly for near-field interference suppression and resource allocation, remains largely unexplored.

To address these challenges, this study investigates multi-user downlink XL-MIMO communication systems and proposes a quality-of-service (QoS)-aware joint user scheduling and power control algorithm. By analyzing the spatial correlation of near-field beam focusing vectors, we establish a dual-domain (angle and distance) interference suppression mechanism. This mechanism forms the basis of our proposed spatial correlation-based scheduling (SCS) algorithm. Combined with zero-forcing (ZF) precoding and dynamic power allocation, this approach aims for efficient resource allocation while satisfying user QoS. Furthermore, this study extends the proposed algorithm to modular XL-MIMO systems, analyzing how modular deployment can enhance spatial resolution and proposing an adapted scheduling algorithm (modular SCS (SCS-mod)) tailored for this architecture. Simulation results demonstrate that the proposed algorithms significantly outperform existing benchmark schemes in terms of sum spectral efficiency and the number of scheduled users, exhibiting particularly strong interference suppression capabilities in dense-user and high-power scenarios. Furthermore, the dual-domain scheduling framework proposed in this paper provides a foundational approach that can be extended to other emerging architectures, such as reconfigurable intelligent surface (RIS)-assisted systems and cell-free XL-MIMO architectures (Liu et al., 2024; Lee et al., 2025). Integrating our framework with these technologies constitutes a promising avenue for future research.

2 System model and problem formulation

Fig. 1 shows the considered multi-user XL-MIMO downlink communication system. In this system, a base station (BS) with an N -element uniform linear array (ULA) serves K users, each with a single antenna. Without loss of generality, we assume that the ULA is placed along the y axis and is symmetric with respect to the origin. The spacing between adjacent antenna elements is d , with $d = \frac{\lambda}{2}$, where λ is the carrier wavelength.

To accurately describe the near-field channel in the XL-MIMO system, we use the uniform spherical wave (USW) model (Li et al., 2024). The channel

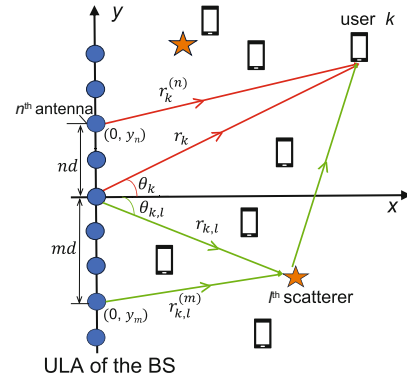


Fig. 1 A multi-user XL-MIMO downlink communication system

vector for user k can then be written as

$$\mathbf{h}_k = \sqrt{N} g_k \mathbf{b}(r_k, \theta_k) + \sqrt{\frac{N}{L_k}} \sum_{l=1}^{L_k} g_{k,l} \mathbf{b}(r_{k,l}, \theta_{k,l}), \quad (1)$$

which contains one line-of-sight (LoS) path and L_k non-line-of-sight (NLoS) paths for user k . $g_k = \sqrt{\frac{\kappa}{\kappa+1}} e^{-j\frac{2\pi}{\lambda} r_k}$ denotes the gain of the LoS path, where κ is the Ricain factor representing the power ratio between the LoS and NLoS paths. r_k denotes the distance from user k to the center of the ULA, and θ_k denotes the angle of user k with respect to the positive x axis. For the l^{th} NLoS path, $g_{k,l}$ is its gain following $g_{k,l} \sim \mathcal{N}_{\mathbb{C}}(0, \sigma_l^2)$, with $\sigma_l^2 = \frac{1}{\kappa+1}$. $r_{k,l}$ is the distance between the scatterer and the center of the ULA, and $\theta_{k,l}$ is its angle. Finally, $\mathbf{b}(r, \theta)$ is the near-field array response vector, given by

$$\mathbf{b}(r, \theta) = \frac{1}{\sqrt{N}} \left[e^{-j\frac{2\pi}{\lambda} r^{(-\bar{N})}}, \dots, e^{-j\frac{2\pi}{\lambda} r^{(\bar{N})}} \right]^T, \quad (2)$$

where $r^{(n)}$ is the distance between the n^{th} BS antenna and user k (or a scatterer), and r is the distance between user k (or a scatterer) and the center of the ULA. For simplicity, we assume that N is an odd number, so the antenna indices range from $-\bar{N}$ to $\bar{N}$, where $\bar{N} \triangleq \frac{N-1}{2}$. The coordinate of the n^{th} antenna is $(0, y_n)$, with $y_n = nd$. Therefore, the distance from user k to the n^{th} antenna is

$$\begin{aligned} r_k^{(n)} &= \sqrt{r_k^2 - 2r_k y_n \sin \theta_k + y_n^2} \\ &\stackrel{(a)}{\approx} r_k - y_n \sin \theta_k + \frac{y_n^2 \cos^2 \theta_k}{2r_k}, \end{aligned} \quad (3)$$

where the approximation (a) comes by using the second-order Taylor series expansion for $\sqrt{1+x}$.

Let $\mathcal{S} \triangleq \{1, 2, \dots, K\}$ denote the set of all users. Let $\mathcal{K} \subseteq \mathcal{S}$ be the set of users scheduled for service.

An index $k \in \mathcal{K}$ identifies a user in this set. The signal transmitted by the BS is $\mathbf{x} = \sum_{k \in \mathcal{K}} \mathbf{f}_k s_k$. Here, $\mathbf{f}_k \in \mathbb{C}^N$ is the transmit beamforming vector for user k , and $s_k \sim \mathcal{N}_{\mathbb{C}}(0, 1)$ is the data symbol intended for user k . Therefore, the received signal at user k is given by

$$y_k = \mathbf{h}_k^H \mathbf{f}_k s_k + \sum_{i \in \mathcal{K}, i \neq k} \mathbf{h}_k^H \mathbf{f}_i s_i + n_k, \quad (4)$$

where $n_k \sim \mathcal{N}_{\mathbb{C}}(0, \sigma_n^2)$ is the additive white Gaussian noise (AWGN), and σ_n^2 is the noise variance. Thus, the spectral efficiency for user k is given by

$$R_k = \log_2 \left(1 + \frac{|\mathbf{h}_k^H \mathbf{f}_k|^2}{\sigma_n^2 + \sum_{i \in \mathcal{K}, i \neq k} |\mathbf{h}_k^H \mathbf{f}_i|^2} \right). \quad (5)$$

In XL-MIMO systems, serving many users at the same time can make it difficult to meet their QoS requirements. Therefore, we present our study of the user scheduling problem in this paper. We consider perfect channel state information (CSI) available at the transmitter (If imperfect CSI and spatial non-stationarity are considered, the spatial correlation metrics and channel estimation will be biased. In Section 5, the impact of inaccurate CSI at the transmitter on the performance of the user scheduling technique is numerically evaluated) (De Souza et al., 2023). Our goal is to jointly choose the set of scheduled users $\mathcal{K}$ and design the transmit beamforming vectors $\{\mathbf{f}_k\}_{k \in \mathcal{K}}$ to maximize the sum spectral efficiency. The optimization problem is stated as P0:

$$\max_{\mathcal{K}, \{\mathbf{f}_k\}_{k \in \mathcal{K}}} \sum_{k \in \mathcal{K}} R_k \quad (6a)$$

$$\text{s.t.} \quad R_k \geq \bar{R}_k, \quad \forall k \in \mathcal{K}, \quad (6b)$$

$$\sum_{k \in \mathcal{K}} \|\mathbf{f}_k\|_2^2 \leq P_{\max}, \quad (6c)$$

$$\mathcal{K} \subseteq \mathcal{S}, \quad (6d)$$

where $\bar{R}_k > 0$ for all $k \in \mathcal{K}$ is the minimum spectral efficiency required by user k (the QoS requirement). $P_{\max} > 0$ is the maximum transmit power at the BS. Constraint (6b) ensures that each scheduled user $k \in \mathcal{K}$ achieves at least its minimum required spectral efficiency $\bar{R}_k$. Constraint (6c) limits the total transmit power for all scheduled users to $P_{\max}$. Constraint (6d) specifies that the set of scheduled users $\mathcal{K}$ must be a subset of all users $\mathcal{S}$.

P0 is non-convex with respect to the transmit beamforming vectors $\{\mathbf{f}_k\}_{k \in \mathcal{K}}$. Also, the number of possible choices for the user set $\mathcal{K}$ grows exponentially, making an exhaustive search for the best set too time-consuming. Furthermore, the optimization variables are coupled, which makes it difficult to solve P0 directly.

3 Proposed solution to P0

To address the challenges mentioned above, we design an efficient algorithm to solve P0. Our approach is to break P0 down into two smaller problems (subproblems). Subproblem 1 optimizes the set of scheduled users $\mathcal{K}$, and subproblem 2 optimizes the transmit beamforming vectors $\{\mathbf{f}_k\}_{k \in \mathcal{K}}$. Specifically, we first solve subproblem 1. This subproblem deals with user scheduling by using spatial correlation information of the channels between the BS and the users. Then, using the chosen set of users, we use the ZF beamforming method to design the transmit beamforming vectors. This changes subproblem 2 into a power allocation optimization problem. Finally, our proposed overall algorithm combines the solutions from the user scheduling and power allocation subproblems in order. This gives us a solution to the original P0. The details are elaborated in the following subsections.

3.1 Solution to the user scheduling subproblem

In this section, we propose a scheduling method that uses both user angle and distance. This method analyzes the spatial correlation between the beam focusing vectors of different users. The goal is to effectively reduce IUI and solve the user scheduling problem. However, the set of all users $\mathcal{S}$ can be very large. To reduce the complexity of user scheduling, we divide $\mathcal{S}$ into several subgroups $\mathcal{V}_i$, so that $\mathcal{S} \triangleq \mathcal{V}_1 \cup \mathcal{V}_2 \cup \dots \cup \mathcal{V}_s$, where s is the number of subgroups. This division is based on a chosen angular range Θ . Users within each group $\mathcal{V}_i$ are expected to have similar channel conditions, and we assume that interference between different groups is small enough to be ignored. Let $\mathcal{K}_i \subseteq \mathcal{V}_i$ be the set of users scheduled from group $\mathcal{V}_i$. To simplify the analysis, we consider only the LoS channel and neglect the impact of NLoS paths (Lu and Zeng, 2021), such that Eq. (1) reduces to $\mathbf{h}_k = \sqrt{N} g_k \mathbf{b}(r_k, \theta_k)$, facilitating theoretical

analysis of spatial correlation among users. We define $f(r_k, \theta_k; r_j, \theta_j) \triangleq |\mathbf{b}^H(r_k, \theta_k) \mathbf{b}(r_j, \theta_j)|$ as the correlation of the beam focusing vectors between user k and user j , where $k \in \mathcal{V}_i$ and $j \in \mathcal{K}_i$. Our main goal for user scheduling is to pick a set of users $\mathcal{K}'$ such that the beam focusing vector correlation $f(r_k, \theta_k; r_j, \theta_j)$ between users in the set is low, while trying to make the set as large as possible. We can state the part of this goal related to minimizing correlation as P1:

$$\mathcal{K}' = \arg \min_{\mathcal{K}} f(r_k, \theta_k; r_j, \theta_j) \quad (7a)$$

$$\text{s.t.} \quad \mathcal{K} \subseteq \mathcal{S}. \quad (7b)$$

P1 is a difficult combinatorial problem. To find a good solution to P1, we propose an algorithm called SCS.

Before describing the algorithm, we first look at the spatial correlation between different users. We do this by analyzing the correlation of their beam focusing vectors. The correlation function $f(r_k, \theta_k; r_j, \theta_j)$ can then be written as

$$f(r_k, \theta_k; r_j, \theta_j) = |\mathbf{b}^H(r_k, \theta_k) \mathbf{b}(r_j, \theta_j)| \\ = \frac{1}{N} \left| \sum_{n=1}^N e^{j \frac{2\pi}{\lambda} y_n \Delta_\theta + j \frac{2\pi}{\lambda} y_n^2 \Delta_r} \right|, \quad (8)$$

where $\Delta_\theta = \sin \theta_k - \sin \theta_j$ and $\Delta_r = \frac{\cos^2 \theta_j}{2r_j} - \frac{\cos^2 \theta_k}{2r_k}$. By observing the sum in Eq. (8), we can see that each term in the exponent (the phase) has two parts: (1) a linear phase part $y_n \Delta_\theta$, which depends on the angles; (2) a quadratic phase part $y_n^2 \Delta_r$, which is affected by both the angle and distance. These linear and quadratic phase parts show how differences in angle and distance between users affect their spatial correlation.

We first focus on the linear phase part, which is related to the angle. Suppose that $\frac{\cos^2 \theta_j}{r_j} = \frac{\cos^2 \theta_k}{r_k}$. If we substitute this condition into Eq. (8), the correlation becomes

$$f(r_k, \theta_k; r_j, \theta_j) = \frac{1}{N} \left| \sum_{n=1}^N e^{j \frac{2\pi}{\lambda} y_n \Delta_\theta} \right| \\ = \left| \frac{\sin(\pi N \bar{d} \Delta_\theta)}{N \sin(\pi \bar{d} \Delta_\theta)} \right|, \quad (9)$$

where $\bar{d} = \frac{d}{\lambda}$. Eq. (9) depends only on the angle difference Δ_θ . If we choose Δ_θ such that $\pi N \bar{d} \Delta_\theta =$

$\pm\pi$, then the correlation expression $\left| \frac{\sin(\pi N \bar{d} \Delta_\theta)}{N \sin(\pi \bar{d} \Delta_\theta)} \right|$ becomes 0. From this, we can find that the width of the main beam of this expression is $\frac{2}{N \bar{d}}$. Usually, the spatial angular resolution is defined as half of this main beam width (Li et al., 2024). So, the spatial angular resolution for our system is

$$\Delta_{\theta, \text{res}} = \frac{\lambda}{N d}. \quad (10)$$

If the angular difference between two users, $|\Delta_\theta|$, is greater than or equal to this resolution $\Delta_{\theta, \text{res}}$, the BS can discriminate the users by their angles. In this case, the correlation among users is very small, and hence the IUI becomes negligible for user scheduling. On the other hand, if users have similar angles (meaning $|\Delta_\theta| < \Delta_{\theta, \text{res}}$), their main beam patterns overlap. This causes a strong correlation and a lot of interference. If users are at exactly the same angle, their correlation mainly depends on the quadratic phase part. Lemma 1 below explains this.

Lemma 1 If users k and j are in the same direction (i.e., $\theta_k = \theta_j$) but at different distances (i.e., $r_k \neq r_j$), then their correlation is approximately

$$f(r_k, \theta; r_j, \theta) \approx |f_0(\beta)| = \left| \frac{C(\beta) + jS(\beta)}{\beta} \right|, \quad (11)$$

where $\beta = \sqrt{\frac{N^2 d^2 \cos^2 \theta}{2\lambda} \left| \frac{1}{r_j} - \frac{1}{r_k} \right|}$. $C(\beta) = \int_0^\beta \cos(\frac{\pi}{2} t^2) dt$ and $S(\beta) = \int_0^\beta \sin(\frac{\pi}{2} t^2) dt$ are Fresnel integrals (Sherman, 1962).

Proof The proof is similar to the one for Lemma 1 in (Cui and Dai, 2022), so we do not include it here for brevity.

Lemma 1 shows that how much users' signals affect each other (their coherence) strongly depends on both $|f_0(\beta)|$ and β . To keep the correlation low, we want to make sure that $|f_0(\beta)|$ stays below a certain level, denoted by Δ . First, we find a value β_Δ such that $|f_0(\beta_\Delta)| = \Delta$. Because $|f_0(\beta)|$ generally gets smaller as β gets larger, we need $\beta \geq \beta_\Delta$ to meet our condition. From the condition $\beta \geq \beta_\Delta$, we can find the required condition for the distances r_k and r_j . This condition is

$$\left| \frac{1}{r_j} - \frac{1}{r_k} \right| \geq \frac{2\lambda \beta_\Delta^2}{N^2 d^2 \cos^2 \theta} = \frac{1}{Z_\Delta \cos^2 \theta}, \quad (12)$$

where $Z_\Delta = \frac{N^2 d^2}{2\lambda \beta_\Delta^2}$, and Z_Δ is a distance threshold value. By using this threshold Z_Δ and making sure

that users satisfy the distance condition (12), we can ensure that their spatial correlation $|f_0(\beta)|$ is $\leq \Delta$. This helps reduce IUI for users who are in similar angular directions.

The above analysis shows that in an XL-MIMO system with a large antenna array, the correlation of near-field beam focusing depends on differences in spatial angle and distance between users. This correlation greatly affects the amount of IUI.

Based on the above discussion, our scheduling method, which uses both angle and distance, should make sure that two conditions are met: (1) the angular difference between users, $|\Delta_\theta|$, must be at least $\Delta_{\theta,\text{res}}$; (2) if users do not meet this angle condition, then they must satisfy the distance condition (12). Therefore, to implement our user scheduling for P1, we select users from each group $\mathcal{V}_i$ to form a scheduled user group $\mathcal{K}_i$. We make sure that users selected for $\mathcal{K}_i$ meet both the angle and distance conditions. Finally, we combine all these selected groups $\mathcal{K}_i$ to obtain the final set of scheduled users $\mathcal{K}'$. Algorithm 1 describes this proposed SCS algorithm. In Algorithm 1, its complexity is mainly determined by the dual-domain constraints for user pairs within each group, i.e., steps 8–17 of Algorithm 1. Its complexity is $\mathcal{O}\left(\frac{K^2}{s}\right)$, where K is the number of users and s is the number of subsets.

Algorithm 1 Proposed SCS algorithm

Input: The set of all users $\mathcal{S}$; the spatial angular resolution $\Delta_{\theta,\text{res}}$; the distance threshold parameter Z_Δ

Output: The set of scheduled users $\mathcal{K}'$

```

1: Partition the set  $\mathcal{S}$  into  $s$  subsets  $\mathcal{V}_1, \mathcal{V}_2, \dots, \mathcal{V}_s$ 
2:  $\mathcal{K}_i = \emptyset$ 
3: for  $k$  in each subset  $\mathcal{V}_i$  do
4:   if  $\mathcal{K}_i = \emptyset$  then
5:      $\mathcal{K}_i = \mathcal{K}_i \cup \{k\}$ 
6:   else
7:      $|\Delta_\theta| = |\sin \theta_k - \sin \theta_j|$ ,  $k \in \mathcal{V}_i$ ,  $j \in \mathcal{K}_i$ 
8:     if  $|\Delta_\theta| \geq \Delta_{\theta,\text{res}}$  then
9:        $\mathcal{K}_i = \mathcal{K}_i \cup \{k\}$ 
10:    else
11:       $R = \left| \frac{1}{r_j} - \frac{1}{r_k} \right|$ ,  $k \in \mathcal{V}_i$ ,  $j \in \mathcal{K}_i$ 
12:      if  $R \geq \frac{1}{Z_\Delta \cos^2 \theta}$  then
13:         $\mathcal{K}_i = \mathcal{K}_i \cup \{k\}$ 
14:      else
15:        break
16:      end if
17:    end if
18:  end if
19: end for
20:  $\mathcal{K}' \leftarrow \mathcal{K}_1 \cup \mathcal{K}_2 \cup \dots \cup \mathcal{K}_s$ 

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3.2 Solution to the transmit beamforming vector subproblem

For a given scheduled user set $\mathcal{K}'$, the optimal transmit beamforming vectors $\{\mathbf{f}_k^*\}_{k \in \mathcal{K}'}$ can be obtained by solving subproblem P2:

$$\{\mathbf{f}_k^*\}_{k \in \mathcal{K}'} = \arg \max_{\{\mathbf{f}_k\}_{k \in \mathcal{K}'}} \sum_{k \in \mathcal{K}'} R_k \quad (13a)$$

$$\text{s.t. } R_k \geq \bar{R}_k, \forall k \in \mathcal{K}', \quad (13b)$$

$$\sum_{k \in \mathcal{K}'} \|\mathbf{f}_k\|_2^2 \leq P_{\max}. \quad (13c)$$

P2 is non-convex with respect to the variables $\{\mathbf{f}_k\}_{k \in \mathcal{K}'}$. For simplicity, we employ ZF precoding at the BS (Zhang et al., 2024). Specifically, the precoding vector for user $k \in \mathcal{K}'$ is given by

$$\mathbf{f}_k = \sqrt{\frac{p_k}{[(\mathbf{H}^H \mathbf{H})^{-1}]_{k,k}}} \mathbf{H} (\mathbf{H}^H \mathbf{H})^{-1} \mathbf{e}_k, \quad (14)$$

where $\mathbf{e}_k \in \{0, 1\}^{|\mathcal{K}'|}$ is the k^{th} vector of the standard basis of the $|\mathcal{K}'|$ -dimensional Euclidean space, $\mathbf{H} \in \mathbb{C}^{N \times |\mathcal{K}'|}$ is the channel matrix whose columns are the channel vectors of the users in $\mathcal{K}'$, and $p_k > 0$ is the power allocated to user k . With ZF precoding, IUI is eliminated, i.e., $\mathbf{h}_k^H \mathbf{f}_i = 0$ for all $k, i \in \mathcal{K}'$, where $k \neq i$. Substituting Eq. (14) into Eq. (5), the spectral efficiency for user k becomes (De Souza et al., 2023)

$$R_k = \log_2 \left(1 + \frac{p_k}{\sigma_n^2 [(\mathbf{H}^H \mathbf{H})^{-1}]_{k,k}} \right). \quad (15)$$

Eq. (15) shows that with ZF precoding, the spectral efficiency of user k depends on its allocated power p_k , the noise variance σ_n^2 , and the term $[(\mathbf{H}^H \mathbf{H})^{-1}]_{k,k}$. This term $[(\mathbf{H}^H \mathbf{H})^{-1}]_{k,k}$ accounts for the effect of inter-user channel correlations within the scheduled set $\mathcal{K}'$; a larger value typically indicates stronger detrimental correlation effects, impacting the signal quality for user k (Dong et al., 2024).

Therefore, by substituting the ZF precoder structure in Eq. (14) and the resulting spectral efficiency in Eq. (15) into P2, it can be reformulated as

the following power allocation problem P3:

$$\{p_k^*\}_{k \in \mathcal{K}'} = \arg \max_{\{p_k\}_{k \in \mathcal{K}'}} \sum_{k \in \mathcal{K}'} R_k \quad (16a)$$

$$\text{s.t.} \quad R_k \geq \bar{R}_k, \forall k \in \mathcal{K}', \quad (16b)$$

$$\sum_{k \in \mathcal{K}'} p_k \leq P_{\max}. \quad (16c)$$

The user set $\mathcal{K}'$ obtained from Algorithm 1 is selected based on spatial correlation criteria. However, this selection does not inherently guarantee that a feasible power allocation exists for all users in $\mathcal{K}'$ when addressing P3. Specifically, it may not be possible for all users in $\mathcal{K}'$ to simultaneously satisfy their minimum spectral efficiency requirements (16b) and the total power constraint (16c) (De Souza et al., 2023). Thus, it is necessary to verify the feasibility of the user set $\mathcal{K}'$ for P3.

Let $\mathcal{K}^*$ denote the feasible set of scheduled users. P3 is feasible if and only if the total minimum power required to satisfy the individual spectral efficiency constraints of all users in $\mathcal{K}^*$ does not exceed $P_{\max}$:

$$\begin{aligned} \sum_{k \in \mathcal{K}^*} \bar{p}_k &= \sigma_n^2 \sum_{k \in \mathcal{K}^*} \left(2^{\bar{R}_k} - 1 \right) \left[(\mathbf{H}_{\mathcal{K}^*}^H \mathbf{H}_{\mathcal{K}^*})^{-1} \right]_{k,k} \\ &\leq P_{\max}, \end{aligned} \quad (17)$$

where $\bar{p}_k$ is the minimum power required for serving user k , and $\mathbf{H}_{\mathcal{K}^*}$ is the channel matrix for the users in the set $\mathcal{K}^*$.

Therefore, for a feasible set of scheduled users $\mathcal{K}^*$, the solution to P3 is given by

$$p_k^* = \max \left(\bar{p}_k, \mu - \sigma_n^2 \left[(\mathbf{H}_{\mathcal{K}^*}^H \mathbf{H}_{\mathcal{K}^*})^{-1} \right]_{k,k} \right), \quad (18)$$

where $k \in \mathcal{K}^*$, and $\mu \in \mathbb{R}$ is a constant called the water level. The optimal power p_k^* can be found using a root-finding algorithm (Palomar and Fonollosa, 2005).

However, if the initial set of scheduled users $\mathcal{K}'$ (from Algorithm 1) is infeasible for P3, a feasible subset $\mathcal{K}^*$ is obtained by a user deletion procedure, described in Algorithm 2. This algorithm iteratively removes users to meet the power constraint. Specifically, in lines 3–5, the user with the smallest channel gain (norm squared) is removed from the current set of users. Then, in line 6, the minimum power required to serve the users in the reduced set is calculated using the updated channel matrix. These steps (lines 3–7) are repeated until the feasibility condition (17) is met. The algorithm then outputs the feasible user set $\mathcal{K}^*$. For

Algorithm 2, the complexity mainly depends on the feasibility check and the final water-filling power allocation, i.e., steps 2–7. The complexity of steps 3–4 is $\mathcal{O}(|\mathcal{K}^*|)$, while the complexity of steps 5–6 is approximately $\mathcal{O}(|\mathcal{K}^*|^3)$. The worst-case complexity is $\mathcal{O}(|\mathcal{K}^*|^4)$, but in practice, the number of iterations is much smaller than $|\mathcal{K}^*|$. Thus, the complexity of Algorithm 2 is $\mathcal{O}(|\mathcal{K}^*|^3)$.

Algorithm 2 User deletion procedure

Input: The set of initially scheduled users $\mathcal{K}'$; the minimum spectral efficiency requirements $\{\bar{R}_k\}_{k \in \mathcal{K}'}$; the channel coefficient matrix $\mathbf{H}_{\mathcal{K}'} \in \mathbb{C}^{N \times |\mathcal{K}'|}$ for users in $\mathcal{K}'$; the maximum transmit power $P_{\max}$

Output: The feasible set of scheduled users $\mathcal{K}^*$

- 1: $\mathcal{K}^* \leftarrow \mathcal{K}'$
 - 2: **repeat**
 - 3: $k_{\text{remove}} \leftarrow \arg \min_{k \in \mathcal{K}^*} \|\mathbf{h}_k\|^2$
 - 4: $\mathcal{K}^* \leftarrow \mathcal{K}^* \setminus \{k_{\text{remove}}\}$
 - 5: Construct the channel matrix $\mathbf{H}^* \in \mathbb{C}^{N \times |\mathcal{K}^*|}$ for the users in the current set $\mathcal{K}^*$
 - 6: $\bar{p}_k = \sigma_n^2 (2^{\bar{R}_k} - 1) [(\mathbf{H}^{*H} \mathbf{H}^*)^{-1}]_{k,k}, \forall k \in \mathcal{K}^*$
 - 7: **until** $\sum_{k \in \mathcal{K}^*} \bar{p}_k \leq P_{\max}$
-

3.3 Overall algorithm

The overall algorithm to solve P0 is presented in Algorithm 3. This algorithm jointly optimizes user scheduling and power allocation to maximize the sum spectral efficiency in the multi-user XL-MIMO system. The process involves three main stages. First, an initial set of users $\mathcal{K}'$ is selected by Algorithm 1, which aims to group users with low spatial correlation based on angular resolution and distance criteria to mitigate IUI. Second, if the minimum power required by the users in $\mathcal{K}'$ exceeds the BS's maximum transmit power $P_{\max}$, users are iteratively removed from this set using the deletion procedure in Algorithm 2. This step ensures that the final set of scheduled users, $\mathcal{K}^*$, has a total minimum power demand that respects the power budget. Finally, for the feasible user set $\mathcal{K}^*$, the water-filling algorithm, as described by Eq. (18), is employed for dynamic power allocation. This optimizes the sum spectral efficiency while satisfying each scheduled user's QoS requirement. For Algorithm 3, the complexity is mainly determined by Algorithms 1 and 2; therefore, the overall complexity is $\mathcal{O} \left(\frac{K^2}{s} + |\mathcal{K}^*|^3 \right)$.

Algorithm 3 Proposed algorithm for P0

Input: The set of all users $\mathcal{S}$; the spatial angular resolution $\Delta\theta_{\text{res}}$; the distance threshold parameter Z_Δ ; the maximum transmit power $P_{\max}$; the minimum spectral efficiency requirements $\{\bar{R}_k\}_{k \in \mathcal{K}'}$

Output: The feasible set of scheduled users $\mathcal{K}^*$; the allocated powers $\{p_k^*\}_{k \in \mathcal{K}^*}$

- 1: Generate the initial scheduled user set $\mathcal{K}'$ by using Algorithm 1
- 2: Construct the channel coefficient matrix $\mathbf{H} \in \mathbb{C}^{N \times |\mathcal{K}'|}$, and compute the minimum required total power $\sum_{k \in \mathcal{K}'} \bar{p}_k$
- 3: **while** $\sum_{k \in \mathcal{K}'} \bar{p}_k > P_{\max}$ **do**
- 4: Update the scheduled user set $\mathcal{K}^*$ by deleting users according to Algorithm 2, and recompute $\sum_{k \in \mathcal{K}^*} \bar{p}_k$
- 5: **end while**
- 6: Obtain a feasible scheduled user set $\mathcal{K}^*$
- 7: For all $k \in \mathcal{K}^*$, obtain p_k^* according to Eq. (18)
- 8: **return:** $\mathcal{K}^*$; $\{p_k^*\}_{k \in \mathcal{K}^*}$

4 Extension to modular XL-MIMO communications

The joint optimization framework developed in Section 3 provides an effective methodology for XL-MIMO systems. We now extend this framework to the modular XL-MIMO scenario.

The system setup for modular XL-MIMO is similar to that described in Section 2. The key difference lies in the replacement of the conventional ULA at the BS with a modular ULA (mULA), where the BS consists of M modules, each containing N_m antennas, as shown in Fig. 2. Therefore, the total number of antennas is $N = MN_m$. The aperture size of each module is $S = (N_m - 1)d$. We assume that the distance between the central elements of adjacent modules is Γd , where Γ is a design parameter. For instance, if a modular XL-array is deployed on a building facade with modules separated by windows, Γ would be influenced by the window dimensions. A condition like $\Gamma \geq N_m$ might be typical if modules are physically separated, though practical constraints could lead to other values. In particular, when $\Gamma = N_m$, the mULA reduces to a conventional ULA (a form of collocated XL-array). The total physical size of the mULA is $D = [(M - 1)\Gamma + (N_m - 1)]d$. For notational convenience, we assume that both M and N_m are odd integers. Thus, the module index m and the intra-module antenna index n belong to the sets $\mathcal{M} = \{0, \pm 1, \dots, \pm \frac{(M-1)}{2}\}$ and $\mathcal{N}_m = \{0, \pm 1, \dots, \pm \frac{(N_m-1)}{2}\}$, respectively. Accordingly, the position of the n^{th} antenna element in module m along the y axis is given by $y_{m,n} =$

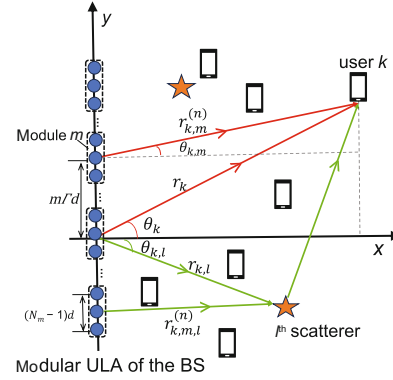


Fig. 2 A multi-user modular XL-MIMO downlink communication system

$(m\Gamma + n)d$. The position vector of this element is $\mathbf{w}_n = [0, y_{m,n}]^T$.

The array response vector $\mathbf{b}(r_k, \theta_k)$ for the mULA can be derived in a manner similar to that for Eq. (2), yielding

$$\mathbf{b}(r_k, \theta_k) = \frac{1}{\sqrt{N}} \left[e^{-j \frac{2\pi}{\lambda} r_{k,m}^{(n)}} \right]_{n \in \mathcal{N}_m, m \in \mathcal{M}}, \quad (19)$$

where $r_{k,m}^{(n)} = \sqrt{r_k^2 - 2r_k y_{m,n} \sin \theta_k + y_{m,n}^2}$ denotes the distance between user k (at (r_k, θ_k) in polar coordinates relative to the array center) and the n^{th} antenna element in module m .

The considered user distance range is $\max\{5D, \frac{4SD}{\lambda}\} \leq r_k < \frac{2D^2}{\lambda}$. Within this range, users are assumed to be in the extended far-field region of each individual module but in the near-field region of the overall array (Li et al., 2023). Consequently, for the purpose of analyzing spatial characteristics, certain approximations can be made: the angle from user k to any module m is approximately $\theta_{k,m} \approx \theta_k$. Furthermore, for deriving simplified correlation properties, the position of an antenna element (m, n) might be approximated by the position of its module's center, i.e., $y_{(m,n)} \approx y_{(m,0)} = m\Gamma d$. The validity and implications of such approximations were discussed in Li et al. (2023). By analyzing the beam focusing correlation $f(r_k, \theta_k; r_j, \theta_j) = |\mathbf{b}^H(r_k, \theta_k) \mathbf{b}(r_j, \theta_j)|$ for the modular XL-MIMO, analogous to the derivation leading to Eq. (8), the spatial angular resolution can be expressed as $\Delta\theta_{\text{res}}^{\text{mod}} = \frac{\lambda}{M\Gamma d}$. The distance constraint between users k and j (when $\theta_k \approx \theta_j = \theta$) can then be derived as

$$\left| \frac{1}{r_j} - \frac{1}{r_k} \right| \geq \frac{2\lambda\beta_\Delta^2}{M^2\Gamma^2 d^2 \cos^2 \theta} = \frac{1}{Z_{\Delta, \text{mod}} \cos^2 \theta}, \quad (20)$$

where $Z_{\Delta, \text{mod}} = \frac{M^2 \Gamma^2 d^2}{2\lambda \beta_{\Delta}^2}$. Here, $Z_{\Delta, \text{mod}}$ represents the effective distance threshold parameter for the mULA, and β_{Δ} is defined as in the context of Lemma 1.

Comparing these expressions with those for the conventional XL-MIMO, it can be seen that the mULA potentially offers different spatial resolution characteristics. If, for instance, $M\Gamma d > Nd$ (i.e., $\Gamma > N_m$), the mULA would provide finer angular resolution. Similarly, the distance resolution properties, characterized by $Z_{\Delta, \text{mod}}$, are scaled by $(\Gamma/N_m)^2$ compared to a continuous ULA of $N = MN_m$ antennas if $N^2 d^2$ is taken as $M^2 N_m^2 d^2$. Due to the challenge of satisfying QoS requirements when serving many users simultaneously in modular XL-MIMO systems, we again consider the user scheduling problem, formulated similarly to P0. To address this, a scheduled user set can be determined using adaptations of Algorithms 1 and 2, followed by power allocation for the selected users. This joint optimization approach remains applicable to modular XL-MIMO systems. We refer to this adapted overall algorithm as SCS-mod.

5 Numerical results

In this section, we present simulation results to demonstrate the performance of the proposed scheduling algorithms. Unless otherwise specified, the simulation parameters are set as follows: the inter-element spacing is $d = \lambda/2$. Given a carrier frequency that results in $\lambda = 0.1256$ m (e.g., around 2.38 GHz), $d = 0.0628$ m. The correlation threshold for Lemma 1 is $\Delta = 0.5$. The system bandwidth is $B = 20$ MHz, and the noise power spectral density is -174 dBm/Hz. The minimum spectral efficiency requirement for each user, $\bar{R}_k$, is varied, but for Figs. 3 and 4, it is set to 15 bit/(s·Hz). The predefined angular range for user grouping (as mentioned in Section 3.1) is $\Theta = \pi/6$. The total number of antennas in the conventional XL-MIMO array is $N = 128$. We consider a Rician fading channel model with one LoS path and $L_k = 3$ NLoS paths, and the Ricain factor is set to $\kappa = 8$. The BS transmit power budget, P_{max} , ranges from 0 dBm to 30 dBm. For the modular XL-MIMO configuration (SCS-mod), the BS has $M = 32$ modules, each containing $N_m = 4$ antennas (totaling $N = MN_m = 128$ antennas). The inter-module

spacing parameter is $\Gamma = 13$. In each Monte-Carlo simulation trial, $K = 100$ users are randomly and uniformly distributed within a cell, with distance $r_k \in [40, 200]$ m from the BS array center and angle $\theta_k \in [-\pi/2, \pi/2]$ relative to the array's broadside.

We compare our proposed algorithms, SCS (for conventional XL-MIMO) and SCS-mod (for modular XL-MIMO), with the following three benchmark schemes:

(1) Clique search-based scheduling (CBS) (De Souza et al., 2023). The CBS algorithm models the user scheduling problem as finding a maximum weight clique in an undirected graph and employs a greedy search. Its complexity is $\mathcal{O}(NK^2 + |\mathcal{K}^*|^3)$, where N is the number of antenna elements.

(2) Distance-based scheduling (DBS) and simplified (DBS-s) (González-Coma et al., 2021). The DBS algorithm schedules users based on an equivalent distance metric, defined in Eq. (7) in González-Coma et al. (2021). Its complexity is $\mathcal{O}(NK|\mathcal{K}^*| + |\mathcal{K}^*|^3)$. The DBS-s is a lower-complexity variant, where the equivalent distance is replaced by the direct distance between the user and the BS array center. Its complexity is $\mathcal{O}(|\mathcal{K}^*|^3)$.

Fig. 3 illustrates the sum spectral efficiency versus the transmit power P_{max} for different scheduling algorithms when $\bar{R}_k = 15$ bit/(s·Hz). The sum spectral efficiency of all algorithms increases with P_{max} , but the growth rate decreases at high power levels, indicating that performance becomes limited by IUI rather than noise. The proposed SCS and SCS-mod algorithms consistently outperform the baseline schemes (CBS, DBS, and DBS-s), especially at high power levels. This superior performance is attributed to their effective spatial correlation-based user selection, which better mitigates IUI. Notably, SCS-mod achieves the highest sum spectral efficiency, benefiting from the potentially enhanced angular resolution and distance discrimination capabilities of the modular XL-MIMO architecture. In addition, it is worth emphasizing that our proposed algorithm exhibits lower complexity than CBS and DBS. Although DBS-s achieves the lowest complexity, it comes at the cost of significantly reduced interference suppression capability.

Fig. 4 shows the number of scheduled users as a function of the transmit power P_{max} , again for $\bar{R}_k = 15$ bit/(s·Hz). As P_{max} increases, all algorithms are able to schedule more users. The proposed

SCS and SCS-mod algorithms schedule significantly more users than the baseline methods. This improvement stems from their ability to select users with lower inter-channel correlation, thereby reducing IUI, which is crucial for supporting a larger number of concurrent users in XL-MIMO systems. The modular design leveraged by SCS-mod further enhances the spatial separability, leading to the highest user scheduling capacity among the considered schemes.

Fig. 5 depicts the impact of the minimum spectral efficiency requirement, $\bar{R}_k$, on the sum spectral efficiency when the transmit power is fixed at $P_{\max} = 30$ dBm. As $\bar{R}_k$ increases, the sum spectral efficiency decreases for all algorithms, because stricter QoS constraints make user scheduling more challenging under the total power limit. Nevertheless, the SCS and SCS-mod schemes maintain significantly higher sum spectral efficiency compared to CBS, DBS, and DBS-s across the range of $\bar{R}_k$ values.

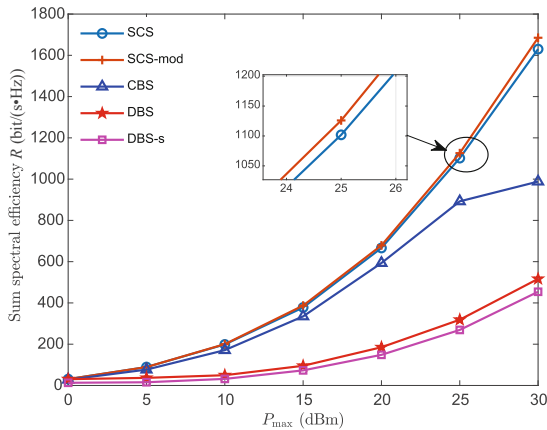


Fig. 3 Sum spectral efficiency vs. transmit power $P_{\max}$ for $\bar{R}_k = 15$ bit/(s·Hz)

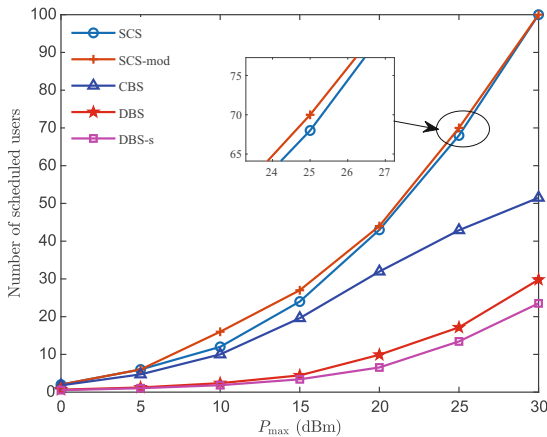


Fig. 4 Number of scheduled users vs. transmit power $P_{\max}$ for $\bar{R}_k = 15$ bit/(s·Hz)

This demonstrates the robustness of the proposed methods in maintaining efficient resource utilization even under more stringent user requirements.

Fig. 6 shows the system's sum spectral efficiency as a function of the inter-module spacing Γ under various transmit power levels. As Γ increases from its minimum value (i.e., $\Gamma = N_m = 4$, corresponding to a collocated XL-MIMO), a significant improvement in sum spectral efficiency is observed. This gain is attributed to the enlarged array aperture, which provides finer spatial resolution and enables our proposed SCS-mod algorithm to achieve more effective user scheduling and interference suppression. However, as Γ further increases, the improvement gradually diminishes because excessive inter-module spacing introduces dense grating lobes, increasing the likelihood of user interference through lobe overlap and offsetting the benefits of higher spatial resolution.

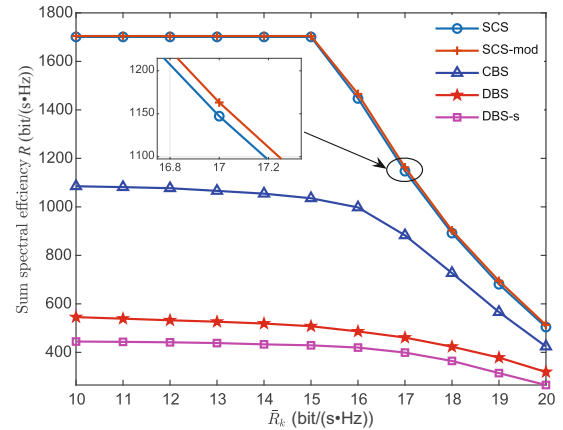


Fig. 5 Sum spectral efficiency vs. minimum spectral efficiency requirement $\bar{R}_k$ for $P_{\max} = 30$ dBm

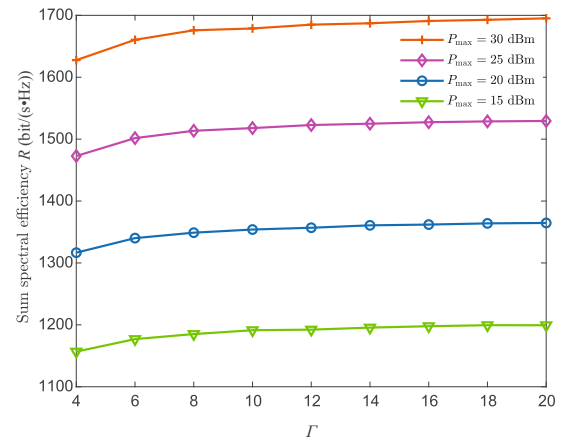


Fig. 6 Sum spectral efficiency vs. different module spacings for $\bar{R}_k = 10$ bit/(s·Hz)

To evaluate the impact of imperfect channel knowledge, we adopt a widely used channel estimation error model. The estimated channel for user k is modeled as $\hat{\mathbf{h}}_k = (\sqrt{1-\alpha^2})\mathbf{h}_k + \alpha\mathbf{e}_k$, where $0 \leq \alpha < 1$, $\hat{\mathbf{h}}_k$ is the estimated channel vector, and $\mathbf{e}_k \sim \mathcal{N}_{\mathbb{C}}(0, \|\mathbf{h}_k\|_2^2 \mathbf{I}_N)$ represents the estimation error (De Souza et al., 2023). The quality of the channel estimate is quantified by the normalized mean squared error (NMSE), defined as $\text{NMSE} = \mathbb{E} \left[\frac{\|\hat{\mathbf{h}}_k - \mathbf{h}_k\|_2^2}{\|\mathbf{h}_k\|_2^2} \right]$, where the expectation is taken over $\mathbf{e}_k$. Fig. 7 illustrates how the sum spectral efficiency of different scheduling algorithms is affected by this channel uncertainty, as measured by the NMSE. As expected, the performance of all algorithms degrades with increasing NMSE. However, our proposed SCS and SCS-mod algorithms consistently outperform the benchmarks, highlighting their robustness to channel estimation errors. In particular, the SCS-mod benefits from the higher spatial resolution of the modular array, whereas the efficiencies of DBS and DBS-s degrade sharply and approach zero when NMSE exceeds -10 dB, indicating their vulnerability to imperfect CSI. These findings underscore the critical importance of designing robust algorithms that account for CSI errors.

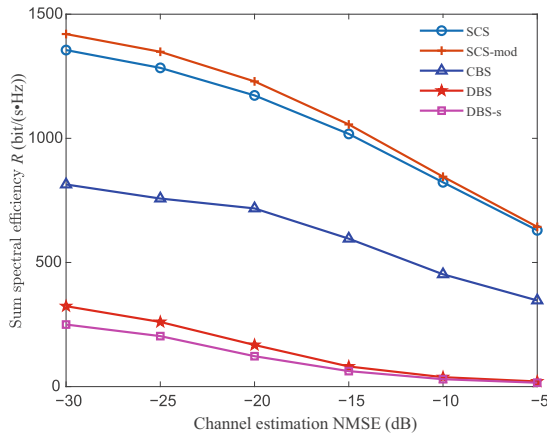


Fig. 7 Sum spectral efficiency vs. channel estimation NMSE for $P_{\max} = 30$ dBm

6 Conclusions

This study addressed user scheduling and resource allocation in XL-MIMO systems, focusing on near-field interference management under high user density. We proposed a QoS-aware joint user scheduling and power control algorithm (SCS) that

maximizes sum spectral efficiency while meeting user QoS. The SCS algorithm employed a spatial correlation-based selection strategy, considering both angular and distance domains, to mitigate IUI. We further extended this framework to modular XL-MIMO architectures with an adapted algorithm (SCS-mod). This SCS-mod algorithm leveraged the distinct spatial characteristics of mULAs to enhance user discrimination and interference suppression. Simulation results demonstrated that our proposed SCS and SCS-mod algorithms significantly outperform existing benchmarks in sum spectral efficiency and the number of scheduled users. The efficacy of the interference management was particularly evident in high-power, dense-user scenarios. Moreover, the proposed methods showed robustness under stringent QoS constraints, validating the benefits of the joint scheduling and dynamic power allocation strategy and the angle-distance dual-domain approach for interference suppression in XL-MIMO communications.

Contributors

Yingliang XIAN and Guangchi ZHANG designed the research. Yingliang XIAN processed the data and drafted the paper. Guangchi ZHANG and Yaqian YI helped organize the paper. Guangchi ZHANG, Miao CUI, Qingqing WU, Xiaoli XU, and Yong ZENG revised and finalized the paper.

Conflict of interest

All the authors declare that they have no conflict of interest.

Data availability

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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