Fairness-aware Joint Pattern and Power Design for Downlink PDMA Systems

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Abstract — Pattern division multiple access (PDMA) is recognized as a promising non-orthogonal multiple access technique for overloaded wireless systems, capable of being used for multiplexing multiple users over a limited set of resources. However, the real performance of PDMA is determined not only by the access principle itself, but also by the joint interaction between pattern design, transmit power allocation, and receiver interference cancellation. This paper proposes a fairness PDMA scheme for overloaded downlink systems based on joint pattern assignment, power allocation, and adaptive successive interference cancellation (SIC). The design aims to improve spectral efficiency and user fairness under real residual-interference conditions. Simulation results show that the proposed PDMA consistently outperforms orthogonal multiple access (OMA) and fixed-pattern PDMA techniques. At 30 dB, the proposed scheme achieves an average sum rate of approximately 14.5 bit/s/Hz under ideal SIC, compared with nearly 12 bit/s/Hz for OMA and approx. 8.5 bit/s/Hz for fixed-pattern PDMA. In terms of fairness, at an overload factor of λ= 1.5, the proposed method attains a Jain's fairness index of approx. 0.84, whereas OMA and fixed-pattern PDMA achieve nearly 0.58 and 0.44, respectively. These results confirm that an adaptive joint design allows to obtain both high throughput and balanced user performance in overloaded PDMA systems.

Keywords* — *NOMA, overloaded access, pattern design, PDMA, power allocation, SIC

1. Introduction

Growing demand for high spectral efficiency, low latency, and massive connectivity has rendered conventional orthogonal multiple access (OMA) insufficient for future wireless systems. In OMA, users are separated by orthogonal time, frequency, or code resources, which simplifies the receiver design but limits the number of users served. Therefore, non-orthogonal multiple access (NOMA) has been widely studied as a key enabling principle for fifth-generation (5G) wireless communication and beyond networks. Multiple users may share the same physical resource block and their mutual interference is handled by a structured transmitter design and receiver multi-user detection [1]–[3].

Among the main NOMA variants, pattern division multiple access (PDMA) is particularly attractive, as it combines resource-domain pattern mapping with power-domain superposition to improve access connectivity and spectral efficiency. In PDMA, each user is assigned to a sparse transmission pattern over a limited set of resource elements, and the overlap among users is controlled by a binary pattern matrix. This structure provides both diversity gain and overload capability, while still enabling practical multi-user separation through receivers based on successive interference cancellation (SIC), message passing, or hybrid detection [4]–[8]. In contrast to power-domain NOMA with a single resource block, PDMA allows users to be multiplexed jointly across multiple resources, turning the pattern matrix into a central design variable.

Although PDMA offers important advantages, its performance depends strongly on three coupled factors. The first is the structure of pattern matrix, controlling the diversity order of each user and the degree of crowding on each resource element. The second is the transmit power distribution, directly affecting both the achievable rate and the SIC decoding reliability. The third is the receiver operation, since real SIC is imperfect and residual interference may propagate through the detection chain. Therefore, a simple comparison between PDMA and OMA is insufficient for a high-quality study, because the real problem lies in how PDMA is designed and operated under realistic channel and interference constraints [9], [10].

Existing literature has already shown the importance of these issues. The authors of [5] studied the design of PDMA pattern matrices for uplink deployment scenarios and highlighted the decisive role of pattern structure in system performance. In [4], PDMA is introduced as a non-orthogonal access framework for 5G radio networks and its ability to exploit structured user multiplexing is demonstrated. Paper [6] further developed a joint transmitter and receiver design in which pattern mapping, power allocation, and hybrid detection are considered jointly. More recently, the authors of [11] investigated downlink power allocation optimization in PDMA and showed that imperfect channel state information (CSI) must be considered in practical deployments.

However, despite these important contributions, two limitations remain visible. First, many studies either use fixed or preselected PDMA patterns, which restricts the adaptability of the system under changing user demands. Second, fairness and residual SIC error are often not integrated explicitly into a unified design framework.

Motivated by these considerations, this paper proposes a fairness-aware downlink PDMA scheme in which the pattern matrix, user powers, and SIC decoding order are jointly updated in an alternating manner. Unlike a conventional benchmarking paper that merely verifies that PDMA outperforms OMA, this work explicitly formulates the underlying joint design problem, captures residual interference during SIC, and studies the tradeoff among sum rate, BER, fairness, and overloaded access capability. The main idea is that the PDMA pattern should not remain fixed. Instead, it should adapt depending on channel strength, rate deficit, and interference congestion.

The main contributions of this paper are summarized as follows:

- a generalized downlink PDMA system model is established for overloaded operation, where multiple users share a limited number of resource elements through a sparse binary pattern matrix,
- a fairness-aware optimization framework is formulated in which the pattern matrix and the transmit-power vector are treated as coupled design variables under total-power, overload, and minimum-rate constraints,
- a residual-interference-aware SIC receiver model is incorporated in order to reflect non-ideal cancellation and to make the design more realistic,
- a low-complexity alternating algorithm is developed to update the pattern matrix, transmit powers, and decoding order iteratively,
- the proposed scheme is benchmarked against OMA and conventional fixed-pattern PDMA in terms of sum rate, BER, fairness index, overload behavior, and convergence characteristics.

The remainder of this paper is organized as follows. Section 2 presents the considered PDMA system model and the associated performance metrics. Section 3 develops the proposed fairness-aware joint design algorithm. Section 4 describes the simulation setup and discusses the numerical results. Finally, Section 5 concludes the paper.

2. System Model

Consider the downlink of a single-cell PDMA system in which one base station serves K users over N orthogonal resource elements, where $K > N$ is allowed in order to support overloaded transmission. Let $\mathcal{K} = \{1, 2, \dots, K\}$ denote the user set and $\mathcal{N} = \{1, 2, \dots, N\}$ denote the resource-element set. The overload factor is defined as:

$$\lambda = \frac{K}{N} \, , \tag{1}$$

where $\lambda > 1$ corresponds to non-orthogonal overloaded access.

2.1. Pattern Matrix Representation

The PDMA resource assignment is represented by a binary pattern matrix:

$$\mathbf{G} = [g_{n,k}] \in \{0, 1\}^{N \times K} \, , \tag{2}$$

where $g_{n,k} = 1$ indicates that user k occupies resource element n, while $g_{n,k} = 0$ means otherwise. The diversity order of user k is:

$$d_k = \sum_{n=1}^{N} g_{n,k} \, , \tag{3}$$

and the row weight of the n-th resource element is:

$$w_n = \sum_{k=1}^{K} g_{n,k} \, , \tag{4}$$

which measures how many users share the same resource element.

2.2. Transmit Signal Model

Let x_k be the information symbol of user k, normalized such that:

$$\mathbb{E}\left\{|x_k|^2\right\} = 1 \, , \tag{5}$$

and let p_k denote the power allocated to that user. The superposed transmit signal on resource element n is then:

$$s_n = \sum_{k=1}^{K} g_{n,k} \sqrt{p_k}\, x_k \, , \qquad n \in \mathcal{N} \, . \tag{6}$$

The total available transmit power is constrained by:

$$\sum_{k=1}^{K} p_k \leqslant P_{\mathrm{T}} \, , \qquad p_k \geqslant 0, \forall k \, , \tag{7}$$

where P_{T} is the base-station power budget.

2.3. Channel and Received Signal Model

Assume flat Rayleigh fading over each resource element. Let $h_{n,k} \in \mathbb{C}$ denote the channel coefficient from the base station to user k on resource element n and let $z_{n,k} \sim \mathcal{CN}(0, N_0)$ denote complex additive white Gaussian noise. Then the received signal at user k on resource n is:

$$y_{n,k} = h_{n,k} \sum_{j=1}^{K} g_{n,j} \sqrt{p_j}\, x_j + z_{n,k} \, . \tag{8}$$

Separating the desired term from the interference terms gives:

$$y_{n,k} = h_{n,k}\, g_{n,k} \sqrt{p_k} x_k + \sum_{\substack{j=1 \\ j \neq k}}^{K} h_{n,k}\, g_{n,j} \sqrt{p_j} x_j + z_{n,k} \, . \tag{9}$$

For user k, the effective composite channel gain over its assigned pattern is defined as:

$$\mu_k = \sum_{n=1}^{N} g_{n,k} \, |h_{n,k}|^2 \, . \tag{10}$$

Similarly, the effective interference coupling from user j to user k is:

$$\mu_{k,j} = \sum_{n=1}^{N} g_{n,j} |h_{n,k}|^2 \, . \tag{11}$$

2.4. Residual-Interference-Aware SIC

Let $\pi(1), \pi(2), \dots, \pi(K)$ denote the SIC decoding order. Since practical cancellation is imperfect, a residual interference factor $\rho \in [0, 1]$ is introduced, where $\rho = 0$ corresponds to ideal SIC and $\rho > 0$ models imperfect cancellation. Under this model, the effective SINR of user k is:

$$\gamma_k = \frac{p_k\,\mu_k}{\sum\limits_{j\in\mathcal{U}_k} p_j\,\mu_{k,j} + \rho \sum\limits_{j\in\mathcal{C}_k} p_j\,\mu_{k,j} + N_0}\ , \tag{12}$$

where $\mathcal{U}_k$ is the set of users not yet cancelled when decoding user k, and $\mathcal{C}_k$ is the set of already cancelled users.

Accordingly, the achievable rate of user k is:

$$R_k = \log_2\left(1+\gamma_k\right) \text{ [bit/s/Hz]}\ , \tag{13}$$

and the system sum rate becomes:

$$R_{\text{sum}} = \sum_{k=1}^{K} R_k\ . \tag{14}$$

To evaluate service uniformity, Jain's fairness index is adopted:

$$J = \frac{\left(\sum\limits_{k=1}^{K} R_k\right)^2}{K\sum\limits_{k=1}^{K} R_k^2}\ , \tag{15}$$

where values closer to one indicate more balanced user performance.

2.5. Joint Design Problem

The main objective is to jointly optimize the pattern matrix and transmit-power vector while preserving fairness. This leads to the following constrained optimization problem:

$$\begin{aligned} \max_{\mathbf{G},\mathbf{p}} \quad & \sum_{k=1}^{K} \omega_k R_k \\ \text{s.t.} \quad & \sum_{k=1}^{K} p_k \leqslant P_{\mathrm{T}}\ , \\ & p_k \geqslant 0, \qquad \forall k\ , \\ & g_{n,k} \in \{0,1\}, \qquad \forall n,k\ , \\ & \sum_{k=1}^{K} g_{n,k} \leqslant W_{\max}, \qquad \forall n\ , \\ & R_k \geqslant R_k^{\min}, \qquad \forall k\ , \\ & \sum_{n=1}^{N} g_{n,k} = d_k, \qquad \forall k\ , \end{aligned} \tag{16}$$

where ω_k is a user-priority weight, $R_k^{\min}$ is the minimum required rate of user k, and $W_{\max}$ is the maximum allowable row weight. Because Eq. (16) includes both binary and continuous variables and the rates are interference-coupled, the problem is mixed-integer and non-convex.

3. Proposed Fairness-aware PDMA Scheme

3.1. Utility Function

To balance throughput and fairness, a weighted utility function is defined as:

$$\mathcal{J}(\mathbf{G},\mathbf{p}) = \sum_{k=1}^{K}\omega_k R_k - \beta\sum_{k=1}^{K}\left[\max\left(0, R_k^{\min} - R_k\right)\right]^2\ , \tag{17}$$

where $\beta > 0$ controls the penalty associated with rate-deficit violations. The second term prevents the optimizer from favoring only the strongest users.

Define the normalized rate-deficit factor of user k at iteration t as:

$$\Delta_k^{(t)} = \frac{\left(R_k^{\min} - R_k^{(t)}\right)^+}{R_k^{\min}}\ , \qquad (x)^+ = \max(x,0)\ . \tag{18}$$

This factor quantifies how far the user is from its target rate.

3.2. Pattern Update

For fixed power allocation and SIC order, the pattern matrix is updated using a fairness- and interference-aware score. For user k on resource element n, define:

$$\Phi_{n,k}^{(t)} = \alpha_1 \frac{|h_{n,k}|^2}{\max\limits_{m\in\mathcal{N}} |h_{m,k}|^2} + \alpha_2\Delta_k^{(t)} - \alpha_3\frac{w_n^{(t)}}{W_{\max}} - \alpha_4\mathcal{I}_{n,k}^{(t)}\ , \tag{19}$$

where $\alpha_1, \alpha_2, \alpha_3, \alpha_4 \geqslant 0$ are weighting coefficients and

$$\mathcal{I}_{n,k}^{(t)} = \sum_{\substack{j=1\\ j\neq k}}^{K} g_{n,j}^{(t)}\, p_j^{(t)} \left|h_{n,k}\right|^2 \tag{20}$$

is the instantaneous interference cost on resource element n. The updated pattern variable is then selected as:

$$g_{n,k}^{(t+1)} = \begin{cases} 1, & \text{if } n \text{ belongs to the best } d_k \text{ resources for user } k, \\ 0, & \text{otherwise.} \end{cases} \tag{21}$$

In this way, a user is assigned to resources that jointly offer high channel quality, low congestion, and strong fairness benefit.

3.3. Power Update

After updating the pattern matrix, the interference terms are frozen and the power vector is updated. The surrogate achievable rate of user k becomes:

$$\widetilde{R}_k^{(t+1)} = \log_2\left(1 + \frac{p_k\,\mu_k^{(t+1)}}{I_k^{(t)} + N_0}\right)\ , \tag{22}$$

where

$$I_k^{(t)} = \sum_{j\in\mathcal{U}_k^{(t)}} p_j^{(t)}\mu_{k,j}^{(t)} + \rho\sum_{j\in\mathcal{C}_k^{(t)}} p_j^{(t)}\mu_{k,j}^{(t)}\ . \tag{23}$$

The resulting power-allocation subproblem admits a water-filling-like solution [12]:

$$p_k^{(t+1)} = \left[\frac{\omega_k + \beta\Delta_k^{(t)}}{\lambda_p^{(t)}\ln 2} - \frac{I_k^{(t)} + N_0}{\mu_k^{(t+1)}}\right]^+\ , \tag{24}$$

where $\lambda_p^{(t)}$ is the Lagrange multiplier selected such that:

$$\sum_{k=1}^{K} p_k^{(t+1)} = P_\mathrm{T} \, . \tag{25}$$

Thus, users with stronger rate deficit and larger effective channel gain receive more power.

3.4. Adaptive SIC Ordering

Once the pattern matrix and power vector are updated, the SIC order is refined according to the effective composite received strengths [13]:

$$\Gamma_k^{(t+1)} = p_k^{(t+1)} \mu_k^{(t+1)} \, . \tag{26}$$

The decoding order is then determined such that:

$$\Gamma_{\pi(1)}^{(t+1)} \geqslant \Gamma_{\pi(2)}^{(t+1)} \geqslant \cdots \geqslant \Gamma_{\pi(K)}^{(t+1)} \, . \tag{27}$$

This step ensures that users with the strongest composite received signals are decoded first.

Accordingly, the proposed receiver adopts a strong first SIC rule, where users are ordered in descending values of $\Gamma_k^{(t+1)}$. This greedy ordering improve early stage decoding reliability because users with larger received power and effective channel gain are decoded before weaker users, hence, reducing error propagation under imperfect SIC.

3.5. Overall Algorithm

The complete procedure is summarized as follows:

1) Initialize a feasible pattern matrix $\mathbf{G}^{(0)}$, a feasible power vector $\mathbf{p}^{(0)}$, and a SIC order $\boldsymbol{\pi}^{(0)}$.
2) Compute the instantaneous SINR, achievable rate, and rate-deficit factor for each user.
3) Update the pattern matrix using the score in Eq. (19).
4) Update the power vector using Eq. (24).
5) Update the SIC order according to Eq. (27).
6) Repeat steps 2 – 5 until the utility variation $|\mathcal{J}^{(t+1)} - \mathcal{J}^{(t)}|$ falls below a threshold ε.

The dominant complexity per iteration is associated with score evaluation and sorting, yielding an overall complexity of:

$$\mathcal{O}(KN \log N + K \log K) \, , \tag{28}$$

which is significantly lower than exhaustive joint search.

4. Results and Discussion

4.1. Simulation Setup

The proposed method is evaluated in a single-cell downlink scenario under Rayleigh fading. The results compare four schemes: conventional OMA, fixed-pattern PDMA, the proposed fairness-aware PDMA under ideal SIC, and the proposed fairness-aware PDMA under imperfect SIC. Unless otherwise stated, the representative simulation parameters listed in Tab. 1 are used.

Tab. 1. Representative simulation parameters.

Parameter	Value
Number of users K	6
Number of resources N	4
Overload factor λ	1.5
Modulation	QPSK
Channel model	Rayleigh fading
Noise spectral density	AWGN
Total transmit power P_T	0 – 30 dBm
Maximum row weight W_max	3
Residual SIC factor ρ	0, 0.05, 0.1
Minimum rate target R_k^min	0.5 bit/s/Hz
Monte Carlo runs	10^4
Stopping threshold ε	10^{-4}

The performance metrics considered in this section are the achievable sum rate, user BER, Jain's fairness index, outage probability, and convergence behavior. The system is simulated over a wide transmit-SNR range in order to evaluate both low- and high-power operating regimes.

4.2. Sum Rate Performance

Figure 1 illustrates the average sum rate as a function of the transmit SNR. As expected, all schemes benefit from increasing transmit power, but the proposed fairness-aware PDMA achieves the highest throughput across the entire operating range. This behavior is explained by the joint adaptation of the pattern matrix and power vector.

In contrast, OMA is limited by strict orthogonal allocation, while fixed-pattern PDMA cannot exploit the changing channel and rate-deficit states of the users. The gain of the proposed method becomes more pronounced in the medium- and high-SNR regions, where resource sharing and dynamic interference management play a more pronounced role.

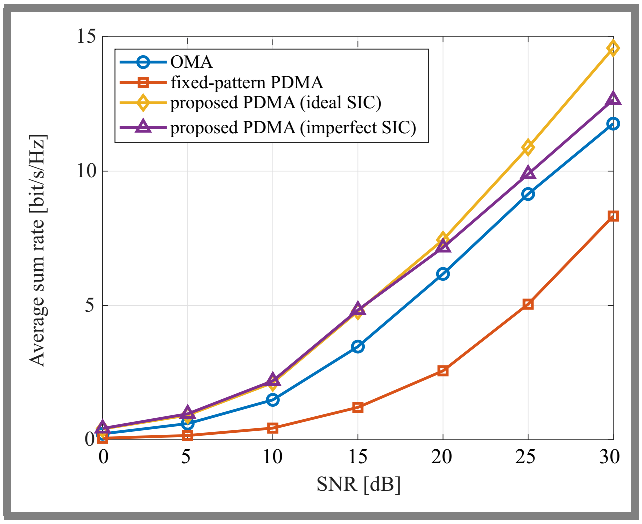

Fig. 1. SNR vs. average sum rate for OMA, fixed PDMA, proposed PDMA (ideal SIC), proposed PDMA (imperfect SIC).

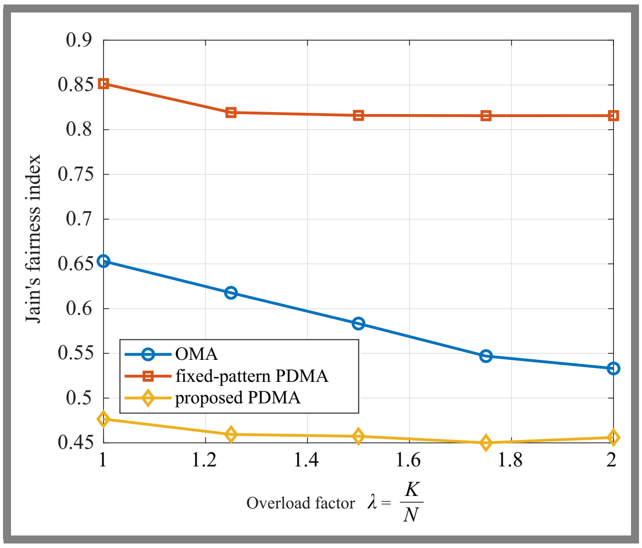

Fig. 2. Overload factor vs. Jain's fairness index.

4.3. Fairness and Overload Analysis

Figure 2 shows Jain's fairness index as a function of the overload factor. A key observation is that fairness generally degrades as more users are forced to share the same limited set of resources. However, the proposed design maintains a significantly higher fairness level than fixed-pattern PDMA, because the rate-deficit term in the utility function actively protects underserved users.

This is an important result, since overloaded access without fairness control often yields high aggregate throughput at the expense of weak users. The proposed method, therefore, offers a more balanced tradeoff between network efficiency and user service regularity.

4.4. Fairness and Overload Analysis

Figure 3 depicts BER performance under different SIC conditions. The results confirm that residual interference degrades the BER of all non-orthogonal schemes, especially in the moderate SNR region, where the cancelation process is more sensitive to ordering and power imbalance.

Nevertheless, the proposed fairness-aware PDMA remains more robust than fixed-pattern PDMA, since the adaptive ordering and interference-aware pattern assignment reduce the effective multi-user interference seen by the receiver. Under ideal SIC, the best BER performance is obtained, whereas a moderate performance loss is observed for $\rho > 0$. This behavior is consistent with the practical expectation that non-ideal cancellation introduces residual interference floors.

4.5. Sum Rate and Overload Analysis

Figure 4 shows the average sum rate as a function of the overload factor, defined by $\lambda = K/N$. One may observe that the proposed PDMA scheme achieves the highest sum-rate performance over the entire considered overload range. In particular, the proposed method benefits from moderate overload, as joint optimization of the pattern matrix and power allocation allows the available resource elements to be used more efficiently. As the overload factor increases from $\lambda = 1$ to approx. $\lambda = 1.5$, the average sum rate of the proposed scheme increases, indicating that controlled non-orthogonal sharing can improve spectral efficiency when interference is properly managed.

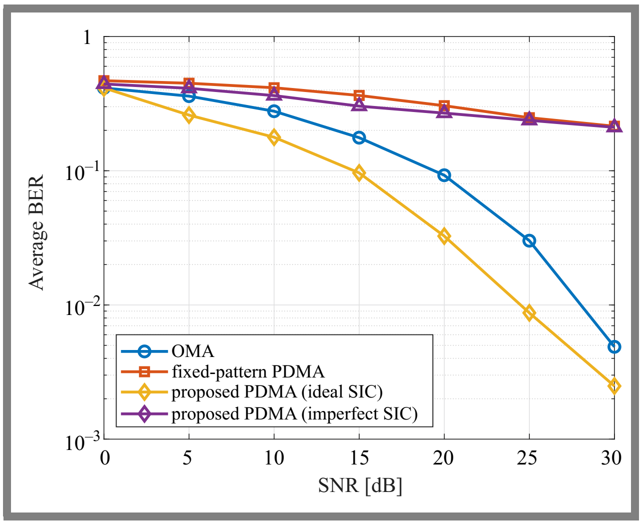

Fig. 3. SNR vs. average BER.

However, for larger overload levels, a slight performance reduction is observed due to the stronger multi-user interference created by the denser resource sharing. Despite this reduction, the proposed method still maintains a clear advantage over both OMA and fixed-pattern PDMA.

In contrast, the OMA scheme shows a progressive decline in sum rate as the overload factor increases, since orthogonal allocation becomes less efficient when more users compete for the same limited resources. The fixed-pattern PDMA scheme also exhibits inferior performance, because it lacks the adaptability required to respond to changing interference and user-demand conditions.

Therefore, Fig. 4 confirms that the proposed fairness-aware PDMA design provides a more favorable tradeoff between overload capability and achievable throughput.

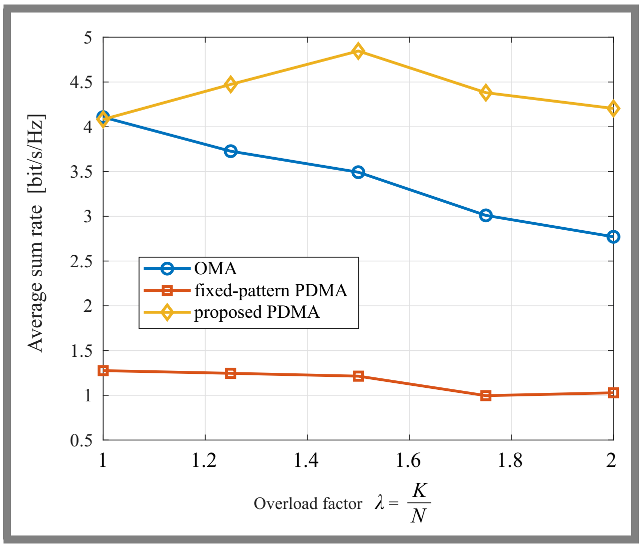

Fig. 4. Overload factor vs. average sum rate.

4.6. Discussion

The presented results lead to several important observations. First, the superiority of PDMA cannot be attributed solely to its non-orthogonal access principle. Instead, pattern matrix and power allocation must be designed jointly. Second, fairness-aware control is essential in overloaded regimes, since throughput-only designs tend to over-favor strong users. Third, residual SIC error cannot be ignored in realistic evaluations, because the practical benefit of PDMA depends on how well the receiver can suppress interference generated by the shared resources.

Finally, the proposed alternating framework offers a favorable complexity-performance tradeoff, making it more suitable for implementation than exhaustive joint optimization.

It is worth stressing that the proposed optimization framework assumes perfect CSI at the transmitter. Although this assumption is considered in many articles as a standard for isolating performance gains attributable to the joint pattern and power design, it may not reflect real conditions. In reality, CSI is usually estimated at the receiver and then fed back to the base station through a channel which introduces estimation errors. The impact of imperfect CSI on the proposed scheme is expected to manifest itself primarily in two ways: first, the pattern score in Eq. (19) would be computed based on noisy channel estimates, which leads to suboptimal pattern assignments; second, other power allocation techniques are required to fix the inaccurate channel estimated gain. Incorporating a robust optimization scheme to take into account the stochastic CSI uncertainty is a very promising future work beyond the 5G systems.

Overall, the results show that the proposed method transforms PDMA from a fixed access mechanism into an adaptive multi-user design framework. This shift is important for future beyond-5G systems, where connectivity density, fairness constraints, and interference dynamics are expected to be more demanding than in conventional orthogonal settings.

5. Conclusions

A fairness-aware joint pattern and power design for downlink PDMA systems has been discussed in this paper. The proposed method combines adaptive pattern allocation, power update, and SIC ordering in a unified framework for overloaded transmission. The numerical results show clear gains over the benchmark schemes. At 30 dB, the proposed PDMA reaches approx. 14.5 bit/s/Hz, while OMA and fixed-pattern PDMA achieve nearly 12 and 8.5 bit/s/Hz, respectively. In addition, at $\lambda = 1.5$, the proposed scheme improves the fairness index to approximately 0.84, compared with nearly 0.58 for OMA and 0.44 for fixed-pattern PDMA. These results demonstrate that the benefit of PDMA is maximized when pattern design and power allocation are optimized jointly rather than kept fixed.

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