

Interference-Aware Swap Matching for Full-Band MU-MIMO-OFDM User Scheduling under Channel Aging

André Almeida Souza Coelho , Rodrigo P. Lemos, Flávio Henrique Teles Vieira

Abstract—This paper proposes a user-scheduling framework for full-band multi-cell MU-MIMO-OFDM downlink systems. Each base station schedules users over a common 100 MHz carrier, while spatial separation is achieved through regularized zero-forcing precoding. The scheduling problem is coupled across cells due to inter-cell interference. We formulate it as a many-to-one matching game with externalities and propose an interference-aware swap-matching algorithm with a mixed throughput/proportional-fair potential. The potential uses an aging-aware rate predictor based on temporal channel correlation. We prove finite convergence to a two-exchange-stable matching and evaluate the proposed method against baseline schemes under channel aging.

Keywords—MU-MIMO-OFDM, user scheduling, matching theory, externalities, RZF precoding, channel aging, 5G NR, proportional fairness.

I. INTRODUCTION

Full-band multi-user multiple-input multiple-output (MU-MIMO) is a natural mechanism for increasing spectral efficiency in cellular downlink systems. Instead of partitioning the carrier bandwidth among scheduled users, a base station (BS) can transmit several spatial streams over the same time-frequency resources and separate them by precoding. This abstraction is consistent with 5G NR(New Radio) physical-layer operation in wide FR1(Frequency Range 1) carriers: NR BS specifications define wide channel-bandwidth operation, while the PDSCH(Physical Downlink Shared Channel) procedures support multi-layer transmission subject to UE(User Equipment) and BS capabilities [1], [2]. Therefore, in the full-band model considered here, a scheduled user is not assigned W/K Hz; each spatial stream is evaluated in bit/s/Hz over the common occupied carrier, and the aggregate bit rate is obtained by multiplying the sum spectral efficiency by W .

User scheduling for this operating mode is a classical but still challenging problem. Assignment-based methods, including the Hungarian algorithm, are attractive when the objective decomposes into fixed pairwise weights; proportional-fair (PF) scheduling [17] improves long-term fairness through historical-throughput weighting. Both become insufficient in full-band multi-cell MU-MIMO, where the utility of any user set depends on the other users co-scheduled in the same and neighboring cells via the RZF(Regularized Zero-Forcing)

precoder, the conditioning of the effective channel matrix, the residual intra-cell interference, and the inter-cell interference (ICI) leaked to other cells. Preferences are thus not fixed prior to the matching.

Matching theory provides a principled language for combinatorial resource allocation. The stable-marriage model of Gale and Shapley [4] and subsequent matching-market theory have been widely adapted to wireless networks [6], [7]. Nevertheless, many wireless systems exhibit *externalities*: the preference between two agents depends on the global matching profile. Such effects are well known to affect stability in matching markets [5], and recent wireless and networked-computing studies have exploited matching with externalities for interference-coupled D2D/NOMA resource allocation [8], secure semantic communications [9], and fog offloading/resource allocation [10]. These works demonstrate the relevance of externality-aware matching, but they do not address the specific full-band MU-MIMO-OFDM scheduler considered here, where the externality is induced jointly by RZF precoder recomputation, spatial user compatibility, and ICI coupling across cells.

Channel aging introduces a second difficulty: the scheduler and the precoder are computed from CSI acquired at pilot time, whereas the physical rate is produced by the channel realization at the data TTI(Transmission Time Interval). We adopt the classical Clarke/Jakes temporal-correlation model [15], whose impact on multiuser/massive MIMO has been characterized in [16]. A scheduler that optimizes an instantaneous rate computed from stale CSI may overestimate spatial separability and underestimate interference. A sound design must therefore rely only on causal information—pilot-time CSI, long-term gains, PF averages, and temporal correlation—while evaluating the final rate with the true aged channel.

This work addresses the gap through IA-SMPF, an interference-aware swap-matching scheduler for full-band MU-MIMO-OFDM under channel aging. Unlike per-cell PF or assignment-based schedulers, it internalizes ICI externalities and RZF conditioning inside the matching preferences; unlike generic matching-with-externalities formulations, it embeds an aging-aware rate predictor tailored to full-band spatial multiplexing. The contributions are: (i) a full-band signal model with $K = M = 4$ users multiplexed per cell over a common 100 MHz carrier; (ii) a many-to-one matching formulation with RZF/ICI externalities; (iii) an aging-aware rate predictor embedded in a mixed sum-SE/PF potential; and (iv) a finite-convergence proof for the proposed swap dynamics.

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The numerical section reports the throughput/fairness tradeoff against per-cell RZF-PF, greedy PF, and random scheduling.

Boldface lowercase and uppercase letters denote column vectors and matrices; $(\cdot)^H$ is the conjugate transpose, $(\cdot)$ a pilot-time estimate, $(\cdot)$ a time average, $\|\cdot\|$ and $\|\cdot\|_F$ the Euclidean and Frobenius norms, $\mathbf{I}_K$ the $K \times K$ identity, and $|\mathcal{S}|$ the cardinality of $\mathcal{S}$. $\mathbb{E}\{\cdot\}$ is the expectation, $\mathbb{C}$ the complex field, $\mathcal{CN}(0, \sigma^2)$ a circularly-symmetric complex Gaussian, $J_0(\cdot)$ the zeroth-order Bessel function of the first kind, and $\binom{U}{K}$ the binomial coefficient.

II. SYSTEM AND CHANNEL MODEL

A. Full-Band MU-MIMO-OFDM Downlink

Consider a downlink network with B cells, illustrated in Fig. 1 for the $B = 3$ configuration adopted in the evaluation. Each BS has $M = N_t$ antennas and serves a pool of U single-antenna users. At every TTI, BS b schedules exactly $K \leq M$ users, denoted by $\mathcal{S}_b(t)$, with $|\mathcal{S}_b(t)| = K$. All users in $\mathcal{S}_b(t)$ occupy the same carrier bandwidth W and the same OFDM resources. Their separation is purely spatial.

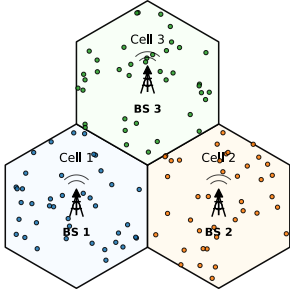


Fig. 1. Three-cell full-band MU-MIMO-OFDM downlink. Each BS is equipped with $M = 4$ antennas and serves a pool of U users, of which $K = 4$ are co-scheduled per TTI over the shared 100 MHz carrier; inter-cell interference couples the cells.

For subcarrier n and TTI t , the transmitted vector of BS b is

$$\mathbf{x}_b[n, t] = \sum_{k \in \mathcal{S}_b(t)} \sqrt{p} \mathbf{w}_{b,k}[n, t] s_{b,k}[n, t], \quad (1)$$

where $p = P_{\text{tx}}/K$ is the per-stream power, $s_{b,k}[n, t] \in \mathbb{C}$ is the unit-variance data symbol intended for user k on subcarrier n at TTI t (i.e., $\mathbb{E}\{|s_{b,k}[n, t]|^2\} = 1$), and $\mathbf{w}_{b,k}[n, t] \in \mathbb{C}^M$ is the unit-norm precoding vector applied by BS b to stream k on the same time-frequency resource, with $\|\mathbf{w}_{b,k}[n, t]\| = 1$. Let $\mathbf{h}_{b',b,k}[n, t] \in \mathbb{C}^M$ be the channel from BS b' to user $k \in \mathcal{S}_b(t)$. Using (1), the received signal of user k is

$$y_{b,k}[n, t] = \underbrace{\mathbf{h}_{b,b,k}^H[n, t] \mathbf{x}_b[n, t]}_{\text{serving-cell signal (desired + intra-cell)}} + \underbrace{\sum_{b' \neq b} \mathbf{h}_{b',b,k}^H[n, t] \mathbf{x}_{b'}[n, t]}_{\text{inter-cell interference (externality)}} + z_{b,k}[n, t], \quad (2)$$

where $z_{b,k}[n, t] \sim \mathcal{CN}(0, \sigma^2)$, with σ^2 computed over the occupied carrier bandwidth including the receiver noise figure. Expanding $\mathbf{x}_b[n, t]$ in the serving-cell term of (2) separates the desired stream from the intra-cell multi-user interference; the inter-cell term is the externality exploited in Section III.

The BS computes an RZF precoder [13], [14] from the estimated pilot-time channel matrix $\hat{\mathbf{H}}_b[n, t_0] = [\hat{\mathbf{h}}_{b,b,k_1}, \dots, \hat{\mathbf{h}}_{b,b,k_K}]$:

$$\mathbf{W}_b[n] = \hat{\mathbf{H}}_b[n] \left(\hat{\mathbf{H}}_b^H[n] \hat{\mathbf{H}}_b[n] + \alpha_{\text{RZF}} \mathbf{I}_K \right)^{-1}. \quad (3)$$

The columns of (3) are normalized to unit norm. In the simulations, $\alpha_{\text{RZF}} = K\sigma^2/p$, i.e., the MMSE-type loading that matches the regularized channel-inversion design of [13].

The instantaneous SINR is used only for performance evaluation with the aged channel:

$$\gamma_{b,k}[n] = \frac{p |\mathbf{h}_{b,b,k}^H[n] \mathbf{w}_{b,k}[n]|^2}{p \sum_{j \in \mathcal{S}_b \setminus \{k\}} |\mathbf{h}_{b,b,k}^H[n] \mathbf{w}_{b,j}[n]|^2 + I_{b,k}^{\text{inter}}[n] + \sigma^2}, \quad (4)$$

where the inter-cell interference term in (4) is

$$I_{b,k}^{\text{inter}}[n] = p \sum_{b' \neq b} \sum_{j \in \mathcal{S}_{b'}} |\mathbf{h}_{b',b,k}^H[n] \mathbf{w}_{b',j}[n]|^2. \quad (5)$$

Following the standard pre-log coherence factor of multiuser MIMO [14], the spectral efficiency is

$$R_{b,k} = \frac{\tau_d}{\tau_c} \frac{1}{N_{\text{sc}}} \sum_{n=1}^{N_{\text{sc}}} \log_2(1 + \gamma_{b,k}[n]) \quad [\text{bit/s/Hz}], \quad (6)$$

and the aggregate throughput is $W \sum_b \sum_{k \in \mathcal{S}_b} R_{b,k}$ bit/s. The bandwidth W is not divided by K .

B. Large-Scale Fading and Channel Aging

The channel coefficient can be written as

$$\mathbf{h}_{b',b,k}[n, t] = \sqrt{\beta_{b',b,k}} \tilde{\mathbf{h}}_{b',b,k}[n, t], \quad (7)$$

where $\beta_{b',b,k}$ contains distance-dependent path loss and log-normal shadowing. The simulation model uses a log-distance urban cellular path-loss law with exponent 3.76 and shadowing standard deviation of 8 dB. Standards-compliant 3GPP channel models, such as TR 38.901, can be inserted in the same framework by replacing $\beta_{b',b,k}$ [3].

Temporal channel evolution is modeled through the Clarke/Jakes correlation law [15]

$$\mathbf{h}(t_0 + \Delta) = \rho_{\Delta} \hat{\mathbf{h}}(t_0) + \sqrt{1 - \rho_{\Delta}^2} \mathbf{e}_{\Delta}, \quad (8)$$

$$\rho_{\Delta} = J_0(2\pi f_D \Delta T_{\text{TTI}}), \quad (9)$$

where $f_D = v f_c / c$ is the maximum Doppler shift. According to the aging model (8)–(9), the scheduler observes $\hat{\mathbf{h}}(t_0)$, large-scale gains, $\bar{R}_{b,k}$, and ρ_{Δ} , but not the future realization $\mathbf{h}(t_0 + \Delta)$. This distinction is essential: scheduling and precoding are causal, while the final rate (6) is evaluated with the true aged channel of (8).

The model (1)–(8) makes the scheduling difficulty explicit: through (3), the utility of each user $k \in \mathcal{S}_b$ depends on the whole $\mathcal{S}_b$ (intra-cell coupling) and, via the second term of (2), on $\{\mathcal{S}_{b'}\}_{b' \neq b}$ (inter-cell externality), with both effects evaluated only from $\hat{\mathbf{h}}(t_0)$ and ρ_{Δ} . Per-user PF metrics cannot represent these couplings; this motivates the many-to-one matching formulation with externalities of Section III.

III. MATCHING FORMULATION

Building on the externality observation closing Section II, let $\mathcal{S} = (\mathcal{S}_1, \dots, \mathcal{S}_B)$ denote the global scheduling profile. The problem is modeled as a many-to-one matching game with quotas $q_b = K$ and externalities [4], [6], [7].

A. Mixed Potential Function

A purely proportional-fair (PF) objective may sacrifice excessive sum spectral efficiency when $K = M$. We instead use the mixed potential

$$\Phi(\mathcal{S}) = \lambda \sum_b \sum_{k \in \mathcal{S}_b} \hat{R}_{b,k}^{\text{age}}(\mathcal{S}) + (1-\lambda) \sum_b \sum_{k \in \mathcal{S}_b} \frac{\hat{R}_{b,k}^{\text{age}}(\mathcal{S})}{(\bar{R}_{b,k} + R_0)^\eta}, \quad (10)$$

where $0 \leq \lambda \leq 1$, $0 \leq \eta \leq 1$, and $R_0 > 0$ prevents singular PF weights. The predictor $\hat{R}_{b,k}^{\text{age}}$ in (10) is not computed with the future channel; it is obtained from the pilot-time channel and the temporal correlation ρ_Δ of (9). A compact predictor is

$$\hat{\gamma}_{b,k}^{\text{age}}[n] = \frac{\rho_\Delta^2 p |\hat{\mathbf{h}}_{b,b,k}^H[n] \mathbf{w}_{b,k}[n]|^2}{\rho_\Delta^2 \hat{I}_{b,k}[n] + (1 - \rho_\Delta^2) I_{b,k}^{\text{err}}[n] + \sigma^2}, \quad (11)$$

where $\hat{I}_{b,k}$ includes estimated intra-cell and inter-cell interference and $I_{b,k}^{\text{err}}$ is a large-scale-fading penalty for residual uncertainty due to aging. In the implementation, $I_{b,k}^{\text{err}}$ is proportional to $p \sum_{b' \neq b} \beta_{b',b,k} \|\mathbf{w}_{b'}\|_F^2$, which is causal and avoids observing the unknown future fading term.

B. Stability and Complexity

Definition 1 (Two-exchange stability): A matching $\mathcal{S}^*$ is two-exchange stable if no admissible intra-cell replacement or two-cell exchange preserves the quotas and increases $\Phi(\mathcal{S})$ by more than $\epsilon > 0$.

The exhaustive network-wide search contains

$$\prod_{b=1}^B \binom{U}{K} = \binom{40}{4}^3 \approx 7.64 \times 10^{14} \quad (12)$$

profiles for the simulated case $B = 3$, $U = 40$, and $K = 4$, which is intractable for TTI-scale scheduling.

IV. IA-SMPF ALGORITHM

This section describes the proposed Robust IA-SMPF (Interference-Aware Swap Matching with Proportional Fairness) algorithm, which implements the matching formulation of Section III. The algorithm operates in three phases: (a) candidate set construction, (b) seed and swap matching iterations. We then prove in (c) finite convergence and analyze computational complexity.

A. Candidate Set Construction

Each cell b builds a candidate set $\mathcal{C}_b$ of size $C \ll U$ using the robust rate predictor, the PF weight, an inter-cell leakage penalty proportional to $\sum_{b' \neq b} \beta_{b',b,u}$, and spatial compatibility. The complete procedure is summarized in Algorithm 1.

B. Seed and Swap Iterations

The initial matching is built per cell using a greedy PF metric combined with a semi-orthogonality test on $\mathbf{h}_{b,u}$, as motivated by linear-precoding multiuser MIMO [11], [12]. From this seed, the algorithm evaluates two admissible operations— intra-cell replacement and inter-cell exchange—scoring each

Algorithm 1 Robust IA-SMPF

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1: Input:  $\hat{\mathbf{h}}, \beta, \rho_\Delta, \bar{R}, K, \epsilon$ 
2: Build candidate sets using robust rate, PF weight, leakage,
   and spatial compatibility
3:  $\mathcal{S}_b \leftarrow$  greedy-PF + semi-orthogonal seed,  $\forall b$ 
4: repeat
5:   for each cell  $b$  and admissible intra-cell replacement
     do
6:     recompute RZF, robust rates, and  $\Delta\Phi$ 
7:     if  $\Delta\Phi > \epsilon$  then
8:       accept the replacement; break
9:     end if
10:  end for
11:  if no intra-cell replacement is accepted then
12:    for each cell pair  $(b_1, b_2)$  and admissible coupled
      exchange do
13:      recompute  $\Delta\Phi$  with updated RZF and ICI
14:      if  $\Delta\Phi > \epsilon$  and participating utilities do not
        decrease then
15:        accept the exchange; break
16:      end if
17:    end for
18:  end if
19: until no admissible swap with  $\Delta\Phi > \epsilon$  exists
20: return  $\mathcal{S}^*$ 

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candidate set with the aging-aware predictor (11) inside the potential (10). A swap is accepted only if it increases (10) by more than ϵ ; inter-cell swaps additionally require that participating cells do not decrease their own utilities, preventing one cell from improving by creating excessive leakage to a neighbor.

C. Convergence and Complexity

Theorem 1 (Finite convergence): For fixed channel estimates, PF averages, temporal correlation, and candidate sets, Robust IA-SMPF terminates after finitely many accepted swaps and returns a two-exchange-stable matching.

Proof: The number of feasible matchings is finite because each cell selects one of $\binom{U}{K}$ subsets. Every accepted swap increases Φ by more than ϵ . For finite transmit power and nonzero noise, all predicted rates are bounded, and therefore Φ is upper bounded. A strictly increasing sequence with increments larger than ϵ cannot be infinite. At termination, no admissible swap yields $\Delta\Phi > \epsilon$, which is exactly two-exchange stability.

If C candidates per cell and N_s scheduling subcarriers are screened, each swap evaluation is dominated by RZF inversions of size $K \times K$ and interference recomputation. The resulting complexity is polynomial in B , C , K , and N_s , in contrast with the exponential exhaustive search. The final physical rate is still evaluated over all N_{sc} frequency samples.

V. NUMERICAL RESULTS

Table I summarizes the simulation setting. The baselines are per-cell RZF-PF (which ignores ICI externalities), GreedyPF (a single-cell PF metric), and Random scheduling.

TABLE I
SIMULATION PARAMETERS.

Parameter	Value
Cells/users per cell	$B = 3, U = 40$
Antennas/scheduled users	$M = K = 4$
Carrier/bandwidth	$f_c = 2$ GHz, $W = 100$ MHz
Transmit power/noise figure	$P_{tx} = 46$ dBm, $F = 9$ dB
Large-scale fading	log-distance, exponent 3.76, $\sigma_{SF} = 8$ dB
Frequency samples	$N_{sc} = 64$ for rate evaluation
Speeds	3, 30, 120 km/h
Baselines	RZF-PF, GreedyPF, Random

Fig. 2 shows that Robust IA-SMPF provides the largest sum spectral efficiency over the three mobility regimes considered. At low and moderate mobility, the gain is explained by the combined selection of strong, spatially compatible, and low-leakage user groups. At 120 km/h, the performance of all CSI-dependent methods collapses because ρ_Δ is small and the data phase occupies only a limited portion of the coherence block; nevertheless, the aging-aware predictor preserves a small advantage.

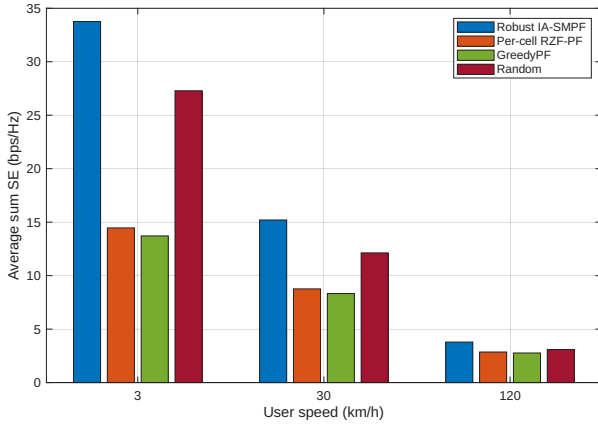
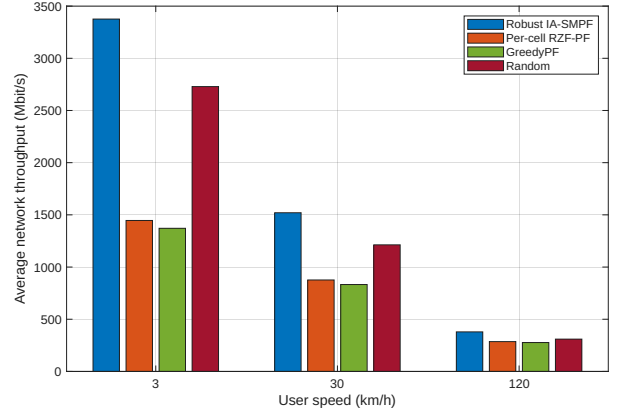
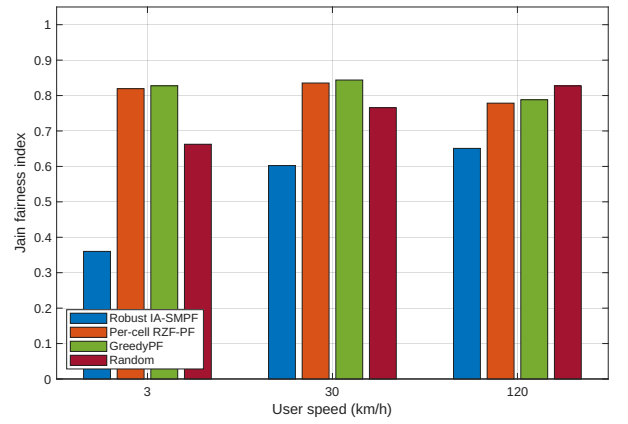

 Fig. 2. Average network sum spectral efficiency versus speed for full-band MU-MIMO-OFDM with $K = M = 4$.

 TABLE II
MEAN SUM SPECTRAL EFFICIENCY AND JAIN FAIRNESS FOR THE EVALUATED CONFIGURATION.

Speed	Method	Sum SE [bps/Hz]	Jain
3	Robust IA-SMPF	36.1	0.31
3	Per-cell RZF-PF	15.0	0.80
3	GreedyPF	14.0	0.81
3	Random	27.5	0.62
30	Robust IA-SMPF	15.8	0.55
30	Per-cell RZF-PF	8.8	0.82
30	GreedyPF	8.1	0.83
30	Random	12.0	0.71
120	Robust IA-SMPF	3.9	0.63
120	Per-cell RZF-PF	3.1	0.75
120	GreedyPF	2.9	0.76
120	Random	3.1	0.80

Table II quantifies both the spectral-efficiency gain and the fairness penalty of the proposed scheduler; the absolute throughput and the Jain index across the three mobility regimes are reported in Figs. 3 and 4. At 3 km/h, Robust IA-SMPF reaches 36.1 bps/Hz, i.e., gains of approximately 141%, 158%, and 31% over per-cell RZF-PF, GreedyPF, and Random scheduling, respectively. Notably, Random attains a higher sum SE than the two PF baselines (27.5 against 15.0 and 14.0 bps/Hz). This is the expected consequence of proportional fairness rather than a baseline artifact: by


 Fig. 3. Average network throughput versus user speed for full-band MU-MIMO-OFDM sharing the same 100 MHz carrier ($K = M = 4$).

 Fig. 4. Jain fairness index versus user speed for the evaluated schedulers ($K = M = 4$).

weighting the instantaneous rate by the inverse historical throughput, RZF-PF and GreedyPF deliberately promote rate-starved, typically cell-edge users, raising their Jain index to ≈ 0.8 at the cost of sum SE, whereas Random samples user groups uniformly and occasionally selects spatially favorable sets. By maximizing the ICI-aware mixed potential (10), the proposed method instead dominates every baseline in sum SE while retaining a tunable fairness term, exploiting spatial compatibility and ICI-aware grouping when the pilot-time CSI remains highly correlated with the data channel. The price of this opportunistic behavior is the lower Jain index ($J = 0.31$ against ≈ 0.8): the proposed scheme should thus be read as a throughput-oriented scheduler with PF regularization, not a max-min policy.

At 30 km/h, the same table shows that the Robust IA-SMPF gain persists under moderate channel aging, with 15.8 bps/Hz against 12.0 bps/Hz for Random and below 9 bps/Hz for the per-cell baselines. The Jain index increases to 0.55, indicating that mobility partially reduces the scheduler's ability to repeatedly exploit the most favorable spatial groups. At 120 km/h, all methods converge to a low-SE regime because ρ_Δ is small and only a short data phase remains after pilot acquisition. Even in this severe case, Robust IA-SMPF retains a small sum-SE advantage (3.9 bps/Hz), but the reduced margin indicates the physical limit of stale-CSI scheduling. Therefore, Table II is central to the interpretation of the results: it demonstrates a consistent sum-SE advantage

while making the throughput/fairness tradeoff explicit.

Fig. 5 confirms the throughput/fairness tradeoff at the operating point of Table II: the proposed scheduler produces a much longer high-SE tail, while a fraction of users obtains lower average rates. This tradeoff is made explicit and controllable through the mixed-potential weight λ , as characterized next.

To show that the throughput/fairness operating point is a design choice rather than a fixed property, Fig. 6 sweeps the mixed-potential weight $\lambda \in [0, 1]$ at $v = 3$ km/h. As λ decreases from 1 to 0, the fairness term progressively dominates and the scheduler trades sum SE for fairness, moving monotonically along a well-defined Pareto frontier from $(J, SE) \approx (0.16, 41)$ at $\lambda = 1$ to $(0.65, 28)$ at $\lambda = 0$; Table II ($\lambda = 0.75$) lies between these endpoints. The PF baselines (RZF-PF and GreedyPF, $J \approx 0.82$) are strictly dominated in sum SE at comparable fairness, while Random falls essentially on the $\lambda = 0$ point. A single interpretable parameter therefore spans a continuum of operating points that the baselines cannot reach.

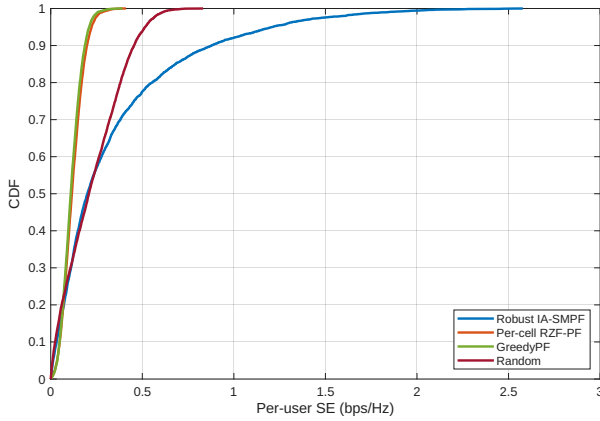


Fig. 5. Per-user spectral-efficiency CDF at $v = 3$ km/h. Robust IA-SMPF improves the upper tail but sacrifices fairness relative to purely PF-oriented baselines.

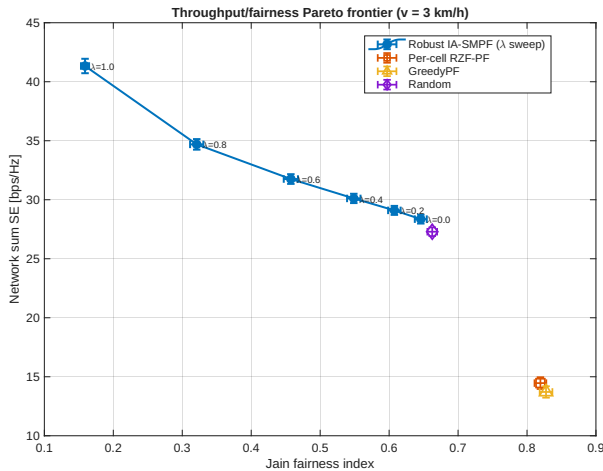


Fig. 6. Throughput/fairness Pareto frontier obtained by sweeping the mixed-potential weight $\lambda \in [0, 1]$ at $v = 3$ km/h. The proposed Robust IA-SMPF spans a monotonic continuum of operating points; the per-cell RZF-PF and GreedyPF baselines are strictly dominated by the frontier in sum SE, while Random scheduling lies essentially on the low- λ end of the frontier. Error bars denote 95% confidence intervals over the Monte Carlo setups.

VI. CONCLUSION

This paper formulated full-band MU-MIMO-OFDM scheduling as a matching game with externalities and proposed Robust IA-SMPF, a low-complexity swap-matching scheduler accounting for RZF conditioning, inter-cell interference, proportional-fair regularization, and channel aging. Four users per cell share the same 100 MHz carrier through spatial multiplexing, without bandwidth partition. The results show that the robust potential outperforms random, per-cell RZF-PF, and greedy PF baselines in sum spectral efficiency, with an explicit and tunable fairness tradeoff characterized by the λ sweep. Future work will address pilot-estimation errors, adaptive throughput/fairness weighting, and standards-compliant 3GPP UMi-LOS/UMa scenarios.

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REFERENCES

- [1] 3GPP, "NR; Base Station (BS) radio transmission and reception," TS 38.104, V18.9.0, Rel. 18, Apr. 2025.
- [2] 3GPP, "NR; Physical layer procedures for data," TS 38.214, V18.7.0, Rel. 18, Jul. 2025.
- [3] 3GPP, "Study on channel model for frequencies from 0.5 to 100 GHz," TR 38.901, V19.0.0, Rel. 19, Jul. 2025.
- [4] D. Gale and L. S. Shapley, "College admissions and the stability of marriage," *Amer. Math. Monthly*, vol. 69, no. 1, pp. 9–15, Jan. 1962.
- [5] E. Bodine-Baron, C. Lee, A. Chong, B. Hassibi, and A. Wierman, "Peer effects and stability in matching markets," in *Proc. Int. Symp. Algorithmic Game Theory (SAGT)*, Amalfi, Italy, 2011, pp. 117–129.
- [6] Y. Gu, W. Saad, M. Bennis, M. Debbah, and Z. Han, "Matching theory for future wireless networks: Fundamentals and applications," *IEEE Commun. Mag.*, vol. 53, no. 5, pp. 52–59, May 2015.
- [7] S. Bayat, Y. Li, L. Song, and Z. Han, "Matching theory: Applications in wireless communications," *IEEE Signal Process. Mag.*, vol. 33, no. 6, pp. 103–122, Nov. 2016.
- [8] M. K. Awad, M. W. Baidas, A. A. El-Amine, and N. Al-Mubarak, "A matching-theoretic approach to resource allocation in D2D-enabled downlink NOMA cellular networks," *Physical Communication*, vol. 54, Art. no. 101837, 2022.
- [9] X. Yang, H. Yang, Y. Jiang, A. Alphones, and L. Xiao, "Game-guided matching theory-based resource allocation for secure semantic communications," *IEEE Trans. Veh. Technol.*, vol. 74, no. 5, pp. 8357–8362, May 2025.
- [10] J. Xu, Y. Yao, X. Xu, W. Feng, and P. Li, "Joint optimization of task offloading and resource allocation of fog network by considering matching externalities and dynamics," *IEEE Trans. Mobile Comput.*, vol. 24, no. 4, pp. 2534–2550, Apr. 2025.
- [11] Q. H. Spencer, A. L. Swindlehurst, and M. Haardt, "Zero-forcing methods for downlink spatial multiplexing in multiuser MIMO channels," *IEEE Trans. Signal Process.*, vol. 52, no. 2, pp. 461–471, Feb. 2004.
- [12] T. Yoo and A. Goldsmith, "On the optimality of multiantenna broadcast scheduling using zero-forcing beamforming," *IEEE J. Sel. Areas Commun.*, vol. 24, no. 3, pp. 528–541, Mar. 2006.
- [13] C. B. Peel, B. M. Hochwald, and A. L. Swindlehurst, "A vector-perturbation technique for near-capacity multiantenna multiuser communication-Part I: Channel inversion and regularization," *IEEE Trans. Commun.*, vol. 53, no. 1, pp. 195–202, Jan. 2005.
- [14] E. Björnson, J. Hoydis, and L. Sanguinetti, "Massive MIMO networks: Spectral, energy, and hardware efficiency," *Found. Trends Signal Process.*, vol. 11, no. 3–4, pp. 154–655, 2017.
- [15] R. H. Clarke, "A statistical theory of mobile-radio reception," *Bell Syst. Tech. J.*, vol. 47, no. 6, pp. 957–1000, Jul.–Aug. 1968.
- [16] K. T. Truong and R. W. Heath, Jr., "Effects of channel aging in massive MIMO systems," *J. Commun. Netw.*, vol. 15, no. 4, pp. 338–351, Aug. 2013.
- [17] F. P. Kelly, A. K. Maulloo, and D. K. H. Tan, "Rate control for communication networks: Shadow prices, proportional fairness and stability," *J. Oper. Res. Soc.*, vol. 49, no. 3, pp. 237–252, Mar. 1998.