



ORIGINAL RESEARCH ARTICLE

PARTICLE SWARM OPTIMIZATION BASED RESOURCE ALLOCATION FOR  
HIGH ALTITUDE PLATFORM NETWORKS

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ABSTRACT

High Altitude Platforms (HAPs) are emerging as cost-effective aerial communication nodes capable of providing broadband wireless coverage over large geographical areas. However, efficient resource allocation remains a key challenge due to channel variability, power constraints, and user heterogeneity. This paper proposes a Particle Swarm Optimization (PSO)-based framework for joint subcarrier and power allocation in an OFDMA-based HAP communication system. The proposed approach employs PSO for adaptive subcarrier assignment and integrates the water-filling algorithm for power allocation. Performance is evaluated against conventional resource allocation schemes, including Max-SNR, Round Robin, and Proportional Fair. Simulation results demonstrate that the proposed PSO-based framework achieves competitive spectral and power efficiency, a more balanced distribution of user capacity, and a significant reduction in computational complexity, with an average execution-time reduction of approximately 97% compared to conventional methods. These results highlight the practicality of the proposed approach for real-time and adaptive resource management in next-generation HAP-based aerial communication networks.

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1.0 Introduction

High Altitude Platforms (HAPs), typically deployed in the stratosphere at altitudes between 17 and 22 km, have emerged as a promising solution for providing wide-area wireless coverage with quasi-stationary operation, reduced latency, and rapid deployment compared to conventional terrestrial communication systems (Arum Steve Chukwuebuka & Grace David, 2019; Kurt *et al.*, 2021). Due to their elevated position, HAPs can function as airborne base stations, enabling reliable broadband connectivity in remote and underserved regions while supporting high-capacity communication services (GSMA, 2021; Mershad *et al.*, 2021). Consequently, HAP-based communication architectures are increasingly regarded as key enablers for next-generation and beyond 5G/6G wireless networks.

With the exponential growth of mobile broadband demand and heterogeneous quality-of-service requirements, efficient radio resource allocation has become a critical challenge in HAP-assisted Orthogonal Frequency Division Multiple Access (OFDMA) systems. Conventional resource allocation schemes such as Maximum Signal-to-Noise Ratio (Max-SNR), Round Robin (RR), and Proportional Fair (PF) are widely adopted due to their simplicity and low computational complexity (Shu'aibu, 2009; Yusuf *et al.*, 2021). However, these approaches often exhibit limited adaptability under the dynamic channel conditions, user mobility, and interference variability inherent to aerial platforms, leading to inefficient spectrum utilization, unbalanced user performance, and degraded system efficiency (Suleiman *et al.*, 2021).

To overcome the limitations of traditional heuristic-based schemes, recent research has increasingly explored bio-inspired and evolutionary optimization algorithms, including Genetic Algorithms, Firefly algorithms, and Particle Swarm Optimization (PSO), for solving complex and nonlinear optimization problems in wireless

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communication networks (Abedi *et al.*, 2022; Demir *et al.*, 2018). PSO-based techniques have been successfully applied in various aerial and integrated communication scenarios. For instance, UAV swarm-enabled post-disaster communication networks employ PSO to optimize collaborative beamforming and UAV placement, achieving enhanced transmission rates and robustness (Zheng *et al.*, 2025). Similarly, evolutionary PSO-based spatial deployment strategies have been proposed for emergency ad hoc networks, incorporating environmental awareness to improve transmission quality in urban disaster scenarios (Chen *et al.*, 2025). In low-altitude air-ground cooperative systems, PSO combined with convex optimization has been shown to significantly improve throughput and convergence speed through joint trajectory and communication optimization (Hu *et al.*, 2025). Other studies extend PSO-based optimization to broader system objectives, including computation offloading and semantic communication in multi-UAV networks (Han *et al.*, 2025), fairness-oriented capacity optimization in space-air-ground integrated networks (Xu *et al.*, 2025), and centralized power and beamforming optimization in HAPS-UAV integrated sensing and communication architectures (Kanani *et al.*, 2025). While these works demonstrate the versatility and effectiveness of PSO and related optimization techniques, they primarily focus on deployment, trajectory planning, sensing, coverage optimization, or centralized coordination, often involving high computational complexity and limited suitability for real-time implementation.

In the specific context of HAP communication systems, existing studies largely rely on static or heuristic resource allocation strategies with limited adaptivity (Ming-cheng & Tsai, 2020). Although recent investigations into HAPS-Reconfigurable Intelligent Surface (HAPS-RIS) and HAPS-International Mobile Telecommunications (HAPS-IMT) frameworks highlight the growing importance of dynamic and intelligent resource control (Alfattani *et al.*, 2022; Wang *et al.*, 2022). Joint subcarrier- and power-level resource allocation tailored to uplink HAP-OFDMA systems remains largely unexplored. In particular, the integration of PSO-based adaptive subcarrier allocation with optimal power distribution techniques such as the classical water-filling algorithm, under practical computational constraints, has received limited attention in the literature.

Motivated by these gaps, this paper proposes a PSO-based adaptive resource allocation framework for uplink OFDMA-enabled HAP communication systems. In the proposed approach, PSO is employed to intelligently allocate subcarriers based on channel conditions, while the water-filling algorithm is used to optimally distribute transmit power across the allocated subcarriers. Unlike existing works that emphasize complex deployment geometry, centralized coordination, or multi-layer optimization, this study adopts a clean and simplified system model, thereby reducing computational complexity and enhancing real-time applicability. The proposed framework is systematically benchmarked against conventional Max-SNR, PF, and RR schemes using consistent performance metrics, including spectral efficiency, user capacity, robustness, and computational efficiency, to clearly demonstrate its effectiveness and practical relevance.

The remainder of this paper is organized as follows. Section 2 presents the system model and assumptions, detailing the proposed PSO-based subcarrier allocation and water-filling power allocation methodology. Section 3 discusses the simulation results and performance evaluation, and Section 4 concludes the paper with directions for future research.

## 2. Materials and Methods

This section presents the comprehensive methodology adopted in this study. It describes the system model, including the underlying mathematical formulation, and details the objective functions and constraints used to evaluate the performance of the proposed algorithm. The resource allocation framework, optimization strategy, and performance evaluation metrics are also clearly defined to ensure reproducibility and technical clarity.

### 2.1 System Model

We consider a single High-Altitude Platform (HAP) uplink communication system based on Orthogonal Frequency Division Multiple Access (OFDMA). The HAP operates as an aerial base station that receives uplink transmissions from multiple ground users within its coverage area.

Let  $K$  denote the number of users and  $N=10$  the total number of available subcarriers. According to the OFDMA principle, each subcarrier can be assigned to only one user at any given time, thereby avoiding intra-cell interference. The objective of the proposed system is to efficiently allocate subcarriers and transmission power to users in order to enhance overall system performance.

## 2.2 Channel Model

The uplink channel between each user and the HAP is modeled using the Friis free-space transmission model, which is suitable for high-altitude line-of-sight communication links. The received power at the HAP is given by

$$P_{r(d)} = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \quad 1$$

where  $P_t$  represents the transmit power of the user,  $G_t$  and  $G_r$  are the transmit and receive antenna gains, respectively,  $d$  is the propagation distance between the user and the HAP,  $\lambda$  is the carrier wavelength, and  $L$  denotes the system loss factor. This model captures the distance-dependent path loss characteristics of the uplink channel.

## 2.3 OFDMA-Based HAP Model

Based on the estimated channel conditions, the achievable uplink data rate of user  $k$  on subcarrier  $n$  is expressed as

$$R_{kn} = B \log_2 \left( 1 + \frac{P_{kn} H_{kn}}{N_0} \right) \quad 2$$

where  $B$  is the bandwidth of each subcarrier,  $H_{kn}$  is the channel gain between user  $k$  and the HAP on subcarrier  $n$ ,  $P_{kn}$  is the allocated transmit power, and  $N_0$  denotes the noise power. This expression follows the Shannon capacity formulation and is used to evaluate the performance of different resource allocation strategies.

## 2.4 Particle Swarm Optimization for Subcarrier Allocation

Particle Swarm Optimization (PSO) is employed to determine the optimal subcarrier allocation due to its effectiveness in solving nonlinear and combinatorial optimization problems (Abedi et al., 2022; Demir et al., 2018).

In the proposed framework, each particle represents a candidate subcarrier-to-user assignment matrix. The fitness function is designed to maximize the total system capacity while maintaining balanced resource allocation among users. During the optimization process, particles iteratively update their positions and velocities based on individual and global best solutions.

The particle position updates are given by

$$X_i^{t+1} = X_i^t + V_x^t \quad 3$$

$$Y_i^{t+1} = y_i^t + V_y^t \quad 4$$

while the velocity updates follow

$$V_x^{t+1} = \omega V_x^t + c_1 r_1 (p_{best} - X_i^t) + c_2 r_2 (g_{best} - X_i^t) \quad 5$$

$$V_y^{t+1} = \omega V_y^t + c_1 r_1 (p_{best} - V_y^t) + c_2 r_2 (g_{best} - V_y^t) \quad 6$$

where  $\omega$  is the inertia weight controlling exploration,  $c_1$  and  $c_2$  are acceleration coefficients,  $r_1$  and  $r_2$  are random variables uniformly distributed in  $[0, 1]$ ,  $p_{best}$  and  $g_{best}$  denote the personal and global best solutions, respectively. This mechanism enables adaptive subcarrier assignment based on instantaneous channel conditions.

## 2.5 Water-Filling Power Allocation

After subcarriers have been assigned by the PSO algorithm, transmit power is allocated using the classical water-filling algorithm. (Shu'aibu, 2009), which aims to maximize capacity under a total power constraint. The power allocated to user  $k$  on subcarrier  $n$  is expressed as

$$P_{kn} = \max \left( 0, \mu - \frac{1}{H_{kn}} \right) \quad 7$$

where  $\mu$  denotes the water level, computed as

$$\mu = \frac{P_k + \sum_{n \in S_k} \frac{N_0}{H_{k,n}}}{|S_k|} \tag{8}$$

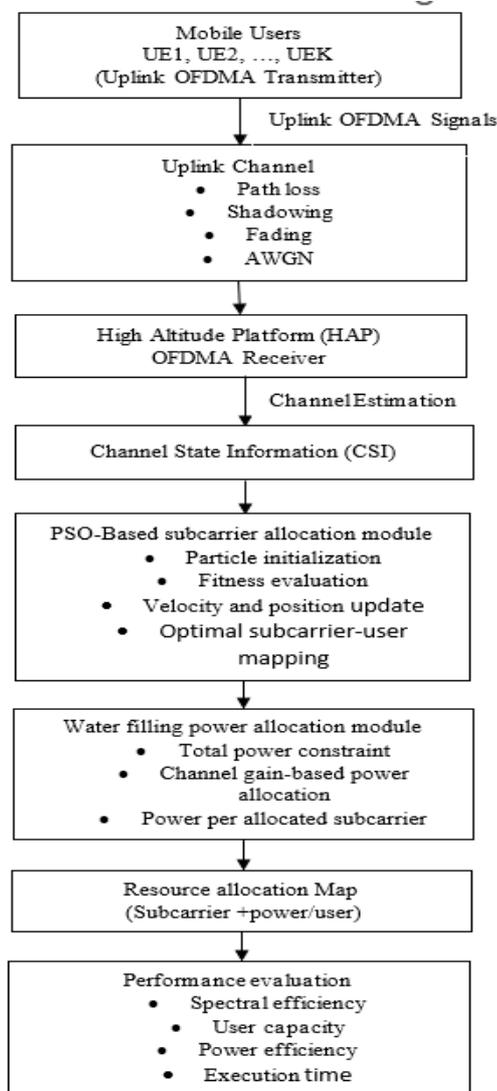
Here,  $S_k$  represents the set of subcarriers allocated to user  $k$ , and  $|S_k|$  is the number of allocated subcarriers. The water level  $\mu$  is selected such that the total allocated power satisfies

$$\sum_{n \in S_k} P_{kn} = P_{total} \tag{9}$$

This allocation strategy assigns more power to subcarriers with stronger channel gains, thereby improving spectral efficiency and overall system performance.

### 2.6 System Architecture

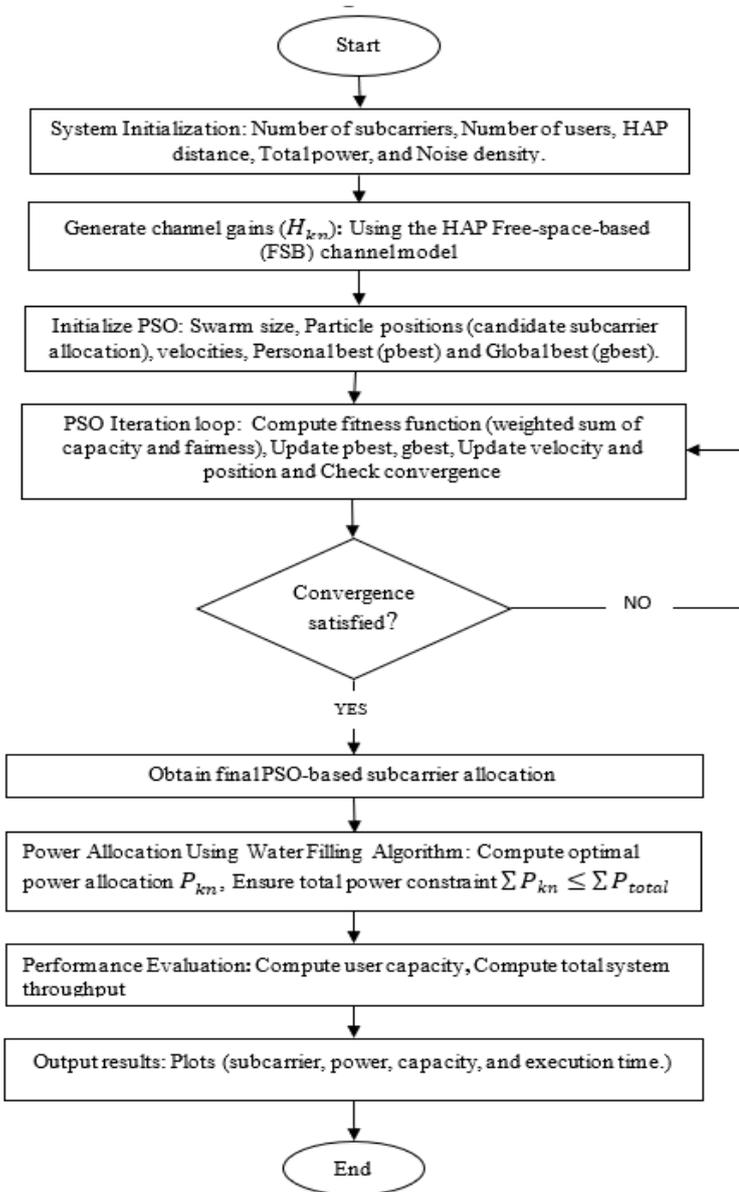
Figure 1 illustrates the system block diagram and architectural design of the proposed PSO-based uplink HAP-OFDMA framework, showing the interaction between users, channel modeling, subcarrier allocation, power allocation, and performance evaluation modules.



**Figure 1:** System architecture of proposed HAP-OFDMA system

### 2.7 Algorithm flowchart

Figure 2 presents the flowchart of the proposed PSO-based subcarrier and power allocation algorithm, detailing the initialization, fitness evaluation, particle update, convergence check, and final resource allocation steps.



**Figure 2:** Flowchart of PSO-based subcarrier and power allocation for HAP-OFDMA systems

**Table I:** Simulation Parameters

S/N	Parameter	Settings
1	Number of HAPs	1
2	HAPs Altitude	20km
3	HAPs coverage	100km×100km
4	Power	10Watts
5	Number of subcarriers	10
6	Number of users	5
7	Frequency	2GHz
8	Bandwidth	20MHz
9	Multi-paths	6 Rayleigh multi-path
10	Number of particles	30
11	Other PSO parameters	$C_1=1.5$ , $C_2=1.5$ , and $W=0.7$

### 3. Results and Discussion

This section presents a comprehensive performance evaluation of the proposed PSO-based resource allocation scheme using multiple metrics, including subcarrier allocation efficiency, spectral efficiency, power efficiency, user capacity, and computational overhead. The proposed approach is systematically compared with conventional schemes, namely Max-SNR, Proportional Fair (PF), and Round Robin (RR), to assess their relative performance under heterogeneous user and channel conditions. The results highlight how the PSO-based scheme adaptively balances resource utilization, robustness, and computational efficiency, making it well-suited for practical and real-time HAP-OFDMA deployments.

### 3.1 Subcarrier Allocation Efficiency

This subsection evaluates the subcarrier allocation efficiency of the proposed PSO-based scheme in comparison with conventional methods, namely Max-SNR, Proportional Fair (PF), and Round Robin (RR). The qualitative allocation trends are illustrated in Fig. 3, while the corresponding numerical values are explicitly summarized in Table 2.

As shown in Table 2, the Max-SNR scheme allocates a larger number of subcarriers to users with favorable channel conditions, particularly Users 4 and 5, reflecting a strong bias toward instantaneous channel quality. While this strategy can maximize short-term throughput for selected users, it leads to imbalanced subcarrier utilization at the system level. The RR scheme distributes subcarriers uniformly across all users, with each user receiving two subcarriers; however, this uniform allocation is achieved by completely ignoring channel variations, which limits allocation efficiency. The PF scheme attempts to balance channel awareness and allocation fairness but still exhibits uneven subcarrier distribution under heterogeneous channel conditions.

In contrast, the proposed PSO-based approach achieves a more robust and controlled subcarrier allocation by jointly considering channel conditions and system-level optimization objectives. As observed in Table 2, PSO avoids excessive allocation to a small subset of users while maintaining effective utilization of the available subcarriers. Rather than pursuing peak allocation gains, the PSO-based scheme provides a balanced and stable allocation strategy, which is more suitable for dynamic and real-time HAP communication environments. This robust allocation behavior establishes a strong foundation for the comparative evaluation of spectral efficiency, power efficiency, and user capacity presented in the subsequent subsections.

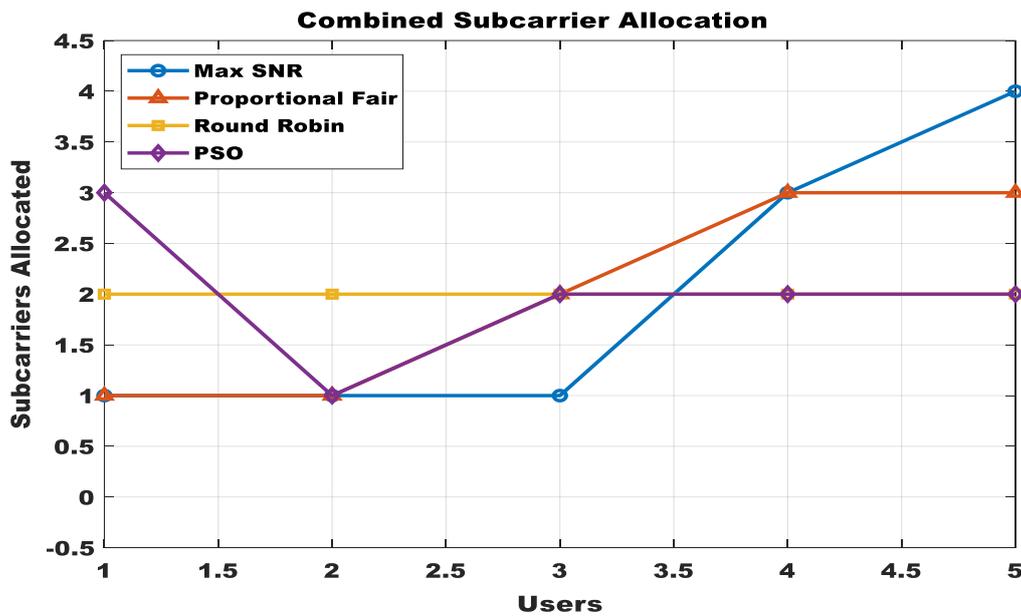


Figure 3: Subcarrier allocation, All methods vs PSO

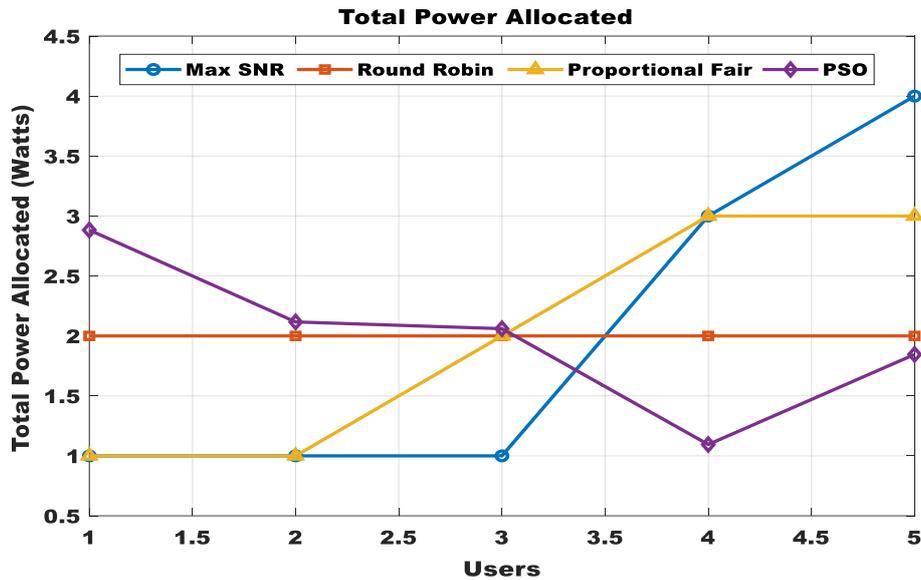
Table 2: Subcarrier Allocation per User for Different Resource Allocation Schemes

User	Max-SNR	Proportional Fair (PF)	Round Robin (RR)	PSO (Proposed)
User 1	1	1	2	3
User 2	1	1	2	1
User 3	1	2	2	2
User 4	3	3	2	2
User 5	4	3	2	2
<b>Total Subcarriers</b>	<b>10</b>	<b>10</b>	<b>10</b>	<b>10</b>

### 3.2 Power Allocation Analysis

This subsection examines the power allocation behavior of the proposed PSO-based scheme combined with the water-filling (WF) algorithm, in comparison with Max-SNR, Proportional Fair (PF), and Round Robin (RR) schemes. The resulting power distribution across users is illustrated in Fig. 4, while the corresponding power efficiency results are summarized in Table 4.

As shown in Figure 4, the water-filling algorithm enables adaptive power allocation by assigning higher power levels to subcarriers with stronger channel gains. Within the proposed framework, PSO first identifies subcarriers with higher utility, thereby allowing the water-filling process to operate on a more favorable and efficiently selected subcarrier set. This coordinated optimization results in a more controlled and effective power distribution compared to conventional schemes.



**Figure 4:** Power allocation, All methods vs PSO

The Max-SNR approach concentrates transmit power on users with strong instantaneous channel conditions, leading to highly uneven power allocation. In contrast, the RR scheme distributes power uniformly across users, completely ignoring channel variations and consequently limiting power utilization efficiency. The PF scheme provides partial adaptation to channel conditions but exhibits reduced flexibility under heterogeneous and time-varying channel scenarios. The proposed PSO-based approach dynamically adjusts power allocation across users, avoiding excessive power concentration while still exploiting favorable channel conditions.

These qualitative observations are quantitatively supported by the results reported in Table 4, where the proposed PSO-based scheme achieves competitive power efficiency relative to conventional methods while maintaining a more balanced and robust power utilization profile. This confirms that the combined PSO and water-filling strategy is well-suited for practical and real-time HAP-OFDMA deployments, where efficient power utilization and algorithmic stability are critical.

### 3.3 Spectral Efficiency Performances

This subsection evaluates the spectral efficiency performance of the proposed PSO-based resource allocation scheme in comparison with Max-SNR, Proportional Fair (PF), and Round Robin (RR) methods. The user capacity trends are illustrated in Fig. 5, while the corresponding numerical values used to compute spectral efficiency are summarized in Table 3.

As shown in Figure 5, the PSO-based scheme achieves a more stable capacity distribution across users by avoiding subcarrier assignments associated with poor channel conditions. The Max-SNR scheme exhibits highly uneven performance, with capacity concentrated on users experiencing favorable channel gains, whereas the RR scheme maintains nearly constant capacity across users due to its channel-agnostic allocation strategy. The PF scheme improves upon RR by incorporating limited channel awareness but still experiences performance degradation under heterogeneous channel conditions.

The proposed PSO-based approach adaptively aligns subcarrier assignment with channel quality, resulting in a more balanced utilization of available spectral resources. When normalized by the system bandwidth, the numerical results reported in Table 4 indicate that the PSO-based scheme achieves competitive spectral efficiency relative to Max-SNR and PF, while outperforming RR. Although greedy schemes may achieve higher peak efficiencies for selected users, the PSO-based approach provides a robust trade-off between spectral

efficiency and allocation stability, making it more suitable for dynamic and real-time HAP-OFDMA deployments.

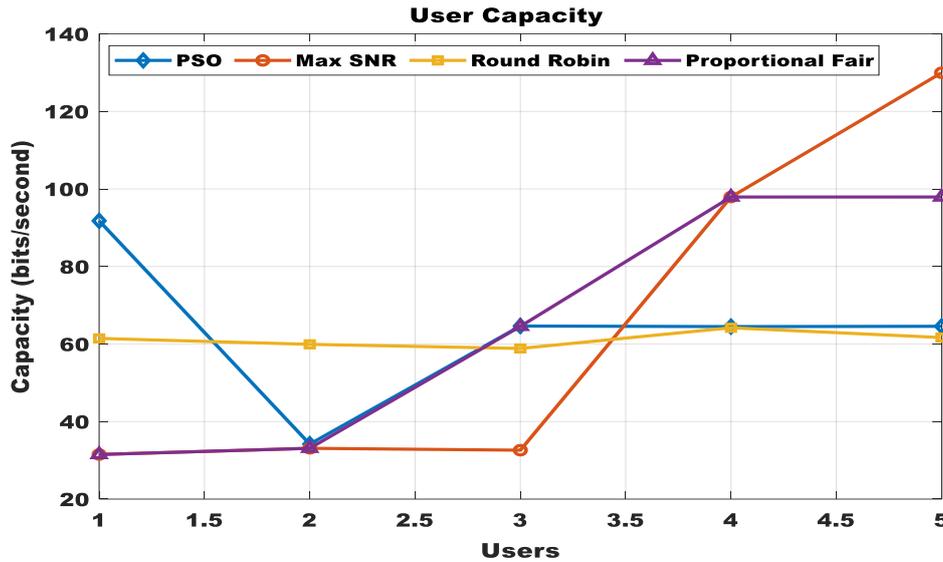


Figure 5: User Capacity Performance Across All Allocation Methods

Table 3: Per-User Capacity (bps) for Different Resource Allocation Schemes

User	PSO	Max-SNR	Round Robin	Proportional Fair
1	92	32	62	32
2	35	34	60	34
3	65	33	59	65
4	65	98	64	98
5	65	130	62	98

Table 4: Capacity, Spectral Efficiency, and Power Efficiency

Method	Avg. Capacity (Mbps)	Bandwidth (MHz)	Spectral Efficiency (bps/Hz)	Total Power (W)	Power Efficiency (Mbps/W)
Max-SNR	65.4	20	3.27	10	6.54
Round Robin (RR)	61.4	20	3.07	10	6.14
Proportional Fair (PF)	65.4	20	3.27	10	6.54
PSO (Proposed)	64.4	20	3.22	10	6.44

### 3.4 Computational Complexity Analysis

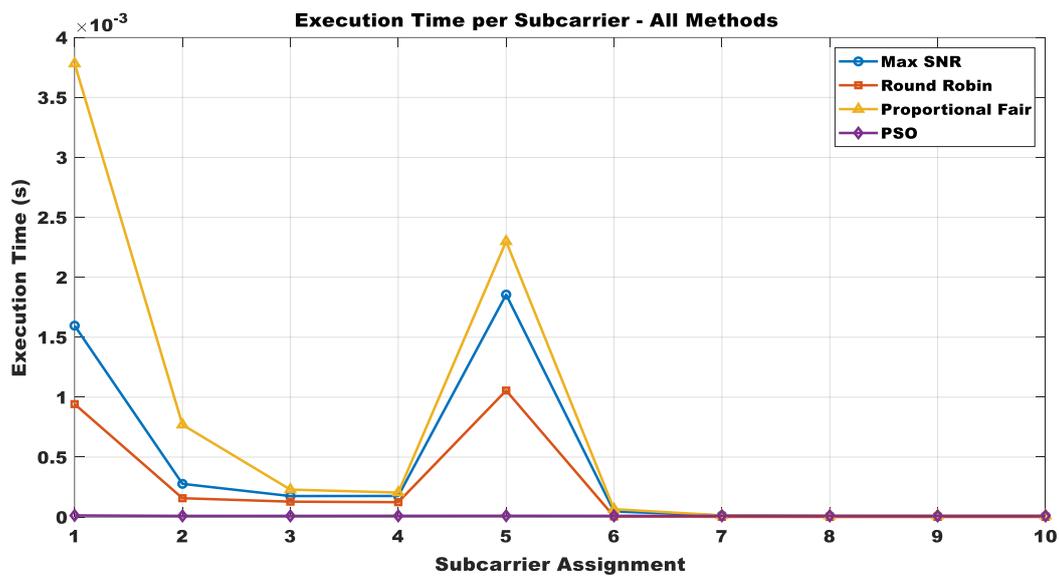
This subsection evaluates the computational complexity of the proposed PSO-based resource allocation scheme in comparison with Max-SNR, Proportional Fair (PF), and Round Robin (RR) methods. The execution time variation with respect to subcarrier assignment is illustrated in Fig. 6, while the corresponding average execution times are summarized in Table 5.

As shown in Fig. 6, the proposed PSO-based scheme consistently achieves significantly lower execution time across all subcarrier assignments. This improvement is primarily attributed to the vectorized implementation and parallelized fitness evaluation adopted in the PSO framework, which substantially reduces computational overhead compared to conventional allocation schemes.

The Max-SNR and PF schemes incur higher execution times due to repeated per-user and per-subcarrier computations, while the RR scheme, although simpler, still exhibits non-negligible processing delay as the number of subcarriers increases. In contrast, the PSO-based approach maintains near-constant execution time, demonstrating superior scalability and robustness with respect to system size.

Quantitatively, the numerical results reported in Table 5 show that the proposed PSO-based scheme reduces execution time by approximately 97.3% compared to Max-SNR, 97.8% compared to Proportional Fair, and

93.6% compared to Round Robin. When averaged across all conventional schemes, this corresponds to an overall execution-time reduction of approximately 97%, confirming the suitability of the proposed approach for real-time HAP-OFDMA communication systems, where rapid and adaptive resource allocation is essential.



**Figure 6:** Execution Time vs Subcarrier Assignment

**Table 5:** Average Execution Time Comparison of Resource Allocation Schemes

Method	Average Execution Time (s)
Max-SNR	0.00042659
Round Robin (RR)	0.00018044
Proportional Fair (PF)	0.00051540
PSO (Proposed)	$1.1522 \times 10^{-5}$

#### 4. Conclusion

This paper presented a PSO-based resource allocation framework for uplink OFDMA-enabled High Altitude Platform (HAP) communication systems, where subcarrier assignment is adaptively optimized using Particle Swarm Optimization and power allocation is performed via the water-filling algorithm. The proposed framework was evaluated against conventional schemes, including Max-SNR, Round Robin, and Proportional Fair, using multiple performance metrics.

Simulation results demonstrate that the proposed PSO-based approach achieves competitive spectral and power efficiency while providing a more balanced and stable resource allocation across users. Most notably, the proposed scheme significantly reduces computational complexity, achieving an average execution-time reduction of approximately 97% compared to conventional methods. This substantial reduction in processing time highlights the practical suitability of the proposed approach for real-time HAP resource management, where fast adaptation to dynamic channel conditions is essential.

Despite these advantages, the current study is limited to a single-HAP, uplink-only system model with simplified channel assumptions. Future work will focus on extending the proposed framework to multi-HAP cooperative scenarios, joint uplink-downlink optimization, and the incorporation of more realistic channel and mobility models. In addition, integrating reinforcement learning-assisted PSO techniques is envisaged to further enhance adaptability, scalability, and robustness in next-generation aerial communication networks.

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