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Performance Evaluation of Heterogeneous Networks with User Association Strategies in mm Wave Communications

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Abstract

This paper evaluates various user association strategies in heterogeneous networks (HetNets) as user density increases from 5 to 50. Through Monte Carlo simulations, seven distinct strategies are analyzed based on key performance metrics: Sum Rate, Energy Efficiency (EE), Spectral Efficiency (SE), and Outage Probability. The research explores multiple association criteria, including Multi-Attribute Decision Making (MADM), maximum Rate, EE, SE, Signal-to-Interference-plus-Noise Ratio (SINR), Signal-to-Noise Ratio (SNR), and minimum distance. Results indicate that different strategies excel in specific performance areas. The Sum Rate and EE strategies consistently outperform others in maximizing network throughput, particularly in high-density scenarios. For Energy Efficiency, the minimum distance and Rate strategies are most effective, with EE close behind. The minimum distance strategy also excels in achieving high Spectral Efficiency. In terms of Outage Probability, the minimum distance approach demonstrates the lowest values, followed by EE, indicating their reliability in maintaining performance as networks scale. This study highlights the critical importance of selecting appropriate association strategies to meet specific network objectives and operating conditions in HetNets.

Keywords: User Association, Heterogeneous Networks, mmWave Communications, Energy Efficiency, Spectral Efficiency, Sum Rate, Outage Probability.

1. Introduction

Wireless communications are rapidly evolving, driving an enormous need for higher data rates, broader coverage, and greater system capacities. Traditional homogeneous network architectures struggle to scale and meet these expanded demands, making Heterogeneous Networks (HetNets) a promising solution for satisfying the demands of the digital age. HetNets are introduced as a design architecture that incorporates various cell structures and technologies under a unified framework . This architecture leverages multi-tier cellular networks, including macro, micro, pico, and femtocells, combined with higher-power macro-cells. The aim is to optimize coverage, capacity, and network performance by exploiting the unique characteristics of different cell types.

HetNets are primarily considered to address the limitations of traditional macro-based cellular networks, which often cannot meet the increasing demands of users and rising density. In areas where macro cell coverage already exists, small cells can supplement the macro network by offloading capacity and expanding the overall footprint. One significant advantage of HetNets is their potential to increase Spectral Efficiency (SE). By allowing the same frequency spectrum to be reused across multiple network tiers, HetNets can significantly boost overall system capacity, especially in densely populated areas. Additionally, placing small cells closer to users enhances signal strength and data rates.

Another critical aspect of HetNet deployments is energy efficiency. Small cells typically consume less power than macro base stations, leading to reduced energy usage on average. This not only benefits the environment but also lowers operating costs for network operators. However, deploying HetNets also presents challenges, such as coordinating handovers, managing interference between network tiers, and optimizing user association strategies.

Interference mitigation is a key research area in 5G standardization and beyond, with researchers and engineers developing innovative algorithms to address these challenges. Approaches range from high-level intra-cell interference management schemes to model-based, machine learning-optimized strategies. As 5G and beyond continue to develop, HetNets will play a crucial role in the telecommunications industry. These networks will serve as the foundation for ultra-dense deployments, supporting applications such as enhanced mobile broadband, massive machine-type communications, and Ultra-Reliable Low-Latency Communications.

In this paper, we evaluate different user association strategies in HetNets as user density increases from 5 to 50. We analyze various association criteria, including Multi-Attribute Decision Making (MADM), maximum Rate, Energy Efficiency (EE), SE, Signal-to-Interference-plus-Noise Ratio (SINR), and Signal-to-Noise Ratio (SNR). We then evaluate performance metrics such as Sum Rate, EE, SE, and Outage Probability. The goal is to identify the best strategies under different network conditions and observe how these strategies scale in congested networks. By examining a wide spectrum of performance criteria, this study aims to provide a comprehensive understanding of the trade-offs involved in designing association strategies.

Ultimately, the objective is to contribute to the development of more efficient 5G and beyond 5G networks by informing the selection of user association strategies that best meet the diverse demands of modern wireless networks.

1. Related work

Recent research has increasingly focused on optimizing user association and resource allocation in HetNets, aiming to enhance performance in terms of Quality of Service (QoS), Spectral Efficiency (SE), and Energy Efficiency (EE). Fu and Wang [7] developed a joint user association and resource allocation algorithm that integrates application-specific objectives within an interactive optimization framework. Similarly, Alhashimi et al. [8] introduced an innovative approach to Two-Tier HetNet matching games, facilitating user association and channel allocation.

Various strategies have been proposed to address the complexities of 5G and 6G networks. Dyavappanavar et al. (2024) [15] presented distributed matching algorithms designed to accommodate high-bandwidth users in 5G HetNets. Nauman et al. (2024) [16] explored NOMA-enabled vehicular-aided HetNets, proposing a three-stage iterative algorithm for resource allocation. Kim et al. (2024) [17] introduced a deep reinforcement learning-based scheme for joint user association and resource allocation, emphasizing max-min fairness in environments with limited information exchange.

Energy efficiency and network architecture have also been key areas of concern. Haghgoy et al. [18] proposed downlink-uplink decoupled user association schemes for wireless-powered full-duplex HetNets, demonstrating significant improvements in energy efficiency. Huang et al. [19] introduced a dynamic hierarchical game model for wireless backhaul-enabled networks, where evolutionary games are played at the user level, and Stackelberg differential games dominate the resource layer.

Further research has aimed to increase overall network capacity. Chinipardaz et al. [20] focused on backhaul-limited HetNets, employing load-balancing and interference management techniques with both centralized and distributed implementations. Sharma et al. [21] proposed a three-phase heuristic strategy for load balancing, energy efficiency, and QoS enhancement in 5G HetNets using Markov chain models. Tolba et al. [22] developed a collaborative user association, service caching, and task offloading strategy for multi-tier communication edge computing HetNets, effectively reducing system delay and hardware complexity.

These studies collectively highlight the ongoing efforts to improve HetNet performance through innovative user association and resource allocation strategies, addressing challenges related to QoS, spectrum efficiency, energy efficiency, and network complexity across various architectures and technologies.

2. Research Methodology

This section outlines the methodology used to evaluate different user association strategies within HetNets as the number of users increases from 5 to 50. The methodology employs Monte Carlo simulations, incorporating various user association concepts and analyzing key performance metrics to thoroughly investigate how HetNets operate under different conditions. The process steps of the proposed methodology are illustrated in Figure 1.

Once the network topology is generated, the simulation calculates several network parameters. These include the distance between User Equipments (UEs) and Base Stations (BSs), path loss (using log-distance models with a propagation exponent, alpha, set to 1.86 for both macro and small cells), and received power levels. The SINR calculation considers interference from all other base stations in the network, providing an accurate representation of radio network performance under varying user distributions and channel conditions.

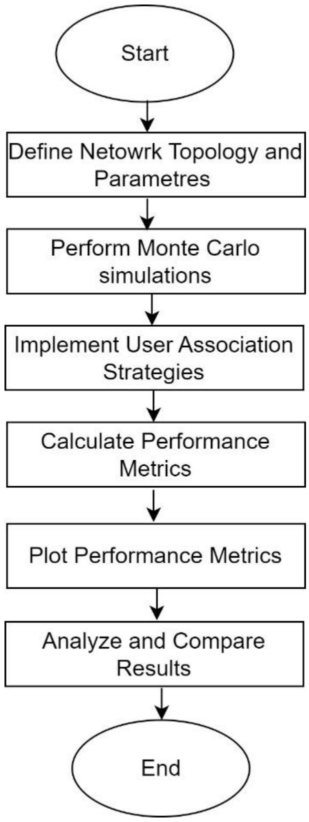

Figure 1: The flowchart illustration of methodology steps

Table 1 presents the parameters used in the simulations, while Figure 2 illustrates a network topology comprising a Macro Base Station (MBS) and eight Small Base Stations (SBSs). Table 2 details the main system parameters for the wireless network simulation, including frequency plans, bandwidth allocation, and transmission power levels for different network elements (MBS, SBS, UE). Additionally, Table 2 includes noise power and circuit power consumption values, essential for analyzing network performance and energy efficiency.

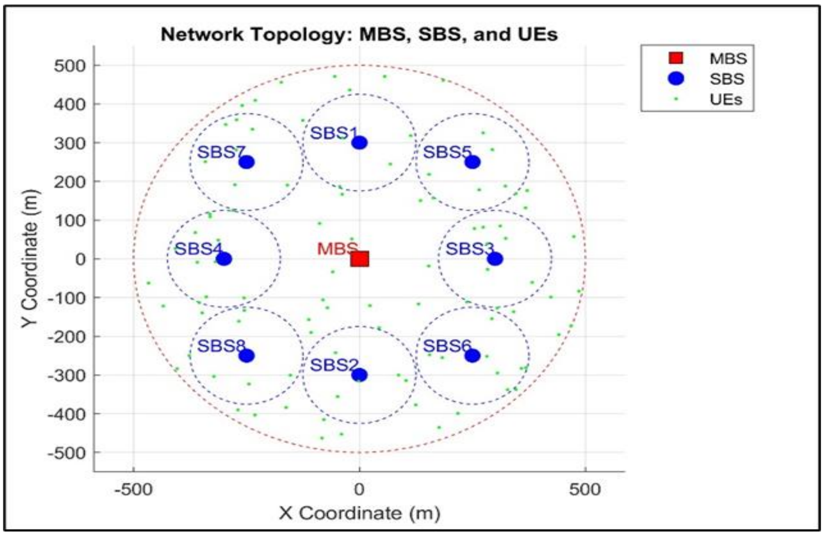

Figure 2 : The proposed network topology

Table 1: Simulation parameters

Parameters	**Values**
Set Simulation Parameters	
Number of MBS (N_MBS)	1, located at (0, 0) with 500m coverage radius
Number of SBS (N_SBS)	8, located at specific coordinates with 125m coverage radius each
User equipment (UE) densities (N_UEs1)	Ranging from 5 to 50 in increments of 2
Channel Parameters	
Center frequency	28 MHz
Subcarrier bandwidth	1 MHz
Total bandwidth	20 MHz
Number of channels	20
Noise power	-175 dBm/Hz
Transmission Powers	
MBS	40 dBm (10 W)
SBS	20 dBm (0.1 W)
UEs	20 dBm (0.1 W)
Circuit Power Consumption	0.1 W

Table 2 : System parameters and their values

System Parameters	**Values**
Center frequency	28 MHz
Subcarrier bandwidth	1 MHz
Total bandwidth	20 MHz
Number of channels	20
Noise power	-175 dBm/Hz
MBS transmission power	40 dBm (10 W)
SBS transmission power	20 dBm (0.1 W)
UE transmission power	20 dBm (0.1 W)
Circuit power consumption	0.1 W

3.1 Monte Carlo Simulation

To account for the randomness in user distributions and channel conditions, we employed a Monte Carlo simulation approach. We conducted 10,000 simulation runs to ensure statistical reliability. In each iteration, the simulation begins by generating a network topology where UEs are randomly deployed within a 200m x 1400m area. This area spans from -500m to +500m relative to MBS.

3.2 User Association Strategies

The MATLAB simulation implements and evaluates seven distinct user association strategies to compare their effectiveness in a heterogeneous network environment. These strategies include:

- MADM (Multi-Attribute Decision Making): Considers multiple network parameters to make association decisions.
- Maximum Sum Rate: Prioritizes the highest achievable data rate.
- Maximum Energy Efficiency (EE): Focuses on optimizing power usage.
- Maximum Spectral Efficiency (SE): Aims to maximize the utilization of the available spectrum.
- Maximum SINR (Signal-to-Interference-plus-Noise Ratio): Prioritizes signal quality while accounting for interference.
- Maximum SNR (Signal-to-Noise Ratio): Prioritizes signal quality without considering interference.
- Minimum Distance: Associates users with the nearest base station.

These strategies are based on a channel-restricted minimum value association algorithm, ensuring that the number of users associated with each base station does not exceed its capacity. This extensive approach allows for a comprehensive comparison of the impact of diverse association criteria on network efficiency under various conditions below various situations.

3.3 Performance Metrics

This research evaluates four critical performance metrics: MADM, Sum Rate, EE, and SE to analyze different user association techniques in heterogeneous networks. These metrics are assessed using specific equations and measured across varying user densities and association schemes, as detailed below:

a. Sum Rate

The sum Rate metric quantifies the aggregate data throughput across all network users for all users:

$$Sum\ Rate\ = \sum (Data\ Rate\ ) \tag{1}$$

$$Data\ Rate\ =\ Subchannel\ .\ log_2(1+SINR\ ) \tag{2}$$

Where SINR (Signal-to-Interference-plus-Noise Ratio) is calculated as:

$$\text{SINR}=\frac{\text{Pr}}{\text{Interference + Noise power}} \tag{3}$$

b. Energy Efficiency

EE measures the power resource utilization effectiveness where :

$$\text{EE}=\frac{\log_2(1+\text{SINR})}{P_{circuit}+P_{tx}} \tag{4}$$

$P_{circuit}$ is the circuit power consumption, and P_{tx} is the transmission power.

This EE metric helps understand which association strategies are most effective regarding data rate per unit of power consumed, a crucial factor for sustainable network operations.

c. Spectral Efficiency

SE indicates the degree of spectrum utilization, where :

$$SE=\frac{\text{Data Rate}}{\text{Subchannel}} \quad (5)$$

This metric is vital for assessing how efficiently each association strategy utilizes the limited spectrum of resources, especially as user density increases.

d. Outage Probability

This represents the likelihood of users failing to achieve the minimum required data rate.

$$Outage\ Probability = \frac{N_{UEs} - \sum(\text{Data Rate} \geq \text{RateThre})}{N_{UEs}} \quad (6)$$

N_{UEs} is the total number of users, and RateThre represents a minimum required data rate threshold. It reveals the reliability and QoS for each association strategy at different network loads in terms of outage probability. The modelled metrics are simulated per user, and 10,000 Monte Carlo iterations are used to ensure the statistical reliability of averages. The effect of both factors is plotted over increments as a function of increasing user densities between 5 and 50 users on semi-logarithmic scales (to aid in visualizing performance trends across large network variations).

2.4 Performance Metric Calculation

The MATLAB simulation calculates key performance metrics to compare each user association strategy. These calculations include:

- Shannon-Hartley Theorem: This theorem provides an upper bound on the information transfer rate in a noisy channel, which is used to calculate data rates. It helps assess how effectively each strategy utilizes power resources, contributing to the calculation of energy efficiency. Additionally, it provides insights into the utilization of the available frequency spectrum.
- Energy Efficiency: EE is derived from the data rates and power usage, offering a perspective on how efficiently each strategy manages energy consumption.
- Spectral Efficiency: SE is calculated to understand how well the strategies maximize the utilization of the available frequency spectrum.
- Outage Probability: This metric represents the probability that the achieved data rate falls below a threshold of 100 kbps, indicating the reliability of the user association strategies.

This comprehensive measurement toolkit allows for evaluating performance from various perspectives, including raw data rates, resource utilization, and reliability, under different user association strategies.

3. Results and Discussion

This section demonstrates performance metrics under several user densities by contrasting seven distinctive strategies while concentrating on the primary four keys (Sum Rate, EE, SE and Outage Probability) to assess their advantages and scalability comprehensively.

4.1 Sum Rate

The Sum Rate trends across different user counts for seven user association strategies are shown in Figure 3. The top performers, Sum Rate and EE, grow much faster than the next in line. MADM has a reasonable performance and gains significantly after about 25 users. Sum Rates for academic SINR, SNR and SE Strategies were lower initially but started to have more power around 20 to 25 users. All strategies generally improve with user count, reflecting increased network capacity, though with varying degrees of Efficiency.

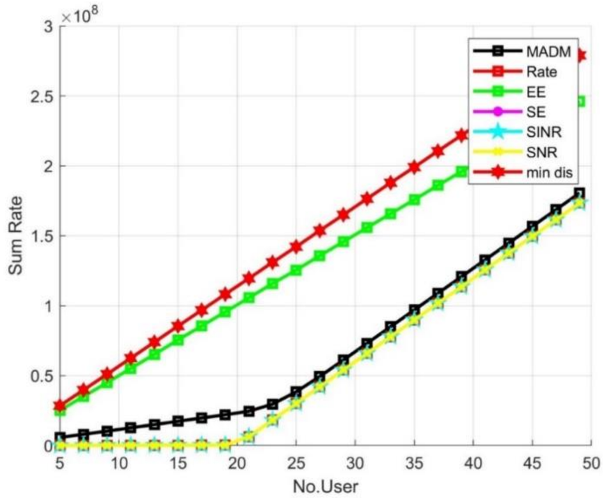

Figure 3: Sum Rate performance comparison for various user allocation strategies

4.2 Energy Efficiency

Figure 4 displays EE trends for seven allocation strategies as users increase from 5 to 50. The min dis and Sum Rate (shortened to be the rate in the figures) strategies consistently show the highest EE, with EE being closely followed. MADM demonstrates moderate performance, improving notably beyond 25 users. SINR, SNR, and SE strategies exhibit lower EE initially but show increased Efficiency around 20 to 25 users. All strategies generally improve with user count, indicating better power utilization as the network scales, though with varying degrees of effectiveness across different user densities.

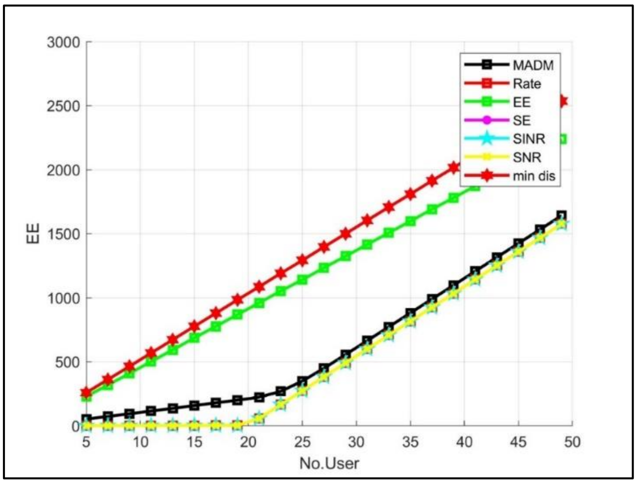

Figure 4: EE comparison for various user allocation strategies

4.3 Spectral Efficiency

Figure 4 illustrates the SE trends for seven user association strategies as the number of users increases from 5 to 50. The min dis strategy consistently demonstrates the highest SE, reaching approximately 280 at 50 users, closely followed by the Rate strategy at about 250. The EE strategy performs well, achieving an EE of around 240 at maximum user density. MADM, SINR, SNR, and SE strategies exhibit lower initial performance, starting at about 25 SE for five users, but show improved Efficiency as user numbers increase, converging to approximately 180 SE for 50 users. All strategies display a linear increase in SE with user count, with the min dis strategy showing the steepest slope, rising from about 30 to 280 across the user range.

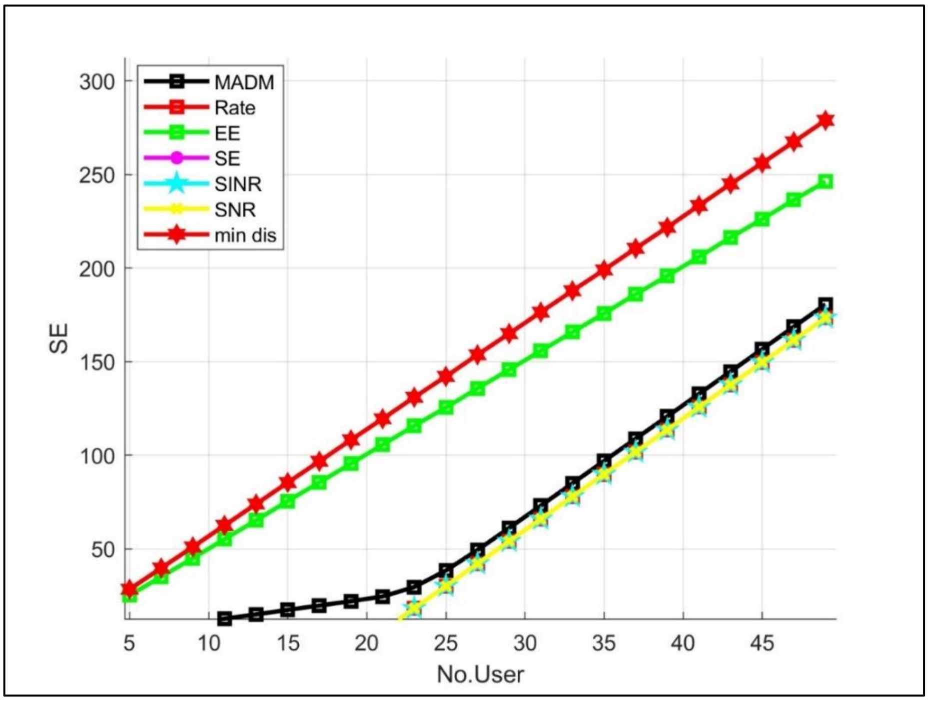

Figure 4: Spectral Efficiency comparison for various user allocation strategies

4.4 Outage Probability:

Figure 5 illustrates the Outage Probability for seven allocation strategies as the number of users increases from 5 to 50. The "min dis" strategy consistently shows the lowest outage probability, followed by "EE". MADM maintains a steady mid-range performance. Notably, Rate, SE, SINR, and SNR strategies start with the highest outage probability, remaining constant until about 20 users, then decreasing significantly as user count increases. This suggests these strategies become more reliable in denser networks while "min dis" and "EE" maintain consistent performance across all user densities.

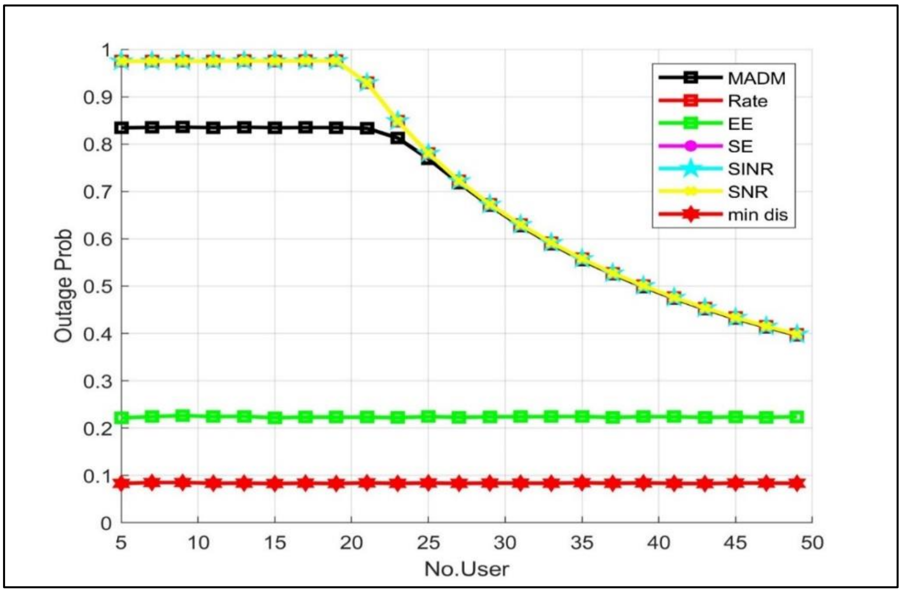

Figure 5: Outage Probability comparison for various user allocation strategies

4. Conclusion and Future Work

This paper evaluated various user association strategies in heterogeneous networks (HetNets) as user density increased from 5 to 50. The results demonstrate that different strategies excel in specific performance metrics. The Sum Rate and Energy Efficiency strategies consistently outperformed others, showing superior network throughput maximization, particularly in denser scenarios. Energy Efficiency was primarily driven by the "Minimum Distance" and "Rate" strategies, closely followed by EE, highlighting their effectiveness in optimizing power usage. For Spectral Efficiency, the "Minimum Distance" strategy exhibited the best performance, achieving approximately 280 at 50 users, with "Rate" following at around 250, demonstrating their capability to effectively utilize the available spectrum. In terms of Outage Probability, the "Minimum Distance" strategy consistently recorded the lowest values, followed by EE, suggesting their reliability in maintaining network performance as user density increases.

The "Minimum Distance" strategy emerged as the best-performing approach across multiple metrics, consistently delivering top or near-top results across all four primary performance metrics. Its efficiency is largely attributed to its ability to reduce interference, efficiently allocate channel resources, and optimally assign subscribers to the nearest base stations. The "Sum Rate" strategy was also highly competitive, particularly in enhancing Sum Rate and EE performance. These findings underscore the importance of carefully selecting user association strategies based on specific network objectives and operating conditions.

For future work, research should focus on developing adaptive strategies that can dynamically adjust their behavior in response to changes in network conditions and user density. Such approaches could potentially combine the strengths of multiple methods, leading to optimized performance across a broader range of metrics.

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