Comparative analysis of uplink power control schemes in user-centric cell-free massive MIMO

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Abstract

User-centric cell-free massive multiple-input multiple-output (UC-CFmMIMO) is a promising architecture for next-generation wireless networks. It removes cell boundaries and enables cooperative transmission from distributed access points (APs), improving spectral efficiency (SE), connectivity, and user fairness. To fully leverage these advantages-especially in dense deployments-effective uplink power control (UPC) strategies are crucial for managing interference and balancing throughput with fairness. This paper compares three UPC methods: (i) Full power control (Full), (ii) fractional power control (FPC), and (iii) a fixed-point algorithm (FPA) for max-min fairness. The simulation results obtained from a network with 50 APs and 10 user equipments (UEs) highlight key trade-offs. Full offers the highest median per-user SE (3.089 bit/s/Hz) and total SE (34.81 bit/s/Hz), but yields low fairness. FPA achieves the best fairness, with a minimum SE of 2.1 bit/s/Hz, while FPC provides an intermediate solution. In scalable scenarios with more APs, Full and FPC further increase total SE, while FPA consistently leads in minimum SE. Regarding computational efficiency, FPC remains faster in small- to medium-scale networks, whereas the execution time of FPA grows more slowly with network size, demonstrating better scalability for large systems. In summary, Full is ideal for throughput-focused systems. FPA suits fairness-oriented designs. FPC offers a tunable and scalable balance between the two.

***Keywords**: User-centric cell-free massive MIMO; Uplink power control; Fractional power control; Max-min fairness; Total SE optimization*

Abbreviations

AP	Access Point
FPA	Fixed-Point Algorithm
FPC	Fractional Power Control
Full	Full Power Control
MIMO	Multiple-Input Multiple-Output
SE	Spectral Efficiency
UE	User Equipment
UPC	Uplink Power Control
UC-CFmMIMO	User-Centric Cell-Free Massive Multiple-Input Multiple-Output

1. Introduction

Next-generation wireless networks are rapidly evolving to meet escalating demands for higher data rates, ubiquitous connectivity, and enhanced user experience. UC-CFmMIMO stands out as a promising architecture to address these requirements, effectively eliminating traditional cell boundaries by allowing multiple distributed APs to cooperatively serve each user. This paradigm shift offers significant potential for improving SE, ensuring user fairness, and enhancing overall network capacity, particularly in dense deployment scenarios [1]-[4].

Central to realizing the full potential of UC-CFmMIMO is the effective management of uplink transmissions. UPC is crucial for mitigating inter-user interference, which is inherent when numerous users transmit simultaneously to multiple APs. Proper UPC strategies are vital not only for maximizing system throughput but also for conserving UE energy and guaranteeing a minimum quality of service across all users [2], [5]-[9].

However, selecting an appropriate UPC strategy involves navigating a fundamental trade-off between maximizing the overall system SE and maintaining fairness among users. Aggressively pursuing higher SE might lead to significant disparities in user data rates, while prioritizing fairness could potentially limit the network's total capacity [10]-[14]. Several UPC approaches exist, ranging from the simple full power transmission-where all UEs transmit at maximum power-to adaptable heuristic methods like FPC, which can be tuned to balance different objectives. Another approach aims to optimize for fairness, such as maximizing the minimum user signal-to-interference-plus-noise ratio (SINR), often requiring iterative methods like FPA to find the solution [15]-[20]. While these methods are conceptually understood, and prior works such as [2], [9] have investigated aspects of their performance trade-offs, a unified and consistent simulation-based comparison-specifically tailored to the UC-CFmMIMO architecture-remains underexplored.

This paper aims to fill this gap by providing a comprehensive quantitative comparison of different UPC strategies, specifically evaluating Full, FPC (e.g., tuned towards throughput), and the performance achieved via max-min fairness optimization (often solved using FPA). Our primary contribution is the systematic evaluation and analysis of these methods based on key performance indicators, namely SE and user fairness, within a common UC-CFmMIMO framework. By elucidating the performance characteristics and inherent trade-offs of each strategy, this work seeks to offer valuable insights and practical guidance for selecting and implementing UPC mechanisms in future UC-CFmMIMO deployments.

The remainder of this paper is structured as follows: Section 2 describes the system model of the considered UC-CFmMIMO network. Section 3 formulates the UPC

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problems. Section 4 presents various UPC schemes, including Full, FPA, and FPC. Section 5 provides numerical results, performance evaluations, and key findings. Finally, Section 6 concludes the paper and outlines potential directions for future work.

2. System model

We study a UC-CFmMIMO network composed of K single-antenna UEs and L APs, each equipped with a single antenna. The wireless channel linking AP l to UE k in a given coherence block is represented by $\mathbf{h}_{kl} \in \mathbb{C}^N$. The channel is modeled using the block-fading, where $\mathbf{h}_{kl}$ is time-invariant and frequency-flat in a coherence block with τ_c symbols in time division duplex protocol. Total block length τ_c is broken down into three component τ_p symbols used for uplink pilot transmission (enabling channel estimation of $\hat{\mathbf{h}}_{kl}$) [2], [21]-, [23]; τ_u allocated to uplink data, and τ_d allocated to downlink data. In coherence block, the channel is randomly generated according to a correlated Rayleigh fading model $\mathbf{h}_{kl} \sim \mathcal{N}_{\mathbb{C}}(\mathbf{0}_N, \mathbf{R}_{kl})$, while $\mathbf{R}_{kl} \in \mathbb{C}^{N\times N}$ is the spatial correlation matrix between AP l and UE k. A general expression for UE k's effective SINR under distributed uplink operation is provided in, while $\mathbf{R}_{kl}$, a positive semi-definite matrix, models large-scale fading effects such as shadowing, antenna characteristics, path loss, and spatial correlation.

Uplink transmission powers from all UEs are grouped into a power vector $\mathbf{p} = [p_1, \ldots, p_K]^{\mathrm{T}}$, which affects the entire network. The uplink SE for a given UE k is determined by its SINR, which depend on $\mathbf{p}$. Specifically, the SINR numerator depends on the desired UE's transmit power p_k while the denominator includes interference from all UEs' power levels in $\mathbf{p}$. A general expression for UE k's effective SINR under distributed uplink operation is provided in [2]:

$$\mathrm{SINR}_k(\mathbf{p}) = \frac{b_k p_k}{\mathbf{c}_k^T \mathbf{p} + \sigma_k^2} \quad (1)$$

where:

$$b_k = \left| \mathbf{a}_k^{\mathrm{H}} \mathbb{E}\{\mathbf{g}_{kk}\} \right|^2 \quad \forall k, \quad (2)$$

$$c_{kk} = \mathbb{E}\left\{ \left| \mathbf{a}_k^{\mathrm{H}} \mathbf{g}_{kk} \right|^2 \right\} - b_k \quad \forall k, \quad (3)$$

$$c_{ki} = \mathbb{E}\left\{ \left| \mathbf{a}_k^{\mathrm{H}} \mathbf{g}_{ki} \right|^2 \right\} \quad \forall k, \forall i \neq k, \quad (4)$$

$$\sigma_k^2 = \mathbf{a}_k^{\mathrm{H}} \mathbf{F}_k \mathbf{a}_k, \quad (5)$$

$b_k p_k$ represents the effective power of the desired signal for UE k, $\mathbf{c}_k^T \mathbf{p}$ denotes the total interference power from all other users, and σ_k^2 is the additive noise power at the receiver. A detailed derivation and interpretation of these components can be found in [2]. $\{a_{kl} : k = 1, \ldots, K, l \in \mathcal{M}_k\} \in \mathbb{C}^{LN}$ is the weight that the CPU assigns to the local signal estimate that AP l has of the signal from UE k. The expectation is with respect to the channel realizations.

$$\mathbf{F}_k = \sigma_{\mathrm{ul}}^2 \,\mathrm{diag}\left(\mathbb{E}\left\{ \left\| \mathbf{D}_{k1} \mathbf{v}_{k1} \right\|^2 \right\}, \ldots, \mathbb{E}\left\{ \left\| \mathbf{D}_{kL} \mathbf{v}_{kL} \right\|^2 \right\} \right) \in \mathbb{C}^{L\times L}. \quad (6)$$

Vector $\mathbf{g}_{ki} \in \mathbb{C}^L$ computed as:

$$\mathbf{g}_{ki} = \begin{bmatrix} \mathbf{v}_{k1}^{\mathrm{H}} \mathbf{D}_{k1} \mathbf{h}_{i1} \\ \vdots \\ \mathbf{v}_{kL}^{\mathrm{H}} \mathbf{D}_{kL} \mathbf{h}_{iL} \end{bmatrix}. \quad (7)$$

where $\mathbf{v}_k = \left[\mathbf{v}_{k1}^{\mathrm{T}}, \ldots, \mathbf{v}_{kL}^{\mathrm{T}} \right]^{\mathrm{T}} \in \mathbb{C}^{LN}$ is the combining vector used at the central CPU. $\mathbf{D}_k = \mathrm{diag}\{\mathbf{D}_{k1}, \cdots, \mathbf{D}_{kL}\}$ is a block-diagonal matrix. $\mathbf{D}_{kl} \in \mathbb{C}^{N\times N}$ is a set of diagonal matrices defined for k=1,...,K and l=1,...,L, determining which APs communicate with which UEs. $\mathbf{h}_i : i = \{1, \ldots, K\}$ is the channel vectors from all K UEs. As the result, the uplink SE of UE k depends on $\mathbf{p}$ and it is given by [2]:

$$\mathrm{SE}_k(\mathbf{p}) = \frac{\tau_u}{\tau_c} \log_2\left(1 + \mathrm{SINR}_k(\mathbf{p})\right). \quad (8)$$

3. Problem formulation

UPC involves selecting suitable transmit power levels for the UEs to optimize a specific utility function, most commonly tied to SE. In this work, we focus on two main power control objectives: maximizing the total SE and ensuring fairness through max-min SE optimization.

The goal of max-min SE fairness is to improve equity by maximizing the minimum SE across all UEs, ensuring that the UE with the worst performance is still adequately served. This approach, known as max-min fairness, adjusts the transmit power allocations to balance performance among users. The corresponding optimization problem is defined mathematically as follows:

$$\begin{aligned} (\mathbf{P1}):\ & \max_{\mathbf{p}} \ \min_{k\in\{1,\ldots,K\}} \mathrm{SE}_k(\mathbf{p}) \\ & \text{s.t.} \quad 0 < p_k \le p_{\max}, \quad k = 1, \ldots, K. \end{aligned} \quad (9)$$

While max-min SE fairness prioritizes fairness for UEs with poor channel conditions, it may not fully exploit the potential for higher spectral efficiencies in large networks. In contrast, the total SE maximization problem focuses on maximizing the total number of transmitted bits, irrespective of their distribution among UEs. This approach is particularly suitable for scenarios where each UE only interferes with a small subset of neighboring UEs. The total SE maximization problem can be described by:

$$\begin{aligned} (\mathbf{P2}):\ & \max_{\mathbf{p}} \ \sum_{k=1}^{K} \mathrm{SE}_k(\mathbf{p}) \\ & \text{s.t.} \quad 0 < p_k \le p_{\max}, \quad k = 1, \ldots, K. \end{aligned} \quad (10)$$

4. Uplink power control schemes

4.1 Full power control

Full is the most basic approach: every UE simply transmits using its maximum allowed power at all times. It is equivalent to using the FPC method with the control setting fixed to zero. Interestingly, simulations in [2] demonstrated that this very simple strategy performed extremely well in the evaluated cell-free system. In the uplink, it achieved nearly the highest total data rate (i.e., total SE) across the network, outperforming even the complex max-min fairness optimization in several aspects. This outcome suggests that the inherent design of the cell-free system, when combined with advanced signal processing techniques at the receiver side, was highly effective at managing the interference resulting from all UEs transmitting at full power. This method is inherently scalable, as it requires no complex power control calculations. However, it does not explicitly aim to ensure fairness among users. Nevertheless, the negative impact on the weakest users was not excessively severe, as shown in the presented simulation results.

4.2 Fixed-point algorithm

The FPA is a step-by-step computational procedure designed to find the precise power settings for all UEs that maximize the lowest signal quality (SINR) experienced by any UE in the network. The goal is to make the minimum performance as high as possible for everyone. The algorithm starts with initial power levels. In each step, it adjusts every UE's power based on their current signal quality-typically, UEs with lower quality receive a relative power boost. After adjusting, it scales all UE powers down proportionally so that the UE needing the highest power operates exactly at the maximum limit allowed. This process is repeated iteratively. The algorithm is proven to converge to the unique optimal solution where all UEs achieve the exact same SE [9], [11], [17]. The detailed procedure is summarized in Algorithm 1: FPA for solving the uplink max-min fairness problem, which iteratively updates transmit powers until convergence to the fairness-optimal power allocation is achieved.

To provide deeper insight, the algorithm operates under the principle of max-min fairness: it increases the transmit power of users with weak SINR until all users reach a common SINR target, constrained by their individual power limits. The fixed-point nature of the method ensures that the update rule maintains monotonicity and scalability, key properties that guarantee convergence. Each iteration is computationally lightweight, involving closed-form updates, but the overall scheme is sensitive to the number of users, which impacts scalability. Nonetheless, the approach guarantees fairness by equalizing SE across all UEs, making it highly suitable in scenarios where minimum user experience is prioritized over total throughput.

The feasibility of the max-min SE problem is generally ensured under typical power constraints, provided the network is not heavily overloaded (i.e., the number of UEs K is not excessively large compared to the number of APs L). The FPA inherently guarantees feasibility by iteratively scaling power levels to respect per-user power limits. Moreover, the algorithm is proven to converge to a unique optimal solution under standard assumptions, such as positive channel gains and bounded powers, ensuring that all UEs achieve the same minimum SE at convergence. Although the original max-min SE formulation is non-convex, its quasi-convex nature enables an efficient transformation into a fixed-point form based on standard interference functions. These functions satisfy monotonicity and scalability properties, allowing convergence to the global optimum through iterative updates, as supported by the theoretical foundations in [9], [11], and [17].

Advantages: Algorithm 1 finds the mathematically best solution for maximizing the minimum UE performance (max-min fairness). It converges quickly and has relatively low computational complexity since it only involves iterative closed-form updates of the variables.

Disadvantages: This algorithm is not scalable. As the number of UEs K increases, the computation required grows significantly. It focuses entirely on the weakest UE, which can severely limit the data rates for all other UEs and reduce the network's total throughput, especially in large networks where UEs might not interfere much with the weakest one.

Algorithm 1. FPA for solving the uplink max-min fairness problem.

Initialization: Set initial power $p_i = p_{\max}$ and the solution accuracy $\varepsilon > 0$

1. **while** $\max\limits_{k\in\{1,\dots,K\}} \mathrm{SINR}_k(\mathbf{p}) - \min\limits_{k\in\{1,\dots,K\}} \mathrm{SINR}_k(\mathbf{p}) > \varepsilon$ **do**
2. $\quad p_k \leftarrow \dfrac{p_k}{\mathrm{SINR}_k(\mathbf{p})}, k \in 1,\dots,K$
3. $\quad \mathbf{p} \leftarrow \dfrac{p_{\max}}{\max\limits_{k\in\{1,\dots,K\}} p_k}\mathbf{p}$
4. **end while**

Output: Optimal transmit powers $\mathbf{p}$

Max-min SE $\min\limits_{k\in\{1,\dots,K\}} \dfrac{\tau_u}{\tau_c}\log_2\left(1+\mathrm{SINR}_k(\mathbf{p})\right)$

4.3 Fractional power control

FPC is a classical heuristic originally developed for cellular networks to partially compensate for pathloss disparities among users. It balances between exploiting favorable channel conditions (to enhance SE for nearby UEs) and mitigating interference (to support cell-edge users [2], [21]. Recently, FPC has been adapted to CFmMIMO systems, initially under the assumption that all APs serve all UEs using maximum ratio combining. However, it can be easily adapted to scenarios where each AP serves only a subset of UEs, even when arbitrary combining schemes are used [2], [6], [7]. UE k selects its uplink transmit power as:

$$p_k = p_{\max}\frac{\left(\sum\limits_{l\in\mathcal{M}_k}\beta_{kl}\right)^{\upsilon}}{\max\limits_{i\in\{1,\dots,K\}}\left(\sum\limits_{l\in\mathcal{M}_i}\beta_{il}\right)^{\upsilon}} \tag{11}$$

where the exponent υ dictates the power control behavior. β_{il} is large-scale fading between UE i and AP l, representing average channel strength, $\mathcal{M}_i$ is the set of APs serving UE i, usually chosen based on proximity or signal quality so $\sum_{l\in\mathcal{M}_i}\beta_{il}$ is the total channel gain from UE i to the APs that serve it. The denominator in (11) makes sure that $p_k \in [0, p_{max}]$.

However, calculating the denominator in (11) requires finding the maximum over all K UEs in the network. This makes the method unscalable when the number of UEs k is large. To achieve scalability, we can modify equation (11) by restricting the maximization to a subset of UEs closely related to UE k. Specifically, we utilize the set $\mathcal{S}_k$, defined in , which consists of UEs that are served by at least one common AP as UE k. The size of $|\mathcal{S}_k|$ does not grow unboundedly when K goes to infinity [2], [7].

$$p_k = p_{\max}\frac{\left(\sum_{l\in\mathcal{M}_k}\beta_{kl}\right)^{\upsilon}}{\max_{i\in\mathcal{S}_k}\left(\sum_{l\in\mathcal{M}_i}\beta_{il}\right)^{\upsilon}}, \tag{12}$$

where $\mathcal{S}_k = \{i : \mathbf{D}_k\mathbf{D}_i \neq 0_{LN\times LN}\}$.

In the cell-free adaptation, a UE determines its transmit power based on the combined signal strength it experiences from all the APs currently serving it. This combined strength value is then adjusted using a specific control setting (exponent υ) . To ensure no UE exceeds the maximum allowed power and to maintain scalability, this adjusted value is typically compared against the values of other nearby UEs, and the final power is scaled accordingly. The control setting dictates the behavior [2]:

- When υ=0, the scheme results in full power transmission, meaning that all UEs transmit at their maximum allowed power regardless of their channel conditions. This setting is aligned with total SE maximization in ideal conditions, especially when interference is not a major limiting factor.
- When υ=−1, each UE compensates fully for the pathloss and shadowing variations by inversely scaling its transmit power according to its channel gain. This results in equalized effective received power across users, resembling max-min fairness, but often at the cost of significant throughput loss for most UEs to benefit the weakest one.
- Intermediate values like υ=−0.5 represent a balance between fairness and throughput. This setting mitigates channel disparities without being as aggressive as full channel inversion (υ=−1), and is shown to reduce SIR variation and improve fairness without drastically sacrificing total SE.
- Conversely, setting υ>0 (e.g., υ=0.5) allocates more power to UEs with stronger channels. This approach amplifies the throughput of already favorable links, effectively pushing the SE cumulative distribution function (CDF) curve to the right, resembling the behavior of total SE maximization, but degrades the experience of weaker UEs, resulting in poor fairness.
- In the extreme case where υ=1, FPC performs complete channel inversion, meaning that each UE's transmit power is fully adapted to compensate for its large-scale fading. This ensures that all UEs achieve approximately the same average received signal power, regardless of their location or channel conditions. As a result, the worst-off UEs benefit significantly, with their SIR improving dramatically, which leads to a notable increase in the lower tail of the SE distribution, often measured by the 3%-outage. However, this uniformity comes at the cost of reducing the system's overall throughput: UEs with favorable channel conditions are forced to reduce their power significantly, resulting in a lower average SE. This setting thus prioritizes strong fairness, especially for disadvantaged UEs, but sacrifices the performance potential of users in good conditions. Compared to max-min fairness solutions, υ=1 offers more elasticity-it still provides fairness benefits without the extreme throughput degradation typically seen in hard fairness optimization.

Advantages: FPC offers a versatile and scalable solution for power control in decentralized wireless systems. Its key strength lies in its ability to balance between fairness and SE by simply adjusting a single exponent υ. Unlike rigid optimization-based schemes, FPC requires minimal coordination and can be implemented locally by each UE using only large-scale channel information. Moreover, it offers a pragmatic compromise: settings like υ=−0.5 or 0.5 deliver favorable trade-offs between throughput and fairness without the high complexity of centralized algorithms. In interference-limited environments, this approach helps shape the SIR distribution to mitigate deep fades and improve the predictability of user experience.

Disadvantages: Despite its simplicity and flexibility, FPC is inherently heuristic-it is not derived from directly optimizing an explicit utility function, which limits its theoretical optimality. Performance is sensitive to the choice of υ, and finding the best exponent often requires empirical tuning for specific deployment scenarios. At high fairness levels (e.g., $\upsilon \approx 1$), system throughput suffers due to the overcompensation of weak users, while at high throughput settings (e.g., υ>0), the weakest UEs may experience poor service. Moreover, FPC does not dynamically respond to real-time interference conditions or instantaneous channel variations, making it less adaptive in dense or fast-changing environments compared to more sophisticated optimization-based methods.

5. Numerical results

5.1 Simulation setup

To evaluate the UPC methods in UC-CFmMIMO settings, we simulate a network over a 1 km×1 km area with 50 APs and 10 UEs placed randomly. Each AP is equipped with one antenna, totaling 50 antennas across the network. The simulations span 500 different network setups, each with 50 random realizations, to ensure statistically reliable results. The system operates over a 20 MHz bandwidth, and receiver noise $\sigma^2 = -94\,\text{dBm}$ accounting for both thermal noise and a 7 dB noise figure. Each UE has a maximum uplink transmit power of $p_{\max} = 100\,\text{mW}$, reflecting practical deployment constraints. A 2 ms coherence time and 100 kHz coherence bandwidth define the coherence block, suitable for both indoor and outdoor mobile users in sub-6 GHz bands. Large-scale fading follows the 3GPP Urban Microcell model, while Rayleigh fading is modeled with spatial correlation using a local scattering approach. For UPC evaluation, we compare the following methods: Full serves as a baseline; FPC is implemented based on equation (12) using representative exponents υ=0.5 and the FPA with $\varepsilon = 0.01$ (Algorithm 1) is employed for the max-min fairness problem.

5.2 Performance metrics

System performance is primarily evaluated using SE in bit/s/Hz, focusing on two key aspects: the total SE, which measures total network throughput, and the minimum SE, used to assess fairness and worst-case user performance. The overall SE distribution across UEs is illustrated using CDF curves. In addition to these performance metrics, the computational complexity required to implement each UPC scheme is evaluated, particularly concerning network scalability. Theoretical analysis, notably from [2], indicates that the Full power approach has negligible computational overhead for power decisions and is inherently scalable. The scalable FPC approach, relying on local information and calculations involving the limited set $\mathcal{S}_k$, is also designed for scalability, offering computational cost per UE independent of the total network size *K*. Conversely, the FPA (Algorithm 1) for max-min fairness optimization is non-scalable, with computational complexity per iteration increasing significantly with *K*.

5.3 Key findings

5.3.1 Effectiveness of the schemes

The comparative evaluation of UPC schemes-Full, FPA, and FPC-reveals distinct strengths and trade-offs across three key performance metrics: per-user SE, minimum SE, and total SE. In terms of **per-user SE**, as shown in Figure 1, the Full scheme consistently outperforms the others across various percentiles. At CDF=0.1, Full achieves 1.719 bit/s/Hz, which is higher than both FPA (1.66 bit/s/Hz) and FPC (0.56 bit/s/Hz). At the median point (CDF=0.5), Full remains dominant with 3.089 bit/s/Hz, while FPC slightly surpasses FPA (2.22 vs. 2.104 bit/s/Hz). This trend confirms Full's effectiveness in optimizing individual user throughput, although the gap between FPA and FPC narrows at moderate SE levels, suggesting a shift in relative performance depending on user percentile.

When focusing on **minimum SE**, as depicted in Figure 2, FPA demonstrates a clear advantage in ensuring fairness. At CDF=0.5, which reflects the experience of the most disadvantaged users, FPA achieves 2.1 bit/s/Hz-significantly higher than Full (1.585 bit/s/Hz) and FPC (0.47 bit/s/Hz). Moreover, the CDF curve of FPA exhibits a flatter profile compared to others, indicating more uniform SE distribution across users. In contrast, FPC underperforms significantly at the lower percentiles, highlighting its limitation in supporting users with poor channel conditions.

The evaluation of **total SE**, shown in Figure 3, highlights the superior performance of Full in maximizing overall network capacity. At CDF=0.1, Full reaches 28.574 bit/s/Hz, compared to 22.64 for FPC and 16.629 for FPA. At the median (CDF=0.5), Full again leads with 34.81 bit/s/Hz, outperforming FPC (28.566 bit/s/Hz) and FPA (21.05 bit/s/Hz). While FPC trails behind Full, it consistently surpasses FPA in total throughput, especially in higher SE regions, making it a viable middle ground between fairness and capacity.

In summary, the Full power scheme delivers the highest total and per-user SE, making it ideal for systems prioritizing throughput and scalability. FPA excels in fairness by significantly improving the worst-case user SE, albeit at the cost of reduced total capacity. FPC provides a flexible compromise, offering adjustable trade-offs between throughput and fairness depending on its control parameter setting. These findings underscore the importance of selecting power control strategies based on specific system objectives-whether to maximize throughput, enhance fairness, or balance both.

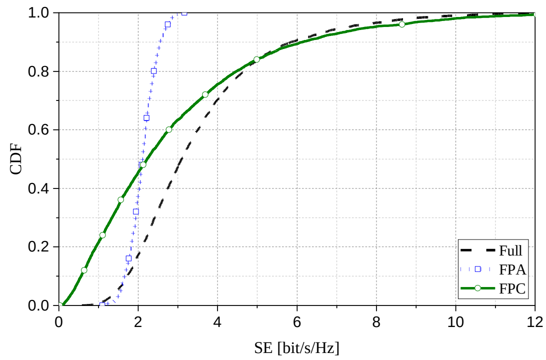

Figure 1. Per-user SE distribution for different UPC schemes. Full achieves the highest median SE, while FPA offers stronger lower-bound fairness.

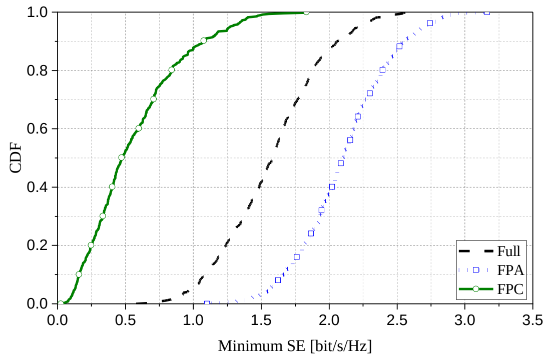

Figure 2. Minimum SE comparison across UPC methods. FPA consistently yields the highest minimum SE, demonstrating superior fairness.

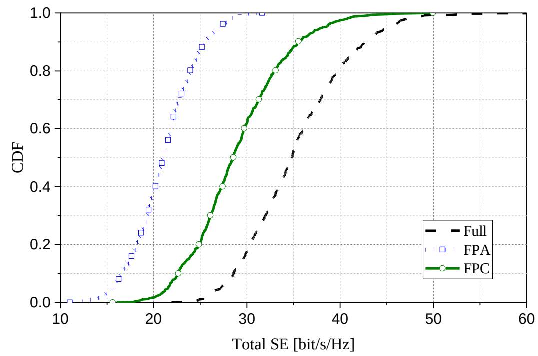

Figure 3. Total SE achieved by each UPC approach. Full performs best in terms of overall system throughput, followed by FPC and FPA.

5.3.2 Impact of number of APs and UEs

This section investigates how the number of APs and UEs affects system performance, evaluated through average minimum SE and average total SE-both of which are critical indicators for assessing network scalability and efficiency.

Figure 4 shows that increasing the number of APs enhances minimum SE across all schemes. At 100 APs, FPA achieves the highest minimum SE of 3.347 bit/s/Hz, outperforming both Full (2.7619 bit/s/Hz) and FPC (1.4215 bit/s/Hz). Similarly, Figure 5 illustrates that total SE also increases with the number of APs. At the 100-AP mark, the Full power scheme reaches 47.2334 bit/s/Hz, the highest among all methods. FPC follows with 40.5637 bit/s/Hz, and FPA trails at 33.4738 bit/s/Hz. These trends indicate that denser AP deployments benefit all schemes, particularly in terms of capacity and fairness for edge users.

Figures 6 and 7 analyze the impact of increasing UE count. As the number of UEs increases from 8 to 15, the average minimum SE decreases for all methods due to heightened inter-user interference. FPA maintains the highest minimum SE, though it declines from approximately 2.357 to 1.629 bit/s/Hz. The Full scheme shows less fairness, with minimum SE dropping from about 1.9 to 0.98 bit/s/Hz. FPC records the lowest minimum SE, falling sharply from 0.81 to 0.3 bit/s/Hz over the same range.

In contrast, the average total SE increases with more UEs, reflecting improved aggregate capacity. Full again delivers the best throughput, rising from 30.086 to 43.727 bit/s/Hz. FPC performs moderately well, with total SE increasing from 25.0 to 36.76 bit/s/Hz, while FPA shows the lowest values, from 18.86 to 24.45 bit/s/Hz.

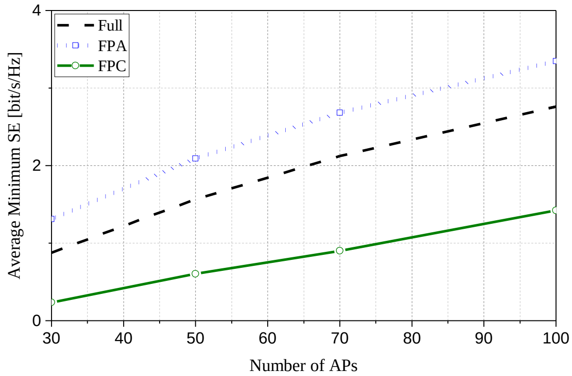

Figure 4. Minimum SE versus number of APs. FPA maintains fairness as AP count increases, while Full and FPC show slower improvements.

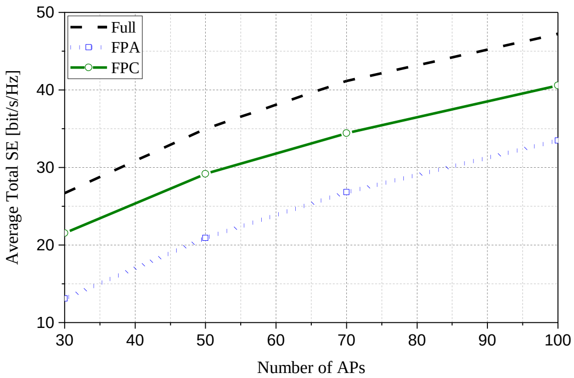

Figure 5. Total SE versus number of APs. Full and FPC scale well with more APs, whereas FPA remains limited in total throughput.

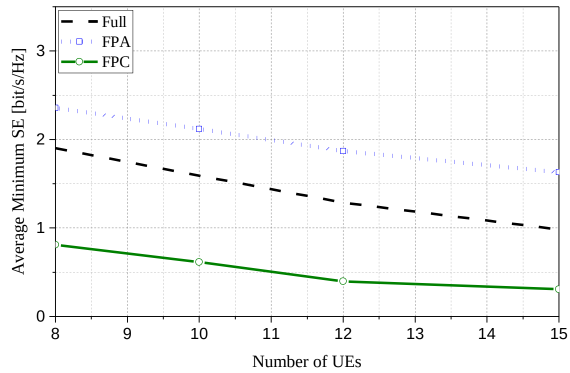

Figure 6. Minimum SE versus number of UEs. FPA maintains robustness under user density, while Full and FPC degrade significantly.

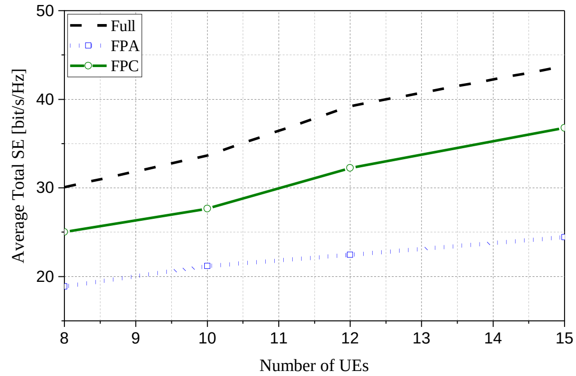

Figure 7. Total SE versus number of UEs. Full achieves the highest throughput, though fairness declines as user count increases.

In summary, these results affirm the trade-offs inherent in UPC design. FPA prioritizes fairness by maximizing minimum SE but sacrifices total throughput. Full maximizes total SE at the expense of user fairness. FPC offers a compromise in terms of throughput but continues to lag behind in supporting worst-case users. The choice of method should therefore align with specific system objectives-whether focused on fairness, capacity, or a balance of both.

5.3.3 Computational time

This section presents a comparative evaluation of the computational efficiency of the FPA and FPC methods in determining transmit power levels across varying network configurations. The average execution time for each scheme is recorded under different numbers of users (K) and APs (L), as shown in Tables 1 and 2. All simulations were performed on MATLAB Online 2024b using an Intel(R) Xeon(R) Platinum 8375C CPU to ensure a consistent and reproducible runtime environment.

From Table 1, where the number of APs is fixed at 50, it is evident that FPC consistently outperforms FPA in terms of computational speed. As the number of users increases from 8 to 30, the average execution time of FPC gradually rises from 3.4 to 7.8 microseconds. This increase is expected due to the growing number of power coefficients to compute. In contrast, FPA exhibits a more pronounced rise in computational time, from 9.8 to 13.4 microseconds. The relative increase is steeper for FPA, as it involves iterative computations and per-user updates that scale less favorably with network size. These results highlight the scalability advantage of FPC in scenarios with high user density.

Table 2 further investigates the impact of increasing the number of APs while fixing the number of users at 10. The results indicate that FPA's computation time gradually increases with L, from 9.7 to 11.8 microseconds, due to its dependence on distributed per-user calculations that interact with multiple APs. In contrast, FPC maintains lower computational times across all AP configurations, ranging from 3.9 to 5.7 microseconds. Although both methods incur additional cost as L increases, FPC shows better computational resilience, suggesting that it is more suitable for dense AP deployments.

In summary, while FPA offers strong performance in fairness, its iterative structure leads to longer computation times, which may be a limitation in latency-sensitive systems. FPC, with its closed-form expression, demonstrates better computational scalability in both user and AP dimensions. This efficiency makes it an attractive solution for real-time and large-scale implementations, especially where fast decision-making is crucial.

Table 1: Average computational time (in microseconds) for FPA and FPC under different numbers of UEs (K), with fixed L=50.

K	**8**	**10**	**12**	**15**	**20**	**30**
FPA	9.8	9.6	9.6	12.1	12.8	13.4
FPC	3.4	3.9	4.8	5.5	6.6	7.8

Table 2: Average computational time (in microseconds) for FPA and FPC under different numbers of APs (L), with fixed K=10.

L	**30**	**50**	**70**	**100**
FPA	9.7	9.6	10.3	11.8
FPC	4.4	3.9	5.6	5.7

6. Discussion

Several recent studies have analyzed UPC in CFmMIMO under various configurations. Compared to [7], where FPC offers flexibility at the cost of reduced worst-case performance, our results confirm that FPA ensures stronger fairness but with sensitivity to poor users. The fairness gain of FPA also aligns with [10], which reports more than double the outage performance over traditional schemes. In contrast to [11] and [12], which emphasize receiver processing techniques, our study isolates the impact of power control, showing that FPA achieves comparable fairness gains even without advanced combining. While [13] explores downlink trade-offs between CF and UC deployments, its uplink results with uniform power control reveal performance disparities across users—issues our FPA explicitly addresses. These observations reinforce the practical relevance of the studied UPC strategies and motivate hybrid or robust approaches under system constraints.

While this study assumes perfect channel state information (CSI) to ensure a fair baseline comparison, practical systems inevitably encounter estimation errors due to noise, pilot contamination, and mobility. These imperfections affect each UPC strategy differently. Full, being independent of CSI, is unaffected but lacks adaptability to dynamic interference. FPC depends only on large-scale fading, which is relatively stable and easier to estimate, making it more robust under practical conditions. In contrast, FPA requires accurate instantaneous CSI to compute SINR and update powers, making it highly sensitive to estimation inaccuracies. This sensitivity may degrade its convergence, stability, and fairness in real deployments, underscoring the importance of future research on robust UPC under imperfect CSI.

7. Conclusion

This work presents a comprehensive evaluation of three UPC strategies-Full, FPC with exponent υ=0.5, and max-min fairness optimization via FPA-in the context of UC-CFmMIMO systems. The study offers a nuanced understanding of the performance trade-offs between user fairness, total system throughput, computational efficiency, and scalability.

Our findings reveal that FPA consistently delivers the best fairness, achieving a minimum SE of 2.1 bit/s/Hz at median CDF, and up to 3.347 bit/s/Hz when the number of APs is increased to 100. However, FPA’s total SE remains the lowest (e.g., 21.05 bit/s/Hz at CDF=0.5) and shows limited scalability, particularly in dense user scenarios. In contrast, Full yields the highest throughput, reaching 34.81 bit/s/Hz at CDF=0.5 and up to 47.23 bit/s/Hz at 100 APs, but suffers from lower fairness (e.g., minimum SE dropping to 0.98 bit/s/Hz with 15 UEs).

FPC, although offering the lowest fairness (e.g., minimum SE down to 0.3 bit/s/Hz at 15 UEs), achieves intermediate total SE performance (e.g., 28.566–40.56 bit/s/Hz) and demonstrates strong scalability. In terms of computational efficiency, FPC is faster in small-scale networks, but the execution time of FPA increases more slowly with the network size. Specifically, FPC requires 3.4–7.8 microseconds under varying numbers of users, while FPA needs 9.6–13.4 microseconds; however, when scaling the number of APs, FPA becomes more favorable, showing better scalability.

In summary, FPA is well-suited for fairness-critical systems, Full is ideal for maximizing throughput in scalable deployments, and FPC offers a flexible and computationally efficient compromise between the two. This work provides practical insights to guide UPC design in next-generation wireless networks.

While this study focuses on the uplink, three strategies can be conceptually extended to the downlink. In this case, FPA-like approaches could be adapted to jointly optimize per-UE fairness through distributed beamforming and coordinated scheduling, whereas FPC principles could be translated into large-scale channel-aware downlink power allocation. Addressing downlink-specific constraints such as precoding feasibility, inter-user interference, and load balancing remains an important challenge.

Future research directions include optimizing the FPC exponent υ to enhance fairness without sacrificing scalability, developing novel scalable fairness-aware algorithms, and extending the current uplink analysis to the downlink with beamforming, user scheduling, and coordination strategies. Additionally, incorporating imperfect channel estimation, delay constraints, and realistic energy consumption models would further bridge the gap between theory and practical deployments. Exploring centralized benchmarks also presents an opportunity for comprehensive performance evaluation.

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