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Social-Spider-Optimized Hybrid Pilot Decontamination: Fairness-Aware Refinement of Soft Pilot Reuse and Weighted Graph Coloring for Multi-Cell Massive MIMO

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ABSTRACT—

Pilot contamination, which is caused by reusing non-orthogonal training sequences in neighboring cells, limits multi-cell massive multiple-input multiple-output (MIMO) systems and does not disappear as the number of base-station (BS) antennas grows. Soft pilot reuse (SPRS) protects cell-edge users with orthogonal pilots, and weighted-graph-coloring pilot decontamination (WGC-PD) assigns the reused pilots of cell-center users greedily. Both are one-shot heuristics whose decisions are never revised. This paper proposes SSO-HPD, a hybrid framework in which a discrete social-spider optimization (SSO) algorithm refines the SPRS+WGC-PD assignment. The optimizer searches over within-cell pilot permutations using female-attraction (row-copy) and male-mating (crossover) operators, and its fitness function combines the sum rate with a low-percentile fairness term. Because the search is seeded with the WGC solution and accepts only improving moves, SSO-HPD never performs worse than its seed. In a 7-cell network with K = 8 users per cell, SSO-HPD increases the average uplink rate by 3.2–4.0% compared with SPRS+WGC-PD and by 7.8–15.0% compared with random reuse as the number of BS antennas grows from 32 to 512, and it raises the median user rate by 9.6%. We also analyze the trade-off between the median rate and the worst-user rate.

***Index Terms*—Massive MIMO, pilot contamination, pilot assignment, soft pilot reuse, graph coloring, social spider optimization, swarm intelligence, 5G.**

I. INTRODUCTION

Massive MIMO is a core technology of 5G because its spectral efficiency scales with the number of BS antennas [1], [2]. In time-division duplex (TDD) operation, the BS estimates the uplink channels from pilots and uses channel reciprocity for downlink precoding. The coherence interval limits the number of orthogonal pilots, so pilots must be reused across cells. Marzetta showed that the resulting pilot contamination does not average out as the number of antennas $M \to \infty$ [1].

Mitigation methods fall into three groups:

1) Estimation-side methods, such as the coordinated covariance-aided estimator of [3].
2) Precoding-side methods, such as pilot-contamination precoding [4] and multicell block diagonalization [5].
3) Pilot-assignment methods, which need only large-scale fading information and leave the estimator and precoder unchanged [7].

Zhu et al. proposed SPRS [5], which gives cell-edge users mutually orthogonal pilots while cell-center users reuse a common pilot set. They later proposed WGC-PD [6], which models inter-user contamination as a weighted graph and colors it greedily. Both methods are greedy and one-shot. SSO [8] models a colony of female and male spiders that communicate through web vibrations, and its gender-specific operators balance exploration and exploitation. We are not aware of earlier work that uses SSO as a refinement stage on top of SPRS and WGC-PD.

TABLE I — Comparison of Mitigation Approaches

Scheme	Side info.	BS coop.	Revisable	Fairness
Coord. est. [3]	covariance	yes	–	–
PCP [4]	β	yes	–	–
SPRS [5]	β	no	–	edge only
WGC-PD [6]	β	central	no	implicit
SSO-HPD	**β**	**central**	**yes**	**tunable**

Contributions. This paper extends the M.Tech thesis work of the first author as follows:

- A hybrid three-stage framework (SPRS → WGC-PD → discrete SSO) in which the swarm acts only on the center-user pilot permutations. Edge-user protection is preserved, and the search space shrinks from τ^{JK} to $((K - K_e)!)^J$.
- A discrete SSO with permutation-preserving operators, seeded with the WGC solution and using greedy acceptance, so it never performs worse than WGC-PD.

- A fairness-aware fitness function, a λ-sensitivity study that quantifies the trade-off between the median and worst-user rates, and a reproducible evaluation against random reuse, SPRS and SPRS+WGC-PD.

II. RELATED WORK

Table I compares representative mitigation schemes. Coordinated estimation [3] achieves strong suppression when users' angular supports do not overlap, but it requires $M \times M$ covariance matrices. Pilot-contamination precoding [4] requires BS cooperation. SPRS [5] lengthens the pilot sequence to protect edge users, and WGC-PD [6] improves the reuse pattern of center users at negligible cost. The survey [7] identifies metaheuristic pilot assignment as an open direction.

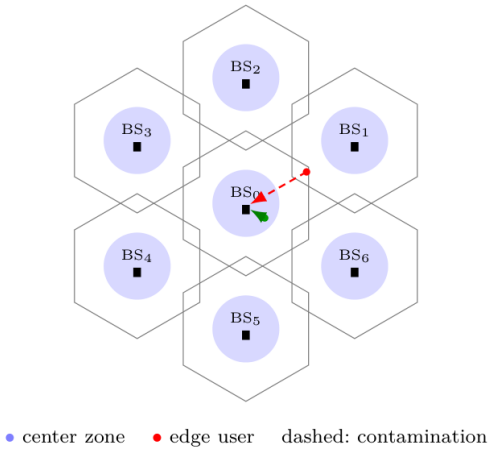


Fig. 1. Seven-cell massive MIMO network. Center zones reuse a common pilot set, and edge users receive orthogonal pilots under SPRS.

III. SYSTEM MODEL

A. Multi-Cell Network

We consider $J = 7$ hexagonal cells of radius $R = 500$ m. Each BS has M antennas and serves K single-antenna users. The channel from user k in cell l to BS j is $\mathbf{g}_{jlk} = \sqrt{\beta_{jlk}}\,\mathbf{h}_{jlk}$ with $\mathbf{h}_{jlk} \sim \mathcal{CN}(\mathbf{0}, \mathbf{I}_M)$ and

$$\beta_{jlk} = z_{jlk} / (d_{jlk}/R)^{\alpha}, \;\; 10 \log_{10} z_{jlk} \sim \mathcal{N}(0, \sigma^2_{\text{sh}}), \qquad (1)$$

where $\alpha = 3.8$ and $\sigma_{\text{sh}} = 8$ dB. Fig. 1 illustrates the network.

B. Achievable Rate under Pilot Contamination

Let π_{jk} be the pilot of user (j, k) and $\mathcal{P}_{jk}$ the set of users sharing it. With minimum mean-square-error (MMSE) estimation, maximum-ratio (MR) combining and pilot length τ, the uplink signal-to-interference-plus-noise ratio (SINR) is [6]

$$\text{SINR}_{jk} = M\beta^2_{jjk} / \left(M\, I^{\text{pc}}_{jk} + (\Sigma_{l,m}\, \beta_{jlm} + 1/\rho)(S_{jk} + 1/(\tau\rho)) \right), \qquad (2)$$

where $I^{\text{pc}}_{jk} = \Sigma_{(l,m)\in\mathcal{P}_{_ljk}\setminus\{(j,k)\}}\, \beta^2_{jlm}$ is the coherent contamination, $S_{jk} = \Sigma_{(l,m)\in\mathcal{P}_{_ljk}\}}\, \beta_{jlm}$ and ρ is the transmit SNR. The rate is $R_{jk} = \log_2(1 + \text{SINR}_{jk})$. As $M \to \infty$, the SINR saturates at $\beta^2_{jjk}/I^{\text{pc}}_{jk}$, which depends only on the pilot assignment.

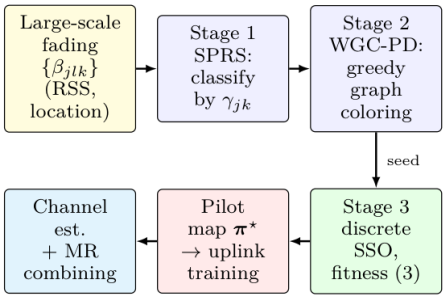


Fig. 2. Block diagram of the three-stage SSO-HPD framework.

C. Problem Formulation

$$\max_{\{\pi_{jk}\}} F(\boldsymbol{\pi}) = \Sigma_{j,k}\, R_{jk} + \lambda\, JK \cdot Q_p\{R_{jk}\}, \qquad (3)$$

subject to $\{\pi_{jk}\}_k$ being a permutation within each cell. Here Q_p is the pth percentile, and we use $p = 10$ and $\lambda = 0.5$. The problem is combinatorial, with a search space of size $(K!)^J$.

IV. PROPOSED SSO-HPD FRAMEWORK

Fig. 2 shows the three stages. All stages use only the slowly varying large-scale coefficients $\{\beta_{jlk}\}$, which do not depend on M.

A. Stage 1: Soft Pilot Reuse

For each user, the interference ratio is $\gamma_{jk} = \Sigma_{l\neq j}\, \beta_{ljk}/\beta_{ijk}$. In each cell, the K_e users with the largest γ_{jk} are classified as edge users and receive pilots from an orthogonal set of size JK_e. The remaining $K_c = K - K_e$ center users share K_c pilots, so the pilot length is $\tau = K_c + JK_e$ [5].

B. Stage 2: Weighted Graph Coloring

Center users are graph vertices. The edge between users (j, k) and (l, m) in different cells has the weight

$$w_{jk,lm} = \beta_{ljk}/\beta_{llm} + \beta_{jlm}/\beta_{jjk}. \qquad (4)$$

Users are processed in decreasing order of total weight, and each user receives the free pilot of its cell with the smallest accumulated weight to users already holding that pilot [6].

Algorithm 1 Discrete SSO refinement (Stage 3)

Require: $\{\beta_{jlk}\}$, WGC seed $\mathbf{\Pi}^{(0)}$, center sets $\mathcal{C}_j$, N_s, T
$\mathbf{\Pi}_1 \leftarrow \mathbf{\Pi}^{(0)}$; other $\mathbf{\Pi}_i \leftarrow$ 1–5 random swaps of $\mathbf{\Pi}^{(0)}$
Evaluate $F(\mathbf{\Pi}_i)$; $\mathbf{\Pi}^\star \leftarrow \arg\max F$
for $t = 1$ **to** T **do**
  for $i = 1$ **to** N_s **do**
    if $i \le 0.7N_s$ (female) **then**
      copy a random row of $\mathbf{\Pi}^\star$; 1 swap in $\mathcal{C}_j$
    else
      cell-wise crossover with $\mathbf{\Pi}^\star$; 1–3 swaps
    end if
    if $F(\tilde{\mathbf{\Pi}}) > F(\mathbf{\Pi}_i)$ **then** $\mathbf{\Pi}_i \leftarrow \tilde{\mathbf{\Pi}}$
  end for
  $\mathbf{\Pi}^\star \leftarrow \arg\max_i F(\mathbf{\Pi}_i)$
end for
return $\mathbf{\Pi}^\star$

C. Stage 3: Discrete Social-Spider Optimization

SSO [8] uses N_s spiders (70% female, 30% male). We define permutation-preserving operators on assignment matrices $\mathbf{\Pi} \in \mathbb{Z}^{J\times K}$:

- *Female (attraction).* The row of a random cell j is copied from the global best $\mathbf{\Pi}^\star$ (the strongest vibration), followed by one random swap among the center users.
- *Male (mating).* Each row is copied from $\mathbf{\Pi}^\star$ with probability 0.5 (cell-wise crossover), followed by 1–3 swaps for stronger exploration.
- *Selection.* A candidate replaces its parent only if it has higher fitness (3).

Swaps act only on center users, so edge users keep their protected pilots. Algorithm 1 and Fig. 3 summarize the procedure.

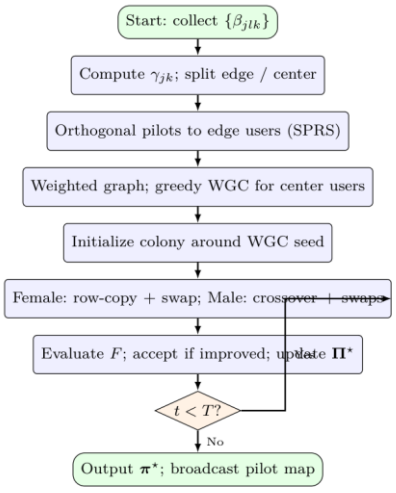


Fig. 3. Flowchart of the SSO-HPD procedure.

D. Complexity and Signaling

Evaluating (2) for all users costs $O(J^2K^2)$, so the SSO stage costs $O(N_sTJ^2K^2)$. With $N_s = 14$ and $T = 30$, this is about 1.3×10^6 multiply–accumulate operations per update. The cost does not depend on M, and the assignment is updated only when the large-scale fading changes. The controller needs the same β_{jlk} values as WGC-PD.

E. Analytical Properties

Lemma 1 (monotonicity). Let $F^{(t)}$ be the best fitness after iteration t. Then $F^{(t+1)} \ge F^{(t)} \ge F(\mathbf{\Pi}^{(0)})$.

Proof. The seed belongs to the initial population. A spider is replaced only when the candidate has strictly higher fitness, so the best fitness in the population cannot decrease. ■

Corollary. With $\lambda = 0$, SSO-HPD achieves a sum rate at least as large as that of SPRS+WGC-PD for every user drop, not only on average.

Asymptotic gain. As $M \to \infty$, (2) gives $\mathrm{SINR}_{jk} \to \beta^2_{jjk}/I^{\mathrm{pc}}_{jk}$. For two assignments π_1 and π_2, the rate difference of user (j, k) therefore approaches

$$\Delta R_{jk} \to \log_2 [\, (1 + \beta^2_{jjk}/I^{pc}_{jk}(\pi_1)) \,/\, (1 + \beta^2_{jjk}/I^{pc}_{jk}(\pi_2)) \,], \qquad (5)$$

which does not depend on M and on the SNR. A better assignment therefore keeps its advantage as M grows. This explains the widening absolute gap in Fig. 4 and the flat SNR curves in Fig. 6.

Search-space reduction. For $J = 7$, $K = 8$ and $K_e = 2$, unrestricted assignment of $\tau = 20$ pilots spans $(20!/12!)^7 \approx 10^{63}$ configurations. Restricting the search to center-user permutations leaves $(6!)^7 \approx 10^{20}$. SSO evaluates only $N_s(T+1) = 434$ of these, so the WGC seed is essential for the search to find good assignments.

Example. Consider two neighboring cells with one center user each that share pilot 1. Their cross-gains are $\beta_{121}/\beta_{111} = 0.3$ and $\beta_{212}/\beta_{222} = 0.25$, so the large-$M$ SINR limits are 1/0.09 = 11.1 and 1/0.0625 = 16, that is, 3.6 and 4.1 bit/s/Hz. If WGC had assigned pilot 1 instead to a user with a cross-gain of 0.6 (because that user was processed first in the greedy order), the limit would fall to 1/0.36 = 2.8, or 1.9 bit/s/Hz. Swapping two pilots within the cell, which is the elementary move of the SSO operators, recovers 1.7 bit/s/Hz for this user.

V. SIMULATION SETUP

Table II lists the parameters. Each point averages 25 user drops, and the CDF uses 60 drops (3360 user rates). All schemes are evaluated with the same drops and the same rate expression (2). Random reuse uses $\tau = K$, whereas the SPRS-based schemes use $\tau = 20$.

TABLE II — Simulation Parameters

Parameter	Value
Cells J / radius R	7 (hexagonal) / 500 m
Users per cell K (edge K_e)	8 (2)
BS antennas M	32–512 (default 128)
Path loss / shadowing	α = 3.8 / 8 dB
Pilot length τ	20 (SPRS-based), 8 (random)
Uplink SNR ρ	−10 to 20 dB (default 10)
SSO population / iterations	14 (70% female) / 30
Fitness weights	λ = 0.5, p = 10
Drops per point	25 (60 for CDF)

VI. RESULTS AND DISCUSSION

A. Rate versus Number of Antennas

In Fig. 4, every scheme improves with M. SSO-HPD is the best at every M (Fig. 5): its gain over SPRS+WGC-PD rises from 3.2% at $M = 32$ to 4.0% at $M = 512$, and its gain over random reuse rises from 7.8% to 15.0%. The gap widens because contamination becomes the dominant term in (2) as M grows. SPRS and SPRS+WGC-PD differ by less than 0.6% on average: greedy WGC mainly redistributes rate among users rather than increasing the sum rate, which motivates the optimization stage.

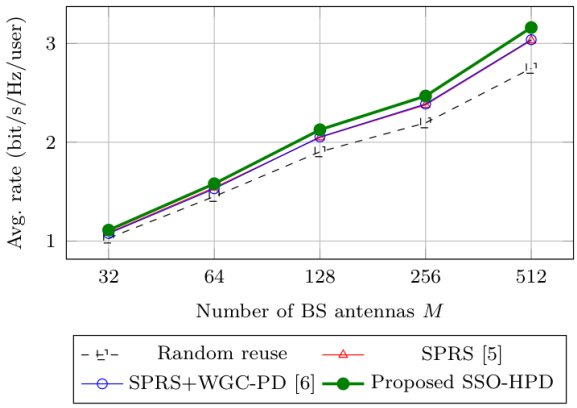


Fig. 4. Average uplink rate versus M (K = 8, SNR 10 dB).

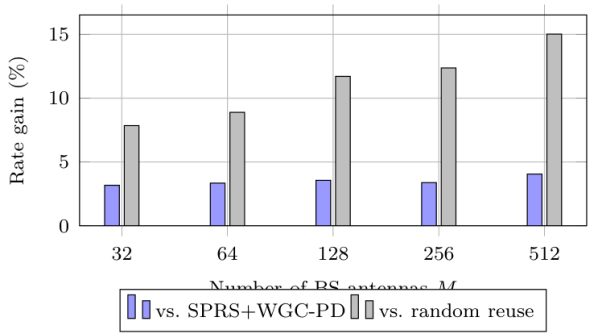


Fig. 5. Relative average-rate gain of SSO-HPD.

B. Rate versus SNR

Fig. 6 shows nearly flat rates from −10 to 20 dB, because the system is interference-limited. SSO-HPD keeps a consistent gain of 0.06–0.08 bit/s/Hz over SPRS+WGC-PD and 0.17–0.20 bit/s/Hz over random reuse, so the gain comes from the assignment structure rather than from transmit power.

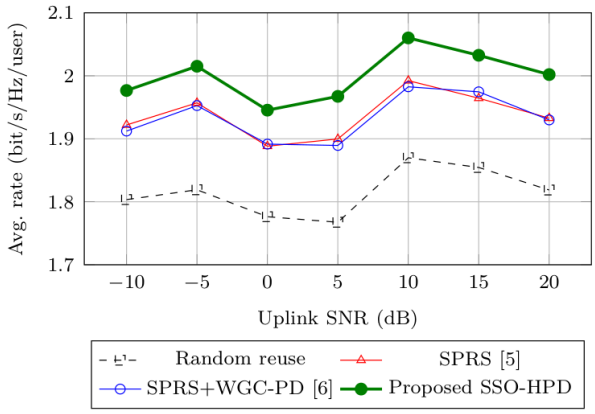


Fig. 6. Average uplink rate versus SNR (M = 128).

C. Rate Distribution

Fig. 7 and Table III show that SSO-HPD achieves the highest median rate, 1.126 bit/s/Hz. This is 9.6% higher than SPRS+WGC-PD (1.027), 22.8% higher than SPRS (0.917) and 51.2% higher than random reuse (0.745). At the 10th percentile, however, SPRS+WGC-PD is best (0.035 versus 0.018). With $\lambda = 0.5$ the sum-rate term dominates the fitness, so the optimizer trades a few worst-user rates for many middle-tier gains. A larger λ or a max–min objective would shift the operating point toward the tail.

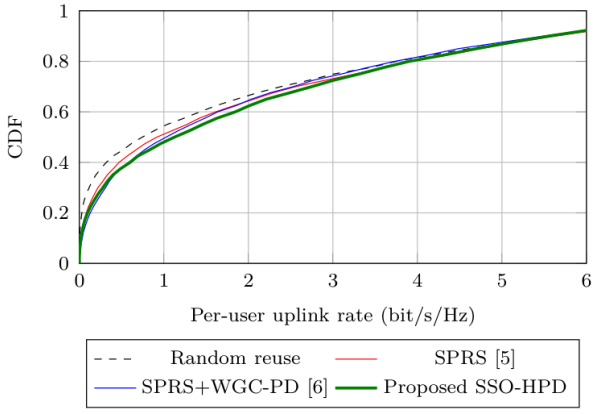


Fig. 7. CDF of the per-user uplink rate (M = 128, SNR 10 dB).

TABLE III — Rate Statistics (bit/s/Hz/user)

Scheme	Mean M=128	Median M=128	10%-ile M=128	Mean M=512
Random reuse	1.785	0.745	0.004	2.747
SPRS	1.899	0.917	0.018	3.030
SPRS+WGC-PD	1.897	1.027	0.035	3.037
SSO-HPD	**1.965**	**1.126**	**0.018**	**3.160**

D. Convergence

In Fig. 8, the normalized best fitness never decreases because acceptance is greedy. About half of the 2.3% fitness gain is obtained within 5 iterations, and the curve flattens after about 25 iterations.

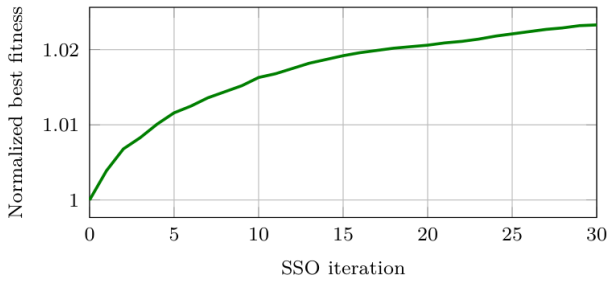


Fig. 8. Convergence of the SSO stage (normalized to the WGC seed).

E. Sensitivity to the Fairness Weight λ

Table IV reports the effect of λ over 30 drops ($M = 128$, 10 dB). Each SSO-HPD result is compared with SPRS+WGC-PD on the same drops. Increasing λ from 0 to 4 raises the ratio of the SSO-HPD 10th-percentile rate to that of WGC-PD from 0.52 to 0.72, while the mean-rate gain stays positive (2.8–5.0%). The tail rate of SSO-HPD nevertheless stays below that of WGC-PD for every λ tested. Percentile-weighted sum-rate objectives therefore narrow, but do not close, the worst-user gap. When cell-edge fairness is the primary objective, the fitness should be replaced by a max–min objective or by a constraint $R_{jk} \geq R_{\min}$. This is an important design guideline for operators.

TABLE IV — Effect of the Fairness Weight λ (M = 128, 30 drops)

λ	Mean rate	Gain vs. WGC-PD	Median rate	10%-ile ratio SSO/WGC
0	2.028	+3.2%	1.220	0.52
0.5	1.966	+5.0%	1.181	0.57
1	1.950	+3.8%	1.126	0.63
2	1.946	+3.3%	1.066	0.70
4	1.956	+2.8%	1.135	0.72

F. Deployment Protocol

A practical deployment of SSO-HPD follows four steps:

1) Each BS measures the large-scale coefficients β_{jlk} from uplink sounding (RSS), averaged over many coherence intervals.
2) The coefficients are reported to a central unit (a C-RAN or O-RAN near-real-time RAN intelligent controller), which hosts the optimizer as a software application.
3) The unit runs Stages 1–3 and returns the pilot map, which costs $\lceil \log_2 \tau \rceil = 5$ bits per user.
4) Re-optimization is triggered when any β_{jlk} changes by more than a threshold, for example 3 dB, or when users arrive or leave.

Because SSO-HPD is seeded with WGC-PD, the controller can stop the search at any iteration and still return an assignment that is at least as good as WGC-PD. This anytime property suits strict control-loop deadlines.

G. Limitations

The limitations of this study are:

1) The rates follow the MR-combining model (2), so gains with MMSE combining may be smaller.
2) The split K_e is fixed.
3) The location- and mobility-based received-signal-strength (RSS) metric of the thesis enters only through β, and mobility-triggered re-optimization is left for future work.

VII. CONCLUSION

This paper proposed SSO-HPD, which refines the SPRS and WGC-PD assignment with a structure-preserving discrete social-spider optimizer and a fairness-aware fitness function. It improves the average uplink rate by up to 4.0% compared with SPRS+WGC-PD and by up to 15.0% compared with random reuse, and it improves the median rate by 9.6%. It never performs worse than its seed and converges within about 25 iterations. Future work

includes adaptive K_c, max–min fitness, cell-free extensions, and joint operation with the beamspace estimator of our companion paper.

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