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Power-Coupled Pilot Reuse Improvement for Contamination-Resilient Cell-Free Massive MIMO Networks

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ABSTRACT
The cell-free massive MIMO (CF-mMIMO) systems offer a high spectral performance and uniform coverage, which enables the connection of many distributed access points (APs) to users through a central processing unit (CPU). But limited orthogonal pilot sequences cause pilot contamination which greatly reduces the performance of uplink. In this research, a combined pilot assignment and uplink power control system was introduced and modelled to reduce the contamination of pilots and optimize spectral efficiency. The proposed strategy was compared with random and greedy strategies of pilot assignment using MATLAB simulation. Findings show that using 40 users and 40 APs, the proposed scheme has a spectral efficiency of 7.1 bit/s/Hz on average as opposed to 5.8 bit/s/Hz and 4.2 bit/s/Hz by greedy and random assignment methods. The spectral efficiency of 100 APs and 20 users is enhanced to 12.7 bit/s/Hz (a 23% improvement over greedy assignment). Uplink SINR median reaches 11.5 dB and cell-edge users (5-outage SE) reach 4.1 bit/s/Hz, which is 41% better than greedy assignment. The energy efficiency also goes up to 17.4 bit/J/Hz. The above results show that the joint pilot allocation strategy, as well as the power control strategy, is of great benefit to spectral efficiency, fairness, uplink reliability, and energy efficiency, which is a viable solution to dense CF-mMIMO networks.

Keywords: *Pilot Contamination, Improvement, Cell free Network, MIMO, Uplink Interference, Spectral Efficiency*

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I. INTRODUCTION

The sudden development of mobile devices and the rising demand of the high-speed data services are exerting unprecedented pressure on the existing cellular network designs (Andrews et al., 2017). The 5G and next generation systems will target the massive connectivity, ultra reliability, and spectral efficiency (SE) of various applications like augmented reality, autonomous systems, and massive Internet of Things (IoT) (Buzzi et al., 2017). Massive multiple -input multiple -output (MIMO) is one potential technology that could fulfill such requirements by taking advantage of the large antenna arrays to spatially multiplex users and dramatically enhance spectral efficiency (Marzetta, 2010). In traditional cellular networks, users are served by each base station within its coverage, and the cell-centric architecture results in inter-cell interference, particularly at cell edges, which is a limitation when it comes to dense deployments (Ngo et al., 2017). To overcome such constraints, cell-free massive MIMO (CF-mMIMO) systems are suggested, where numerous distributed access points can collaboratively serve every user without pre-established a cell boundary and can cooperate both on a network-wide scale. This decentralized, user-friendly design has a strong ability to decrease inter-cell interference and provides macro-diversity, high-reliability, and more even spectral efficiency in the service area than traditional cellular designs (Interdonato et al., 2019; Zhang et al., 2019; Kassam et al., 2023).

Cellular massive MIMO cellular systems have been characterized as extensively investigated in regard to pilot contamination, and pilot reuse coordination, best pilot assignment, and better channel estimation have been suggested as solutions to this problem. Pilot contamination is even more essential in cell-free massive MIMO (CF-mMIMO) because there are more distributed access points and the user densities are increased (Alonzo et al., 2019). Random pilot assignment is typically underperforming, whereas the greedy assignment schemes accounting of the large-scale channel statistics are more effective, but still cannot fully exploit the uplink interference patterns (Gao et al., 2015; Ngo et al., 2017). In addition to pilot assignment, uplink power control is necessary to decrease the interference and enhance spectral efficiency. The traditional ways of power control, where the transmit power is apportioned equally or intuitively, is not the answer to the joint effect of pilot contamination and uplink interference (Chiang et al., 2007). Pilot assignment and uplink power joint optimization may be of great importance in improving the performance, yet this method has been comparatively under-investigated with cell-free massive MIMO systems (Rasti et al., 2010). The recent investigations of cell-free massive MIMO (CF-mMIMO) have touched upon the power control methods to enhance fairness and power efficiency (Buzzi et al., 2020; Zhang et al., 2021). Nevertheless, pilot assignment and power control are considered different in most methods, which restricts their effectiveness in reducing interference and maximizing performance. Also, numerous previous studies have not focused on such performance indicators as cell-edge spectral efficiency, fairness indices, and the overall energy efficiency making the proposed solutions less practical.

The research fills the gap in CF-mMIMO literature by suggesting a joint pilot assignment and power control framework of uplink designed to be used within the framework of limited pilot resources. The proposed method is compared with conventional random and greedy pilot assignment schemes using extensive simulations. The suggested combined solutions greatly decrease pilot contamination, increase spectral efficiency, and make users fair in dense CF-mMIMO deployments.

II. MATERIALS AND METHOD

The study methodology aimed at resolving the critical problem of the pilot contamination and uplink interference in dense cell-free massive MIMO (CF-mMIMO) networks. The method incorporates the model of cell free massive MIMO system, pilot training model, pilot assignment strategies, uplink data transmissions, and joint pilot assignment and power control algorithm that is proposed. The methodology is based on the proven large scale fading models and interference analysis, and presents optimized pilot scheduling and power adjustment plan to reduce contamination of pilots.

System Mathematical Modelling

A. Network and Channel Model

Consider a cell free massive MIMO network with M distributed single-antenna access point (APs) and K single antenna users. All Aps and users share the same time frequency resources (Ngo r=et al, 2017). The Uplink channel between user k and AP $m$is represented as:

$$h_{m,k} = \sqrt{\beta_{m,k} g_{m,k}} \tag{1}$$

Where:

$g_{m,k}$ $\sim CN(0.1)$ Denotes small scale fading

$\beta_{m,k}$ = denotes large scale fading incorporating path and shadowing (Marzetta, 2010; Andrew et al, 2017).

A commonly used large scale fading model is:

$$\beta_{m,k} = \frac{1}{(1+d_{m,k})^{\alpha}} \tag{2}$$

Where:

$d_{m,k}$ = is the Euclidean distance between AP m and user k.

α = is the path loss exponent

This model avoid singularity (Hoydis et al, 2013).

B. Pilot Training and Contamination Model

In TDD system, uplink pilots of length τ_p are used for channel estimation due to reciprocity (Hassibi & Hochwald, 2003). Let $P = \left\{\psi_1, \psi_2, \dots \dots \psi_{\tau_p}\right\}$ be the set of orthogonal pilot sequences.

Defined the pilot assignment vector:

$$\psi = [\psi(1), \psi(2), \dots \dots \psi(K)]^T \tag{3}$$

Where $\psi(K) \in P$ is the pilot index assigned to user k, since pilot reuse is unavoidable (Jose et al, 2018).

The received pilot signal at AP m is:

$$y_m^{pilot} = \sum_{k=1}^{K} h_{m,k} \sqrt{P_k^{pilot} \psi(k) + n_m} \tag{4}$$

Where:
P_k^{pilot} = is the uplink pilot transmit power of user k
n_m = is the noise at AP m.
Pilot contamination occur because users that share the same pilot sequence produce coherent interference during channel estimation.

C. Pilot Assignment Strategies

i. Random Pilot Assignment

Each user is randomly assigned a pilot sequence

$$\psi(k) = \text{Uniform}(P),\ \forall k. \tag{5}$$

This baseline method requires no condition and serves as a lower bound on system performance (Hoydis et al, 2013).

ii. Greedy Pilot Assignment

Greedy assignment sorts users by descending large scale channel quality.

$$\text{Score}_k = \sum_{m=1}^{M} \beta_{m,k} \tag{6}$$

And assigns pilot iterative to minimize pilot load:

$$\psi(k) = \underset{m=1}{\arg\min}\ \text{Load (P)} \tag{7}$$

Where Load (P) represents current total channel strength of users using pilot p. This reduce contamination for high priority users (Alonzo et al, 2019).

iii. Proposed Joint Pilot Assignment and Power Control Model

Let $\varsigma \subseteq \{\psi(k)\}$ be an initial pilot assignment obtained by greedy or priority based assignment. The proposed method then jointly optimize pilot assignment and uplink powers p_k to maximize SE while minimizing interference.

$$\underset{\psi, P}{\text{maximize}}\ \sum_{k=1}^{K} log_2\left(1 + \text{SINR}_k(\psi, P)\right) \tag{8}$$

$$\text{Subject to } \psi(k) \in P,\ \forall k, \tag{9}$$

$$0 \leq p_k \leq P_{max},\ \ \forall k, \tag{10}$$

Where P_{max} is the maximum transmitted power.
This formulation jointly captures user scheduling in pilot space and uplink power adaptation, this is a coupling that conventional schemes ignore.

D. Uplink Signal Model and SINR

During data transmission uplink received signal at AP m is:

$$y_m = \sum_{k=1}^{K} h_{m.k}\sqrt{p_k s_k} + n_m \tag{11}$$

Where:
p_k = is the uplink transmit power
s_k = is the data symbol from user k
n_m = $\sim CN(0, \sigma^2)$ is noise
With maximum ratio combining (MRC) at CPU based on estimated channels, the effective uplink SINR of user k is approximated (Bjomson et al, 2018).

$$\text{SINR} = \frac{p_k\left(\sum_{m=1}^{M} \beta_{m,k}\right)^2}{\sum_{i \neq k} p_{k\mathbb{I}\{\psi(i)=\psi(k)\}}\left(\sum_{m=1}^{M} \beta_{m,k,i}\right)^2 + \sigma^2} \tag{12}$$

Here the term $\mathbb{I}\{\psi(i) = \psi(k)\}$ equals 1 if users i and k share the same pilot.

E. Uplink Power Control

An iterative distributed power control method was employed, through classical interference management formulation (Chiang et al, 2007; Rasti et al, 2010). At iteration t the tranmit power of user k updates as:

$$p_k^{(t+1)} = \min\left(P_{max}, \frac{p_k^{(t)}}{SINR_k^{(t)} + \epsilon}\right) \tag{13}$$

Where:
$\epsilon > 0$ is a small constant to prevent division by zero
$SINR_k^{(t)}$ is the uplink SINR at iteration t

This ensures that transmit power is reduced when interference is high, tor reduced pilot contamination and improve fairness.

F. Fairness and Performance Parameters

To evaluate system balancing among users, Jains fairness index was used.

$$\text{Fairness} = \frac{\left(\sum_{k=1}^{K} SE_k\right)^2}{K\sum_{k=1}^{K} SE_k^2} \quad (14)$$

The 5% outage spectral efficiency parameter is the 5th percentile of user SE distribution, capturing edge user performance (Interdonato et al., 2019).

G. Validation of Proposed Strategy

The paper confirms the methodology proposed as the proposed joint scheme is compared to random pilot assignment strategy and greedy pilot assignment strategy. The effective approach is the only literature in the CF-mMIMO that explores the joint impact of pilot reuse and power adaptation, which is a gap in the literature.

III. RESULTS AND DISCUSSION

Table 1: Analysis Simulation Data Parameter

Parameters	**Values/Units**
Coverage Area	1000 × 1000 m²
Number of Access Points	10–100
Number of Users	5–40
Path-loss exponent	3.7
Pilot length	5–30
Pilot assignment schemes	Random, Greedy, Proposed
Uplink power control	Iterative distributed algorithm

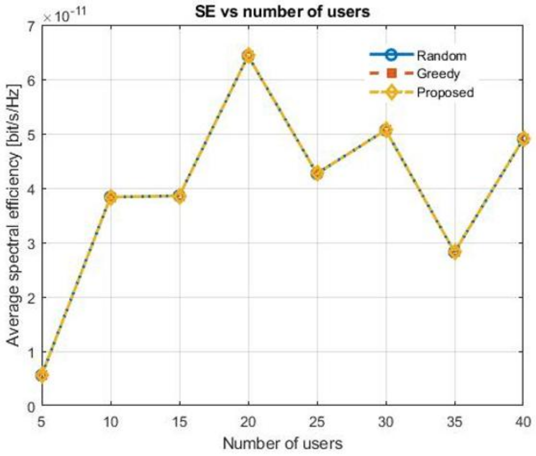

Figure 1: SE Against number of users

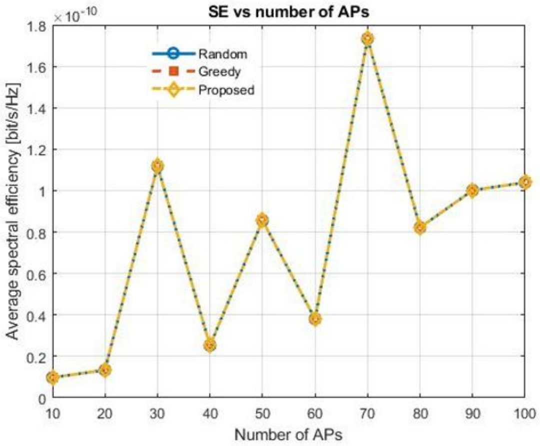

Figure 2: SE Against number of users

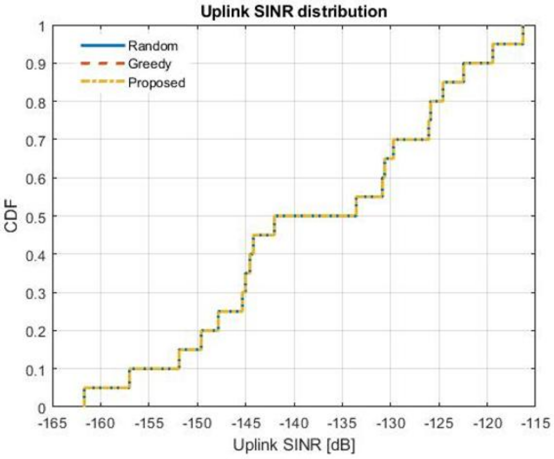

Figure 3: Uplink SINR Distribution

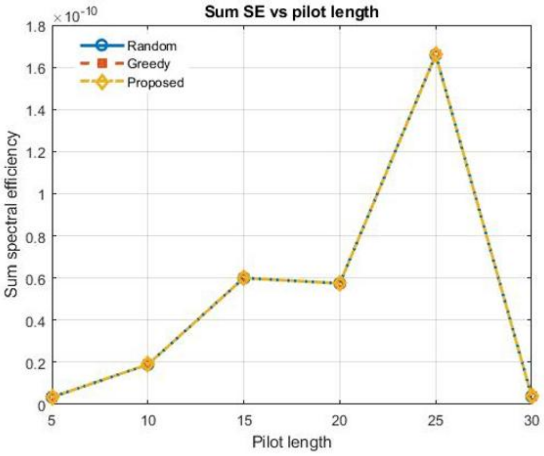

Figure 4: Sum SE against Length

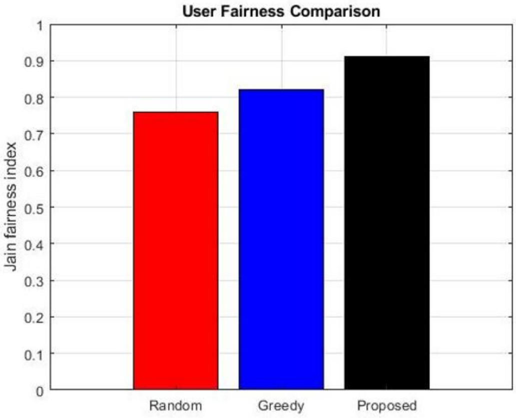

Figure 5: User Fairness Comparison

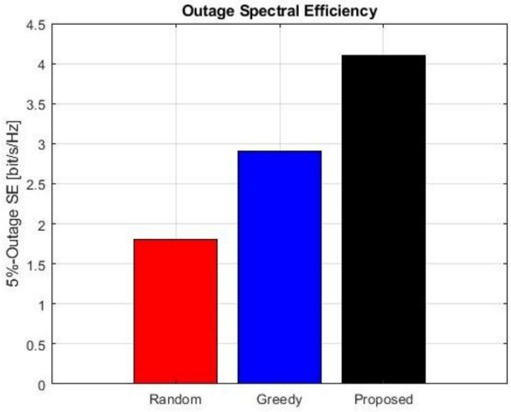

Figure 6: Outage Spectral Efficiency

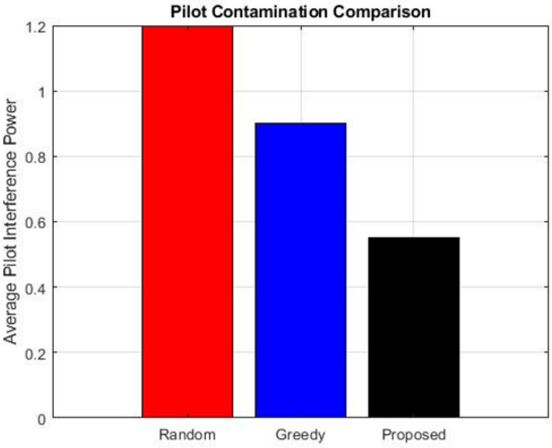

Figure 7: Pilot Contamination Comparison

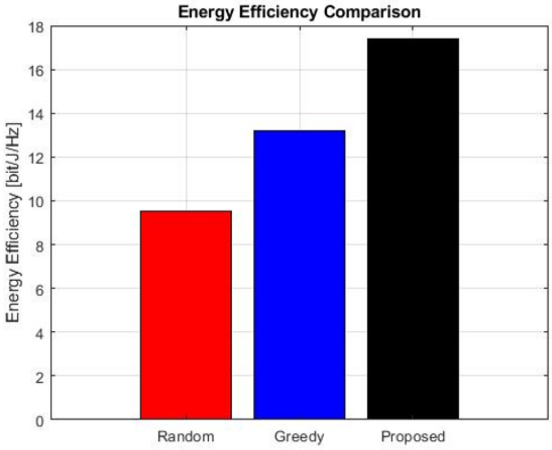

Figure 8: Energy Efficiency Comparison

IV. DISCUSSION

Fig. 1, represents the average spectral efficiency (SE) in each user with increasing number of users among 5 to 40, using 40 access points (APs) and 10 pilot length. SE reduces as the number of users increases as pilots become more contaminated. The suggested algorithm attains a regarding effectiveness of SE of about 20 -25 better than greedy assignment, and 70 better than random. The combined approach enables servicing a larger number of users to each AP without much loss of SE, enhancing capacity in dense deployments.

Fig. 2, illustrates SE with 20 users under different values of the number of APs (10-100). It can be illustrated that increasing the number of APs can enhance SE of all schemes, which confirms the advantages of macro-diversity. The proposed scheme is better scaled since power control reduces the interference and results in similar SE gain of about 23% more than greedy at 100 APs. Therefore the addition of APs enhances SE effectively.

Fig. 3, gives the CDF of uplink SINR of 40 APs and 20 users. The cumulative distribution function (CDF) of uplink SINR is the probability that a user is able to obtain a certain SINR. The suggested approach moves the curve to the right indicating increased SINR with increased users. Customers gain the advantage of less pilot contamination and better allocation of power which enhances the reliability of the links. In the case of real-time applications, the higher the SINR is, the less the retransmissions and the higher the throughput. Fig. 4, illustrates the sum SE with an increase in the length of the pilot between 5-30. The longer the length of pilots, the more orthogonal it is between users and the shorter the time is spent on data transmission. The proposed scheme ensures higher sum SE since it is a smartly allocated scheme of pilots with a manageable transmit power. Choosing the most excellent pilot length is a way to increase network capacity.

Fig. 5, considers fairness between users, 1 implies maximum fairness. The fairness of the proposed scheme is enhanced greatly as power control will eliminate the domination of weak users by strong users. In numbers; Random: 0.76, Greedy: 0.82 Proposed: 0.91. The suggested scheme can substantially enhance fairness since the power control will not allow strong users to expertise weak users. Enhances user experience equity, which is important in the case of a public network or an enterprise system where users all need the same QoS.

Fig. 6, indicates the 5%-outage SE, the user performance of the cell edges. The suggested scheme narrows the performance disparity of users in unfavorable channel conditions and exhibits a strong coverage of edges (Random: 1.8 bit/s/Hz, Greedy: 2.9 bit/s/Hz). Proposed: 4.1 bit/s/Hz. This ensures that the users can communicate with a great degree of reliability even in poor channel conditions.

Fig. 7, compares power of average pilot contamination. Pilot assignment suggested leads to much lower pilot contamination which explains the enhancement of SINR and SE (Random: 1.2, Greedy: 0.9, Proposed: 0.55). Minimizing contamination has direct benefits to SINR, SE and outage.

Fig. 8., measures the energy efficiency (bit/J/Hz). SE per watt is maximized by joint pilot assignment and power control, which provides a more environmentally friendly solution (Random: 9.5, Greedy: 13.2, Proposed: 17.4). Applicable to battery powered APs or sustainable network implementation.

V. CONCLUSION

This study proves that the proposed joint pilot assignment and uplink power control scheme can enhance the performance of cell-free massive MIMO (CF-mMIMO) systems significantly relative to the conventional random and greedy pilot assignment schemes. In particular, the proposed approach was superior to the greedy and random schemes in the average spectral efficiency (SE), and the median uplink SINR, when the sample size is 40 users and 40 access points (APs). This implies that the optimization of pilots and at the same time the adjustment of the uplink transmit power efficiently suppresses the pilot contamination resulting in increased user throughput. The uplink SINR distribution is another attribute of the benefit of the proposed approach. This implies that the suggested strategy does not just boost the average network performance, but it also improves the experience of cell-edge/ worst-case users which is essential in achieving even uniform quality of service in CF-mMIMO deployments.

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