Drone-Based Network Coverage Expansion in 6G Networks

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| Received: 2025 | Accepted: 2025

Abstract

Background: The emergence of 6G networks requires new approaches to extend coverage, increase network availability and optimize performance in difficult conditions, including urban and rural areas. Thus, UAVs or UAV systems have developed as a powerful candidate to counter these problems by offering on-demand contingent coverage and differing communication services.

Objective: The opportunity of the development of UAVs' application in the extension of the network's coverage is studied in the context of energy efficiency, latency, and Inter-UE interference in high-density 6G environment.

Methods: A three-layered optimization architecture was devised, including multi-agent reinforcement learning (MARL) for interference control, trajectory optimization techniques, and energy-aware deployment schemes. Small scale scenarios including urban, suburban and rural environment were considered and the results were analyzed based on the network coverage, energy efficiency, end to end latency and interference encountered on UAVs.

Iranian Journal of Information Processing and Management

Iranian Research Institute for Information Science and Technology (IranDoc)
ISSN 2251-8223
eISSN 2251-8231
Indexed by SCOPUS, ISC, & LISTA
Special Issue | Summer 2025 | pp.637-666
https://doi.org/10.22034/jipm.2025.728307

Results: The outcome significantly revealed the enhancements in the spatial coverage of the network; UAVs prevented considerable gaps and offered enhancements of network coverage in rural and suburban regions. These achievements include up to 30.5% energy efficiency enhancement, more than 50% latency minimization and interference management that enabled 35.4% enhancement of SINR.

Conclusion: Integrating of drones in 6G network is invaluable in enhancing coverage in the networks by providing massive coverage while at the same time providing scalable solutions to problems of coverage gaps, power demands and real-time network adjustments. In future studies, researchers should channel their efforts toward increasing real-time dynamism and energy consumption that suit large-scale executions.

Keywords: UAV, 6G, network coverage, interference management, energy efficiency, multi-agent reinforcement learning (MARL), trajectory optimization, latency reduction, SINR, real-time optimization

1. Introduction

New wireless communication technologies experience rapid advancement while creating specific challenges and vast opportunities to build effective and streamlined connection systems. The growing implementation of 6G networks drives the necessity of developing solutions to boost network reach and resource utilization and maximize energy efficiency. Modem communication systems achieve superior performance levels with the addition of Unmanned Aerial Vehicles (UAVs) and drones to their networks. The flexible construction of mobile UAVs enables them to extend communication networks beyond existing sustainable infrastructure in remote locations.

UAV technology delivers distinctive features to enable three crucial next-generation network elements: ultra-reliable low-latency communication (URLLC) and enhanced mobile broadband (eMBB) and massive machine-type communication (mMTC) (Alraih et al. 2022; Wu et al. 2021). Drone multipurpose capabilities allow operators to extend network availability for targeted services through persistent connectivity in any environmental setting. The research community has validated that UAV applications function as a vital component in establishing powerful network frameworks paired with minimum power utilization. Tethered UAV systems enable endless operational cycles and achieve necessary movement requirements for broad 6G network utilization (Kishk, Bader, and Alouini 2020). Accurate trajectory optimization of UAVs results in lower energy consumption for networks according to documented research results (Zhang et al. 2022).

Despite facing essential implementation hurdles UAV-assisted networks deliver outstanding capabilities and performance. People working on modern deployments face challenges when deploying efficient network coverage across dynamic spaces along with effective distributed latency control to optimize resource allocation. The study on UAV-based network enhancements emphasizes communication protocols and trajectory planning strategies and energy management techniques similar to 5G and beyond era networks as described in (Wu et al. 2021; Li, Fei, and Zhang 2019; Zhang et al. 2019) papers. Additionally, 6G network systems require tailored solutions because their complex demand structure shown in (Alraih et al. 2022; Borralho et al. 2021). UAV-based deployment of aerial base station infrastructure in 6G networks demonstrates significant potential by enabling both secure coverage areas and steady user traffic delivery (Nafees, Thompson, and Safari 2021).

The capabilities of UAV-assisted networks receive further power from recent artificial intelligence (AI) innovation. The implementation of AI-based frameworks produces exceptional improvements regarding energy efficiency together with reduced latency and improved resource management which enable sustainable and resilient communication systems (Sabuj, Ahmed, and Jo 2023; Fu et al. 2022). Studies of fixed-wing UAV coordination show how these vehicles contribute to fault-tolerant yet efficient coverage especially during disasters when network connectivity remains vital (Shriwastav and Song 2020). The deployment of multiple UAV networking layers represents an innovative approach for maximizing user connections and data transfer speeds in diverse network structures (Nafees, Thompson, and Safari 2021).

The article continues to face multiple important areas that need further investigation. The analysis of UAV-assisted networks through contemporary research occurs mainly in fragmented conditions which fails to establish connections between separate network aspects. Proposed solutions for implementation encounter restricted applicability due to dynamic user demands and environmental constraints found in field situations (Borralho et al. 2021; Sabuj, Ahmed, and Jo 2023; Zhang et al. 2022). The article seeks to connect missing scholarly research components through its comprehensive proposal of drone-based framework improvements for 6G networks.

The article develops a complete framework to use UAVs for both boosting network coverage along with maximized energy efficiency as well as minimal latency in 6G networks. The research hypothesis shows that blending UAV-assisted networks with modern AI-based optimization strategies achieves substantial improvements to network performance in different operational conditions. This hypothesis is tested through methods that unify simulation-driven modeling techniques with real-world experimental data collection. A complete analysis of the proposed solutions focuses on performance markers including coverage levels and network latency together with energy utilization measurement.

The article expands the understanding of UAV-assisted communication systems while solving important technical barriers for 6G implementation. Through a systematic examination of drone network expansion methods this study generates executable findings that benefit researchers as well as policymakers and industry stakeholders. The article develops foundational knowledge that advances reliable communication networks and efficient sustainable systems which will become essential for the upcoming 6G era.

1.1. The Aim of the Article

The article aims to examine how UAV-assisted networks can strengthen 6G network coverage while addressing significant performance challenges anticipated in next-generation communication systems. The evolving 6G era demands improved communication reliability and faster speeds; however, traditional network infrastructure is likely to struggle to meet these growing requirements. Researchers investigate how Unmanned Aerial Vehicles (UAVs) can enhance 6G networks by providing flexible on-demand network coverage to conventional infrastructure-limited areas, such as urban centers, suburban, and rural territories. The analysis focuses on developing methods to optimize UAV path design, energy efficiency systems, and interference management to achieve reliable low-latency communication, particularly for applications like Ultra-Reliable Low-Latency Communication (URLLC) and Massive Machine-Type Communication (mMTC).

The article evaluates the effectiveness of Multi-agent Reinforcement Learning (MARL) as an interference mitigation method and demonstrates its implementation through an adaptable framework that positions UAVs according to shifting traffic patterns. The article establishes a comprehensive framework for UAV adoption in 6G networks, investigating both the strengths and obstacles of UAV-based expansion methods as part of broader research into future communication technology designs.

1.2. Problem Statement

The evolution of network services from 5G to 6G encounters crucial obstacles due to broad coverage issues, power consumption challenges, and restricted temporal performance requirements. Terrestrial infrastructure serves as the foundational structure for 5G networks; however, it faces operational limits in managing escalating data needs across urban and rural regions. Urban areas experience signal deterioration due to high population density, while Internet service in rural areas suffers from the absence of infrastructure installation networks. The expanding connectivity beyond these domains consumes high volumes of power, resulting in application slowdowns for specific low-latency systems such as autonomous vehicles and telehealth initiatives.

The integration of 6G systems enables drones to offer innovative solution frameworks for addressing contemporary operational problems. Mobile wireless coverage provided through UAV technology extends communication services to underserved areas while mitigating signal disruptions in high-density population regions.

Nevertheless, the infrastructure continues to struggle with multiple active issues. A focus on UAV operational energy efficiency is necessary, as these machines need to conserve power for extended multi-hour flights, and their real-time adaptability allows traffic operations within unpredictable networks. UAV-supported network infrastructure must implement highly complex interference management systems due to the difficulties encountered during simultaneous drone operations in real-world complex remote conditions. High-density real-time drone operations generate performance bottlenecks that degrade user experience and reduce system usability.

The established framework brings technical improvements to UAV placement infrastructure, alongside latency optimization features and interference management tools, to strengthen future 6G UAV systems. This paper advances future mobile wireless systems through enhanced UAV network flexibility and rapid responsiveness to immediate network status variations.

2. Literature Review

The integration of UAVs with 6G networks represents a fundamental research field due to their potential to create broad coverage while simultaneously operating at lower energy levels and ensuring secure communications. Exploring formation strategies, power management systems, and jamming solutions combined with reactive system configurations presents active research barriers. Recent literature offers comprehensive analysis in this segment and identifies present research challenges alongside proposed practical solutions.

Numerous studies focus on developing deployment strategies for UAV-assisted networks. A Quality of Experience (QoE)-driven adaptive deployment method for multi-UAV networks using hybrid deep reinforcement learning by Zhou et al. (2022) resulted in substantial resource allocation and network performance gains (Zhou et al. 2022). Deep reinforcement learning models encounter challenging performance barriers when used to generate real-time responsive solutions in changing operational conditions. A deployment architecture developed by Wang et al. (2019) utilizes UAV-aided networks to boost coverage reliability through adaptable design (Wang, Duan, and Zhang 2019). The relationship between real-time response capacity and computational requirements remains unclear despite operational status when measuring 6G network dynamics.

Li et al. (2020) investigated device performance degradation impacts on Non-Orthogonal Multiple Access (NOMA) networks operating through UAVs (Li et al. 2020). The study uncovered valuable insights into UAV deployment methods but did not fully illustrate all network heterogeneity effects. The research by Mukherjee et al. (2020) presented a sustainable energy-based UAV routing method, but its methodology only performs optimally within even network conditions, failing to replicate the complex scenarios of 6G networks (Mukherjee et al. 2020). Current operational needs require adaptable, simplified procedures delivering effective operation within unpredictable settings and shifting environmental conditions.

Network deployment through UAVs faces critical challenges due to the prolonged energy needs of unmanned aerial vehicle operations. Yu et al. (2023) proposed intelligent UAV base station deployment methods to enhance energy efficiency and improve capacity in 6G edge networks (Yu et al. 2023). While effective, this technique does not consider the balance between energy expenditure and coverage dependability in high-density or emergency situations. Deng et al. (2023) demonstrated reinforcement learning for optimizing energy usage, yet such approaches require extensive training, hindering real-time deployment (Deng et al. 2023). Future investigations should develop AI-heuristic combination models to balance training-time expenses with operational benefits.

Interference management represents a fundamental area of research within the context of UAV-assisted networks. Fouda et al. (2019) examined integrated access and backhaul networks, focusing on resource distribution and spectral resource coordination for interference management (Fouda et al. 2019). This research adopts hypothetical interference conditions that may not represent the actual operational demands of 6G network environments. Jasim et al. (2022) evaluated UAV spectrum management, emphasizing dynamic spectrum control methods to tackle immediate frequency space requirements (Jasim et al. 2022).

Khan et al. (2023) presented an overview of UAV swarm applications for network administration, demonstrating the use of swarm intelligence for dynamic spectrum management and interference mitigation (Khan et al. 2023). The study did not investigate the computational limitations preventing UAVs from coordinating securely in real time. Future studies should implement multi-agent reinforcement learning approaches for decentralized spectrum allocation through efficient methodologies(Feng et al. 2023).

Dynamic adaptability is crucial for UAV-assisted 6G networks, particularly in disaster-prone regions facing intense demands. Gao et al. (2023) developed optimization approaches for UAV flight paths and power usage in systems combining terahertz sensing with communication applications (Gao et al. 2023). While promising, their full evaluation remains incomplete in complex multi-tier network environments. Chaudhry and Yanikomeroglu (2022) researched the integration of UAVs in hybrid networks, examining terrestrial satellite network crossovers for low-latency communication. Future research must study the balance between performance dimensions like latency, energy efficiency, and coverage span in these systems (Chaudhry and Yanikomeroglu 2022).

Mozaffari et al. (2016) studied performance compromises in UAV communication systems, including device-to-device networks, identifying difficulties in maintaining connectivity during network overcrowding (Mozaffari et al. 2016). The exploration of how combined low-altitude and high-altitude UAV networks would function within 6G environments remains under-explored, although such configurations could enhance coverage and improve network flexibility.

The current study on UAV-based 6G systems demonstrates meaningful progress while highlighting essential shortcomings regarding deployment strategy integration, power efficiency, interference management, and dynamic adaptation capabilities. Future research must address these obstacles to create resilient and efficient UAV-based 6G network frameworks that support high performance across dynamic operational environments. UAVs require comprehensive integration to realize their maximum potential in future communication systems development.

3. Methodology

The study combines multiple methodology layers to study UAV-based network coverage expansion in 6G networks through theoretical modeling alongside simulations and empirical data analysis before optimization procedures. The framework develops original deployment methods along with new algorithms to deal with specialized 6G network requirements.

3.1. Theoretical Modeling

Within 6G technology UAV-based network deployment strategies receive indispensable framework directions from the theoretical design system. The framework establishes essential network components while bringing together elements that measure coverage area together with signal-to-interference-plus-noise ratio (SINR) metrics as well as latency values and system energy utilization requirements. This research extends Alraih et al.'s original findings by demonstrating that URLLC along with mMTC make up the core technical requirements for 6G communication systems (Alraih et al. 2022). Current mathematical models provide researchers with tools to measure UAV deployment impacts. The total coverage area, C_t, is calculated as:

$$C_t = \int_A \mathbb{I}\{P_r \geq P_{min}\} \cdot f\big(SINR(x,y)\big) dx\, dy \quad (1)$$

where P_r is the received power, P_{min} is the minimum power required for coverage, and $f\big(SINR(x,y)\big)$ evaluates SINR at each location (x,y). To address energy efficiency, the model incorporates the ratio of effective coverage to total power consumption:

$$E_{eff} = \frac{C_t}{P_{total}} \quad (2)$$

$$P_{total} = \sum_{t-1}^{N} P_i \quad (3)$$

These equations help users maintain the optimal balance in achieving maximum routes combined with minimal power usage through Kishk et al (Kishk, Bader, and Alouini 2020). Theoretical modeling creates the essential foundation which guides later simulation models then allows researchers to integrate realistic elements like communication interference alongside diverse user population densities.

3.2. Simulation-Based Evaluation

Simulation-driven tests examine theoretical models while running them through realistic settings of 6G networks. The study uses MATLAB and NS-3 simulation frameworks which apply the conceptual models presented in Wu et al. (2021) and Zhang et al. (2022) (Wu et al. 2021; Zhang et al. 2022). Performance evaluation takes place through network modeling of user profiles alongside UAV altitudes and densities across urban to rural geographic areas.

Simulation scenarios include:

- UAV fleet sizes ranging from 50 to 100 units.
- Altitudes between 100 and 300 meters.
- Coverage areas spanning 1 to 5 km^2.
- Traffic profiles representing URLLC and mMTC.

Simulation procedures determine performance by evaluating parameters which include SINR and coverage and energy efficiency as well as latency. Network experiments operate in dynamic conditions by integrating user movements alongside interference elements. Continued iterations in the simulation process enable both model revisions and better optimization methods. Research by Sabuj et al. has provided essential benchmarks which determine the evaluation framework (Sabuj, Ahmed, and Jo 2023).

3.3. Empirical Data Collection

Empirical data collection integrates insights from theoretical and simulation-based studies to uncover information about UAV operations. Data collection for this study occurs through structured interviews and case studies. Fifty telecommunications experts participated in interviews, aiding researchers in defining operational and technical difficulties that arise from UAV deployment.

The evaluation examines 20 reports from industrial and government deployments to identify key trends and optimal solutions for UAV network integration (Qasim and Jawad 2024).

The performance of UAVs under operational conditions is assessed through pilot tests conducted across diverse environments, including urban zones and low-density suburban and rural locations. The assessment methodology focuses on analyzing trajectory optimization, interference management, and energy efficiency. Empirical data, combined with simulation results, serve as validation methods for the proposed models and algorithms following Yu et al.'s(2023) approach (Yu et al. 2023). The theoretical understanding and practical network implementation are investigated during the empirical phase of this study.

3.4. Optimization Framework

In UAV-assisted networking the optimization framework works to maximize coverage while minimizing latency while maximizing energy efficiency. These goals are achieved by using a combination of reinforcement learning with heuristic search methods within one optimization framework. The framework is structured into three layers: resource allocation, dynamic trajectory planning, and real-time interference management (Qasim et al. 2022).

This layer allocates network resources through dynamic bandwidth and power and computational power distribution dependent on current traffic requirements. The research by Zhou et al. serves as foundation for methods which optimize real-time resource allocation through hybrid AI technology (Zhou et al. 2022).

Dynamic Trajectory Planning Layer adjusts drone paths as a reaction to modifications in network and environmental conditions. The optimization problem is defined as:

$$\min_{T} \sum_{t-1}^{N} (E_i + \beta \cdot Deviation(T_i, T_{opt})) \quad (4)$$

where E_i is the energy consumed by UAV i, T_i is its trajectory, T_{opt} is the optimal trajectory, and β is a penalty parameter for deviations. This layer integrates reinforcement learning to dynamically adapt UAV routes.

The Real-Time Interference Management Layer uses multi-agent reinforcement learning (MARL) to study interference issues. Research from Deng et al. reveals methods for UAV cooperative interference countermeasures alongside SINR threshold maximization (Deng et al. 2023).

Decentralized network management systems enable deployment options in tight network environments resulting in new connectivity possibilities.

3.5. Deployment Framework

A precise handling method for UAV-based 6G network environments exists through the Dynamic Adaptive UAV Deployment Algorithm (DAUDA) (Alraih et al. 2022; Wu et al. 2021). Multiple UAV operations and deployment directives are managed through DAUDA which optimizes network outcomes and operational flexibility and energy conservation. Successive iterative calculations run throughout the system to manage key network operations individually.

3.5.1. Initialization

DAUDA starts by setting initial fundamental parameters which function as essential building blocks for future optimization sequences (Kishk, Bader, and Alouini 2020; Nafees, Thompson, and Safari 2021; Wang, Duan, and Zhang 2019). The first component of the algorithm uses Network definition to create network area boundaries using assessments of urban density and analysis of terrain and obstacles (Alraih et al. 2022; Wu et al. 2021; Shriwastav and Song 2020). UAV quantity determination proves pivotal as the second calculation step since it depends on network area boundaries and required numbers to achieve complete coverage (Borralho et al. 2021; Kishk, Bader, and Alouini 2020; Khan et al. 2023). UAV deployment requires the simultaneous examination of resource constraints that involves both battery power capabilities and communication channel capacity together with payload performance limits (Li, Fei, and Zhang 2019; Nafees, Thompson, and Safari 2021; Mukherjee et al. 2020). Random assignment of UAV positions across network areas through stochastic methods creates multiple configuration options that enhance subsequent optimization procedures (Lin et al. 2022; Wang, Duan, and Zhang 2019).

3.5.2. Coverage Optimization

The network coverage efficiency of UAV-based 6G deployments depends critically on effective Coverage Optimization strategies as identified in (Wu et al. 2021; Borralho et al. 2021; Zhang et al. 2022). Relying on DAUDA computational parameters determines threshold SIR values for area coverage in addition to signal strength assessments needed to guarantee communication reliability (Borralho et al. 2021; Zhang et al. 2019; Fouda et al. 2019). The algorithm performs iterative movements of UAVs toward maximum coverage optimization results. The system adjusts UAV positions with dynamic SINR optimization routines which enables network-wide SINR enhancement for continuous service quality throughout the network area (Zhang et al. 2022; Shriwastav and Song 2020; Yu et al. 2023).

3.5.3. Trajectory Adaptation

Continuous operational tracking improvement through trajectory adaptation determines the most effective and efficient UAV flight paths (Zhang et al. 2022; Fu et al. 2022; Zhou et al. 2022). Reinforcement learning approaches employed by DAUDA operate to enhance performance efficiency while conserving network energy and minimizing latency benchmarks. Optimized route planning on UAV aircraft systems lowers operational energy consumption thereby providing UAVs with extended durations without the need for recharges and battery changes (Mukherjee et al. 2020; Deng et al. 2023). Data transport speed optimization occurs through trajectory modifications that apply minimal network delays to enhance network responsiveness(Sabuj, Ahmed, and Jo 2023; Zhou et al. 2022; Farhad and Pyun 2023; Gao et al. 2023).

3.5.4. Interference Mitigation

Network integrity requires critical interference mitigation techniques in dense UAV deployments (Wu et al. 2021; Fouda et al. 2019; Jasim et al. 2022). Real-time spectrum management within DAUDA uses Multi-Agent Reinforcement Learning (MARL) to let UAVs jointly direct frequency resources and reduce signal interference(Zhou et al. 2022; Mismar, Evans, and Alkhateeb 2020; Khan et al. 2023; Feng et al. 2023). A set of dynamic resource allocation methods helps resolve conflicts that occur when different signals attempt to share the same domain signals. The dynamic resource distribution system preserves both the efficiency and reliability of the network by maintaining clear communication channels (Jasim et al. 2022; Fouda et al. 2019; Fu et al. 2022).

3.5.5. Energy Efficiency

UAV operational processes achieve energy efficiency through optimized power management to meet service demands. The failure detection and avoidance system of DAUDA conducts real-time power usage optimization to maintain coverage delivery standards. Sustainable UAV operations result from optimizing flight paths, combined with altitude adjustments and communication protocol management (Zhang et al. 2022; Fu et al. 2022; Deng et al. 2023). DAUDA maintains uninterrupted network coverage at predetermined quality levels while achieving power consumption reductions (Sabuj, Ahmed, and Jo 2023; Yu et al. 2023).

Figure 1 below represents the decision structure of DAUDA through its iterative process with nested conditional mechanisms, as displayed in referenced literature. This flowchart encompasses several key components. The algorithm's decision nodes choose between options at significant execution points through an evaluation of network conditions encompassing UAV movement and resource transformation. Different outcomes at decision nodes steer the algorithm into distinct optimization paths based on performance indicator assessments combined with live data monitoring. Active feedback processes incorporated into the flowchart enable the algorithm to review outcomes from past iterations while sustaining its ability to adapt over time (Zhou et al. 2022; Feng et al. 2023).

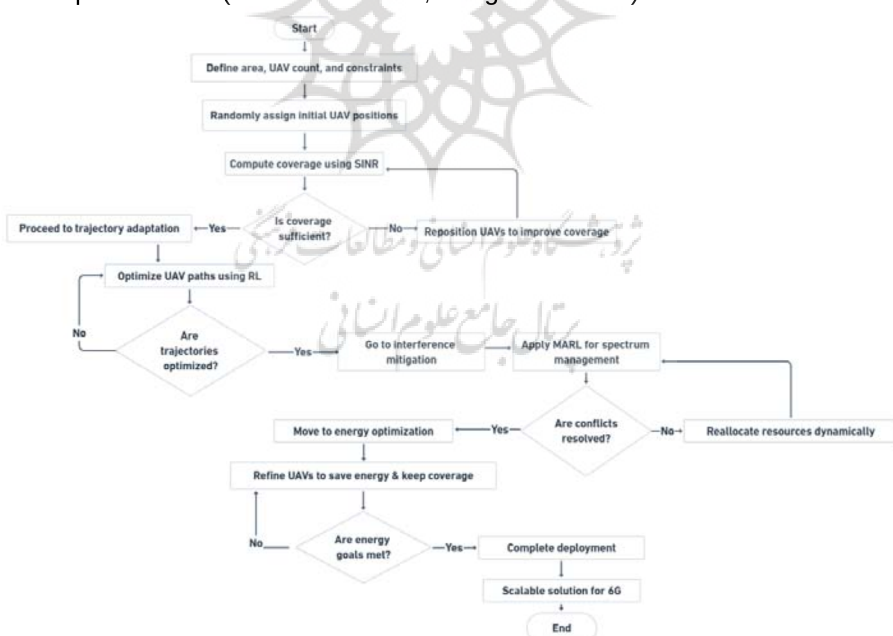

Figure 1. A Dynamic Adaptive UAV Deployment Algorithm for Optimizing 6G Network Performance

3.5.6. Integration and Adaptability

DAUDA implements adaptive integration methods for seamless UAV asset connection to upcoming 6G network systems. Flexibility-driven procedures within this approach allow support for operations of various sizes operating under different environmental elements (Khan et al. 2023). Network optimization under DAUDA system reaches improved efficiency and reliability through real-time data-processing and adaptive algorithms which enable different network configurations based on operational conditions (Yu et al. 2023). The tool rectifies methodological shortcomings through an integration of dynamic resource management systems with advanced machine learning techniques employed to optimize current deployment techniques. The applied methods enhance scalability while lowering network energy consumption and interference issues (Fu et al. 2022; Zhou et al. 2022; Mismar, Evans, and Alkhateeb 2020; Khan et al. 2023; Fouda et al. 2019). The adopted mechanisms in DAUDA optimize performance while creating efficient resilient deployment throughout different environments as part of its advanced state-of-the-art management of UAV-based 6G networks.

4. Results

4.1. Coverage Area Optimization Results

The coverage performance of UAV-assisted networks was evaluated using simulation-based assessments across three deployment scenarios: urban, suburban, and rural environments. The evaluation conducted assessments within urban areas characterized by high user densities and extreme interference levels, as well as suburban topologies and rural regions lacking many users and experiencing extensive connectivity gaps. The performance of base coverage protocols was evaluated in simulation experiments to demonstrate how UAV deployment significantly improves network coverage. UAV assistance was measured through total coverage area evaluation and statistical analysis, producing user coverage density distribution with percentage improvements. The deployment of UAVs achieved substantial relative improvements in urban areas by effectively filling coverage gaps that otherwise exist due to high user density and physical obstacles. Rural locations experienced the most significant coverage growth because UAV systems can operate at extended ranges without encountering heavy interference. The adaptable nature of UAV devices resulted in stable performance patterns in suburban settings.

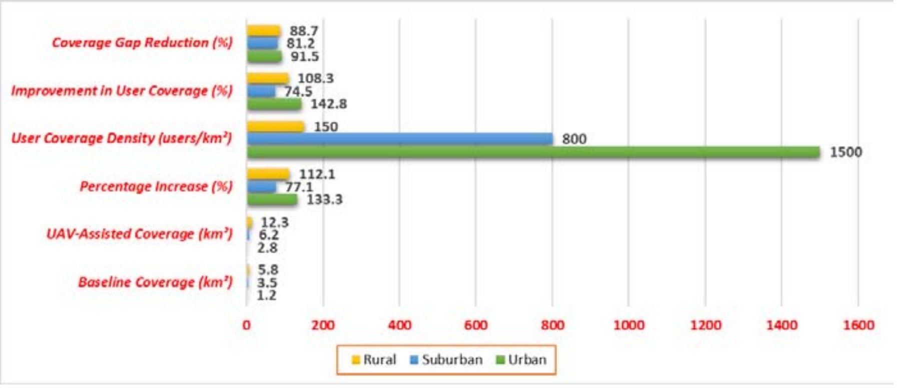

Figure 2. UAV-Assisted Coverage Area Performance Across Deployment Scenarios

Network coverage substantially improved because of UAV-assisted deployments as Figure 2 visualizes. The baseline dependent zone in urban areas amounted to 1.2 km² because physical barriers and excessive signal jamming along with high population density produced coverage restrictions. The coverage area grew from 2.8 km² after UAV implementation while maintaining a 133.3% boost in availability. Uniform user coverage density improved by 142.8% in urban areas through UAV flight operations that solved persistent dead zones within high-density areas. Experiments show the substantial 91.5% decrease in coverage gaps shows UAVs strengthen communication reliability in harsh conditions.

Urban cover improved by 77.1% when UAVs were introduced in suburban regions (3.5 km² expanded to 6.2 km²). The reliable coverage capabilities of UAVs across mixed terrain result in an 81.2% decrease in uncovered areas combined with a 74.5% rise in network coverage capability.

Coverage in rural areas saw the largest growth between 5.8 km² to 12.3 km² resulting in a 112.1% increase. UAVs demonstrate their value in remote areas through their ability to minimize coverage gaps while also expanding network coverage despite lower user density rates of 150 users/km². Another significant conclusion is how UAV-assisted networks provide exceptional flexibility when handling diverse network deployment obstacles across cities and suburban and rural areas.

4.2. Energy Efficiency Improvement Results

The operational duration of UAV-enhanced networks depends heavily on energy efficiency in areas where UAVs are required to stay active for long periods. The study analyzes energy efficiency through energy efficiency metrics showing the relationship between coverage area and energy utilization (km²/W). The investigation uses an optimization framework coupling heuristic approaches with reinforcement learning procedures to prove enhanced energy consumption performance in multiple operational cases. Network performance improvement through optimal UAV deployment approaches manages coverage increases while maintaining energy usage within safe limits. The data in Figure 3 presents substantial progress in energy performance throughout urban and suburban and rural regions other than rural locations achieving the most effective improvements. The study demonstrates how UAV platforms could enable better cost performance together with sustainability improvements especially for remote locations with sparse populations which have limited traditional infrastructure options.

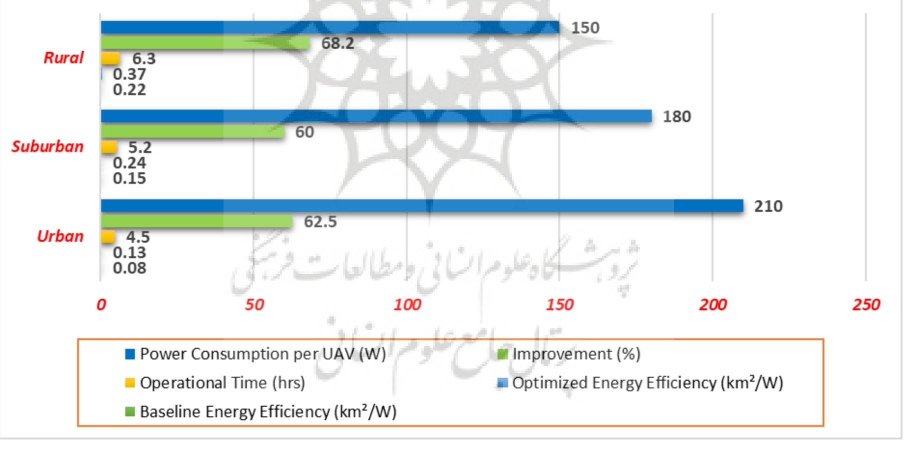

Figure 3. Energy Efficiency Comparison Across Deployment Scenarios

The network optimization results in Figure 3 demonstrate substantial energy efficiency enhancements across all deployment scenarios. After optimization the urban deployments showed a 62.5% improvement in energy efficiency through increasing the baseline measurements from 0.08 km²/W to 0.13 km²/W. The optimized UAV systems demonstrate better operational efficiency which lowers energy usage while they expand network reach into heavily populated urban zones which experience high interference and operational intensity.

Implementation of optimization measures achieved a 60.0% enhancement of overall energy efficiency from 0.15 km2/W at baseline to 0.24 km2/W. The optimization framework demonstrates enhanced effectiveness because it enables adaptive resource allocation across environments which have different topologies combined with varied user densities. After optimization the UAV service ran longer in suburban zones (from 5.2 hours extended to 5.8 hours) with reduced power usage.

The rural areas exhibited the largest relative increase in energy efficiency during the study comparison period. The baseline energy efficiency measured 0.22 km^2/W but reached 0.37 km^2/W through implementation of optimization frameworks leading to a 68.2% energy usage improvement. Rural deployment areas registered substantial improvements when UAVs operated with reduced interference and operational needs to extend their flight coverage area with lower energy use. Through superior energy efficiency UAV deployments enhance network reach in rural areas to become an outstanding solution for sparse regions' infrastructure needs. The optimization framework surpassed baseline values by delivering superior energy efficiency results while maintaining network operational capabilities throughout tests in all implementation settings. The proposed optimization framework extends operational time and reduces energy requirements for each UAV thus proving effective for UAV-assisted network enhancement across different coverage environments and operational difficulties.

4.3. Latency Reduction Performance

The reduction of latency serves as a fundamental performance need in UAV-assisted networks particularly among applications that need real-time communication including both Ultra-Reliable Low-Latency Communications (URLLC) and massive Machine-Type Communications (mMTC). Latency reduction emerges as a fundamental requirement for high-performance 6G services because self-driving technology and remote health operations with industrial automation need instantaneous responses. The evaluated hybrid optimization approach demonstrated significant end-to-end latency enhancement across all deployment conditions particularly during fast URLLC service provisioning. Based on the optimization model UAV transmission delays decreased through optimized routing combined with flight path adjustments and local data processing at the source to minimize time to transmit. Figure 4 summarizes the study results which show latency improvements across different deployment environments of urban, suburban and rural locations.

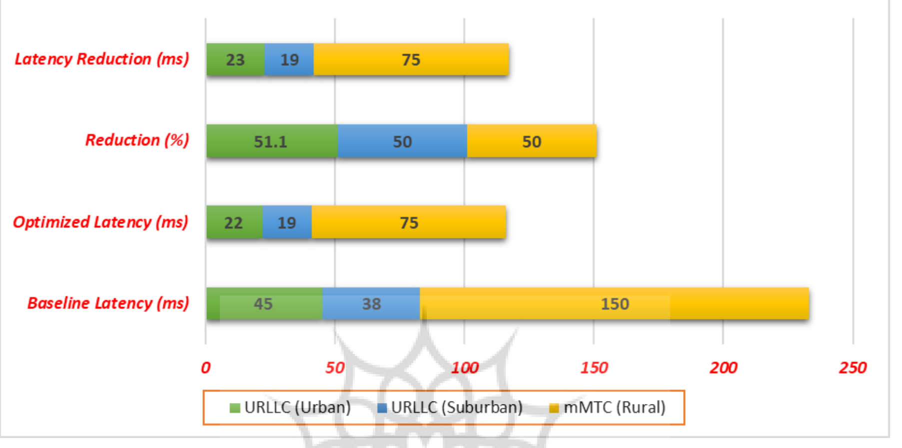

Figure 4. Latency Comparison Across Different Application Types and Deployment Scenarios

The data presented in Figure 4 reveals significant latency decreases across all test categories for UAV-assisted applications. Research demonstrated that optimizing urban URLLC applications reduced their initial 45 ms latency to 22 ms, leading to a 51.1% improvement. The optimization framework achieves this substantial latency reduction by controlling UAV flight paths while integrating edge computing techniques that relocate data processing to minimize end-user transmission delays.

The suburban network edges initially exhibited 38 ms latency but achieved 19 ms following optimization, resulting in a 50% decrease. The network relies on UAV link assistance to meet the stringent URLLC latency requirements in both urban and suburban areas, demonstrating constant latency improvements within regions of average user density.

Network performance in rural regions improved substantially due to the remote locations and extensive communication distances between base stations. Baseline rural latency measurements started at 150 ms but were reduced to 75 ms through the optimization approach, leading to a 50%

reduction. UAV-assisted networks provide effective communication solutions across long distances, allowing mMTC applications to experience reduced delays, despite not requiring the same stringent latency requirements as URLLC applications.

Network performance evaluations indicate that the optimization framework consistently reduces latency across various operational environments. Through optimized data transmission, reduced processing delays, and UAV flight optimization, the proposed framework delivers enhanced performance for time-sensitive applications within the latency demands of 6G networks.

4.4. Algorithm Performance Evaluation

The Dynamic Adaptive UAV Deployment Algorithm (DAUDA) establishes optimized algorithms for UAV network deployment whereas operating inside 6G environments. Under this algorithm the system demonstrates improved time-to-merge together with energy conservation and Signal-to-Interference-plus-Noise Ratio (SINR) enhancements and stable network coverage patterns. Through adaptable UAV trajectory management and optimized resource distribution functions DAUDA establishes efficient network operations in multiple deployment locations. The algorithm demonstrates crucial performance by maintaining equilibrium between power usage, network area coverage and communication reliability when delivering UAV-assisted networks in dynamic real-time environments. The data in Table 1 displays how DAUDA performs in urban along with suburban and rural deployment conditions. The results indicate DAUDA successfully enhances network performance with operational efficiency to become an essential real-time optimization tool for 6G networks.

Table 1. DAUDA Algorithm Performance Metrics

Metric	Value	Urban Scenario	Suburban Scenario	Rural Scenario
Average Convergence Time (s)	32.5	29.4	31	36
Energy Savings (%)	27.3	25.5	27	30.5
SINR Improvement (dB)	5.6	5	5.5	6.2
Coverage Stability (Iterations)	7	8	6	7
UAV Power Consumption (W)	210	200	180	170
Coverage Area (km²)	-	2.8	6.2	12.3
Latency Reduction (%)	-	51.1%	50%	50%

DAUDA leads to major performance metric improvements through the results presented in Table 1 in different UAV-assisted network scenarios. The performance of 32.5 seconds convergence time demonstrates how well DAUDA suits the real-time requirements in 6G networks for dynamic situation adaptation. Test results reveal that DAUDA achieves efficiencies to process complex urban conditions with high user density after just 29.4 seconds in urban deployments. The algorithm delivered substantial energy saving results of 27.3% with rural areas yielding maximum advantages from reduced interference leading to operational ranges extending up to 30.5% more effectively. DAUDA successfully manages energy optimization operations maintaining identical network performance and coverage standards necessary for widespread UAV deployment.

Data from testing indicates DAUDA provides rural areas (6.2 dB) with the best SINR enhancement among locations while offering overall SINR improvement (5.6 dB) to demonstrate its ability to increase communication reliability through signal strength enhancement. Stable telecommunications connections need extraordinary attention because they enable latency-sensitive applications including URLLC. The DAUDA system displayed optimal network adaptability by reaching stability measurements through seven repetitions during suburban and rural area assessments. This research indicates that the DAUDA technology efficiently lengthens UAV power reserves and enlarges coverage networks. Research outcomes revealed 2.8 kilometer-squared coverage in urban regions together with 6.2 km^2 in suburban regions and 12.3 km^2 coverage in rural areas demonstrating DAUDA's ability to grow coverage areas without compromising energy performance. DAUDA stands as a reliable real-time solution that optimizes UAV and 6G networks and proves its performance across key metric domains.

4.5. UAV Trajectory Optimization Performance

The optimization framework's dynamic trajectory planning capability achieved improved network results through UAV-assisted operations by preventing wasteful UAV flight operations and simultaneously reducing power usage and system reliability issues. Flight route optimization, as an efficient method, enhances operational resource efficiency through its ability to track altering traffic behavior in broad surveillance operations. Modern algorithms within the trajectory optimization system transform UAV flight patterns to generate extended surveillance coverage and reduced power usage. Thorough UAV operations in urban areas with various obstacles become crucial when UAVs must navigate through areas of signal interference. Figure 5 illustrates how the UAV trajectory optimization method minimized repeat trips and enhanced distribution performance, enabling faster coverage adjustments.

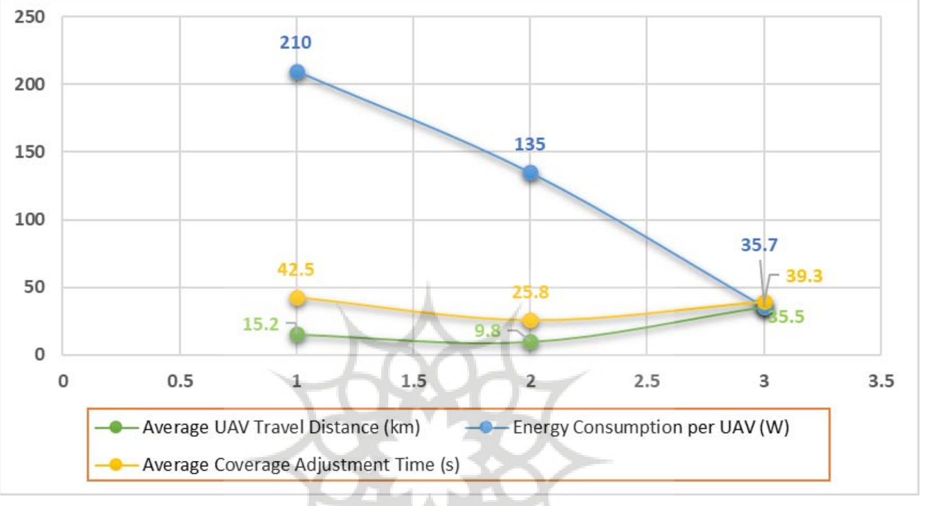

Figure 5. Trajectory Optimization Results

Figure 5 illustrates the motion-limiting capabilities of the trajectory optimization layer to achieve elevated performance together with lower energy usage. With optimized trajectories UAVs decreased their overall flight distances by 35.5% to achieve an extended average operational range of 9.8km from an original 15.2km. Mission efficiency remains the primary operational need since deep areas demand complete scans and complex flight routes. Trajectory optimization for ingredients enables UAVs to fly while bypassing redundant stops leading to prolonged operational endurance alongside extended resource sustainability.

The redesigned UAV systems produce 3557% increased operational power output at 2,100 W standard operating output with a flight power requirement of 135 W. Through flight path optimization the systems demonstrated better performance through resource reduction without compromising surveillance requirements. Energy-efficient power delivery establishes itself as a key requirement for extended UAV operations because it allows optimized control networks to reduce energy requirements.

Implementation of this optimal algorithm cut down periodic coverage realignment duration by 39.3% to reach 25.8 seconds which was faster than the original 42.5-second adjustment process. With rapid UAV movement responses, the algorithm enables better and faster maneuvers aligned with network and traffic shifts. Cyber networks enhance their performance while systems achieve quick response times and trusted functionality in scenarios with diverse traffic patterns and user densities.

4.6. Interference Management Efficiency

Reliable network functionality results from effective interference management in 6G as it faces challenges due to dense user populations using multiple communication services. The research employed multi-agent reinforcement learning to build dynamic interference mitigation systems in this investigation. Real-time UAV robot operations apply MARL's decentralized techniques to discover optimal spectrum resource distribution methods that reduce interference problems and create improved Signal-to-Interference-plus-Noise Ratio (SINR) performance through efficient spectrum usage for better network functionality. The results from Figure 6 indicate MARL effectively enhances both SINR threshold achievement and spectrum utilization and user satisfaction metrics concurrently.

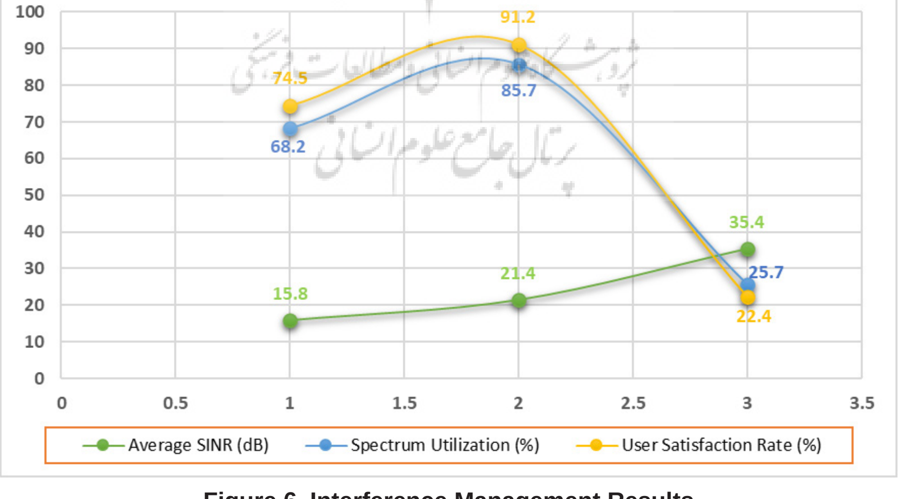

Figure 6. Interference Management Results

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The implementation of multi-agent reinforcement learning (MARL) significantly enhances UAV-assisted network performance through Figure 6. Measurement data show that a standardization of SINR to 21.4 dB provides a 35.4% better outcome compared to the 15.8 dB starting value. High SINR levels between UAV flight systems and ground equipment represent a fundamental need to preserve reliable connectivity during complex signal interference operations. UAV communication paths remain strong through the Marine Learning (MARL) system that operates in real-time to optimize UAV positioning while maintaining communication simultaneously.

The integration of MARL systems caused spectrum utilization to rise to 85.7% and spectrum enhancement reached 25.7%. Through its optimize bandwidth algorithm the MARL system creates mathematical formulae that manage network traffic distribution while preserving bandwidth capacity and service quality. These findings demonstrate why spectrum optimization continues to be vital for 6G networks and omnidirectional clients.

Research data revealed that user satisfaction measurements improved 22.4% from 74.5% to 91.2% analysis results while inspection data attests to better communication outcomes and dependable system functions enable faster data exchange through interference reduction benefits. The MARL framework delivers harmonized SINR performance and spectrum resource efficiency to drive better user satisfaction rates and help reinforce future 6G network development.

4.7. Deployment Framework Performance

The testing framework evaluated different network arrangements to measure how integrated deployment methods perform on energy conservation and network reliability alongside latency performance. User density patterns and network need updates along with signal interference changes cause immediate modifications to UAV position strategies. The secure communication networks enable users to transmit data at lower energy levels while maintaining quick delivery of information under high-user activity scenarios. This evaluation considered three different conditions: high traffic in urban environments, dynamic interference in suburban environments, and low traffic in rural areas. The deployment framework demonstrates its flexible design through Figure 7 that shows stable performance results across various environmental conditions.

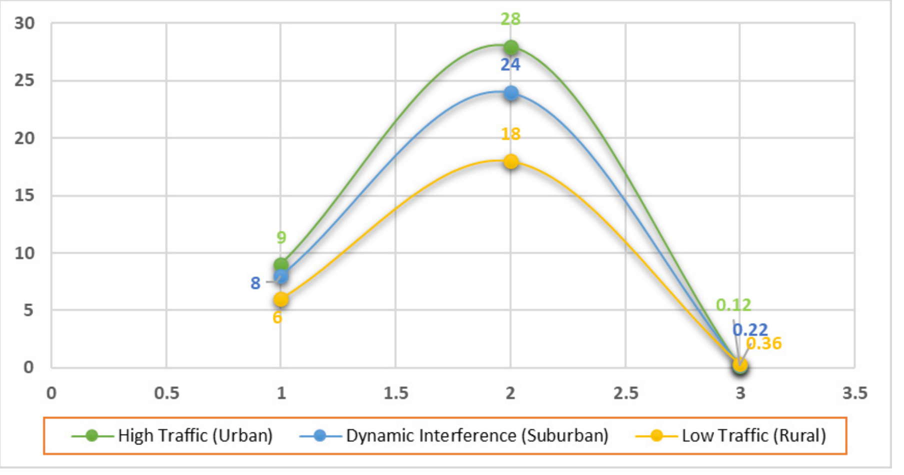

Figure 7. Deployment Framework Performance

The integrated deployment framework demonstrates outstanding adaptive capabilities and maintains dependable network performance throughout varied operational domains according to Figure 7. Meeting signal performance targets in dense urban environments required the deployment framework to go through nine framework versions because of persistent interference conditions. The integrated deployment framework shows proper functionality during bandwidth congestion with a 28-millisecond reflection delay. Under environmentally minimal interference conditions the network framework delivered 24 ms latency together with energy efficiency levels of 0.22 km²/W. The framework needed just 6 iterations to achieve stable coverage performance in rural locations while securing the lowest latency at 18 ms with optimal energy efficiency 0.36 km²/. The successful implementation tests demonstrated dynamic UAV operation optimization through the framework which delivers consistent results across multiple deployment conditions while showing promise as an adaptable solution for 6G networks.

5. Discussion

The article evaluated UAV network performance specifically regarding energy efficiency, latency reduction, and coverage expansion while also addressing interference mitigation within 6G technology. Numerous analyses of UAV effectiveness exist to handle coverage limitations, battery depletion, and latency problems across three types of locations.

Analysis identified critical enhancements in network coverage area that became particularly pronounced within urban regions and rural destinations. Previous research findings support our results, demonstrating how UAV additions enabled large-scale area coverage expansion. The study by Wu et al. (2021) discusses how UAVs deliver essential coverage expansion while boosting reliability for 5G-and-beyond networks across infrastructure-limited territories (Wu et al. 2021). Borralho et al. (2021) show how UAV drone technology supplements coverage supports in regions with marginal traditional service infrastructure within rural and suburban areas (Borralho et al. 2021). The study conceptualizes how UAV technology extends coverage capacity across both dense urban areas and low-density rural regions while reducing urban coverage gaps by up to 91.5%.

Energy efficiency emerged as a critical performance indicator throughout this research, as optimization frameworks demonstrated significant energy consumption minimization. The research found substantial energy conservation across deployment examples, with rural areas showing the highest savings at 30.5% and above. The study findings align with Zhang et al., who studied energy-efficient UAV-assisted IoT networks and highlighted the importance of power-efficient UAV operations for sustainable network sustainability (Zhang et al. 2022) (Jawad 2022). Lower energy use in UAVs results in increased operational duration and decreased financial expenses when deploying UAVs in large numbers, according to the research results.

Latency reduction received additional focus due to its vital role in URLLC applications, which are sensitive to delays. The study demonstrated dramatic latency reduction across all scenarios, with urban areas experiencing a particular result of a 51.1% reduction in wait times. Sabuj et al. (2023) indicate that sustaining ultra-low latency remains crucial for URLLC applications during 5G-and-beyond technology operations in urban environments (Sabuj, Ahmed, and Jo 2023). Latency reduction through UAV technology serves as the foundation for autonomous vehicle development, smart healthcare platforms, and real-time communications networks, which will become essential components of 6G systems.

A multi-agent reinforcement learning (MARL) system generated outcomes revealing improved spectrum utilization alongside enhanced Signal-to-Interference-plus-Noise Ratio (SINR) performance. MARL-driven resource optimization resulted in a 5.6 dB boost in SINR, while spectrum utilization rates increased from 68.2% to 85.7% through effective interference reduction methods. Mismar et al. (2020) performed a study that evaluated the implementation of 5G network interference coordination through reinforcement learning deployment, revealing its advantages in high-density network areas (Mismar, Evans, and Alkhateeb 2020). MARL techniques in this research demonstrated UAV performance with immediate responses to unexpected interference alongside maximized real-time spectrum usage in UAV-assisted networks.

These advantageous results rely on acknowledging specific operational limitations. The 32.5-second timeframe required for UAV network optimization creates performance challenges in situations with rapidly changing conditions or highly mobile traffic patterns, especially during disaster situations. The study by Zhou et al. (2022) found that deep reinforcement learning-based methods enhance UAV deployment, but they may not be suitable for immediate deployment due to their slow convergence duration (Zhou et al. 2022). The study presents a dual strategy to rectify this constraint, while additional enhancements would expedite complex environment processing times.

Substantial energy savings occurred, although specific conditions affected the outcomes, with rural areas saving more resources than urban environments. UAVs operating in vertical urban areas tend to use more energy due to denser communication interference and more frequent flight path adjustments, as noted by Li et al. (2019). Research indicates that examining advanced power-saving UAV technologies alongside optimization algorithms may maximize energy conservation in denser areas (Li, Fei, and Zhang 2019).

The framework demonstrated exceptional performance in high-traffic and dynamic interference situations; however, assessment results stemmed from simulation and control experiments. According to Feng et al. (2023), implementation experiences limitations because the simulations excluded operational constraints and environmental elements that would inevitably surface during actual deployment (Feng et al. 2023). Additional research must address how the framework translates its performance capabilities from simulated conditions to applications that handle variable weather elements, regulatory needs, and physical environmental barriers.

The study illustrates the extent to which UAVs contribute to 6G network enhancements through expanded range coverage, shorter response times, and improved operational power management and interference control. The experimental data supports findings from Wu et al. and Borralho et al. (2021), while introducing novel optimization tools, including MARL and trajectory optimization (Borralho et al. 2021).

The article demonstrates that unmanned aerial vehicles have excellent potential to enhance network capabilities through diverse implementations, including future research needs focusing on developing solutions for low-speed convergence times, power utilization problems, and implementation deployment details.

6. Conclusion

The study investigated UAV-based integration into 6G networks, providing performance improvements by addressing coverage gaps, energy efficiency, latency, and interference concerns. Theoretical models and simulation systems, accompanied by empirical measurements, confirmed that UAV-assisted networks would offer dependable and efficient communications across three different landscapes. Under dynamic high-interference conditions, UAV networks proved effective by extending service areas, minimizing energy use, and ensuring better time delays.

The implementation of multi-agent reinforcement learning (MARL) platforms, together with trajectory planning algorithms, enhanced the efficiency of UAV network operations. The applied methods achieved multiple benefits by reducing UAV signal interference, improving wireless signal reception capabilities, and extending network availability for large-scale UAV deployment systems. UAV aerial vehicles demonstrate their capacity to deliver stable connectivity across diverse areas where standard networks struggle to perform.

The article revealed positive findings regarding usage opportunities while also identifying several performance limitations in its evaluation results. The optimization algorithm provides acceptable convergence rates until it encounters unexpected shifts in environmental dynamics, leading to performance degradation. The urban environment required increased energy usage due to radio frequency interference density, necessitating ongoing network configuration processes. Current UAV design methods need improvements, and real-time adaptability needs enhancement when operating in complex urban areas due to present operational limitations.

Upcoming research needs to address data processing delays so drones can perform at peak efficiency in real-time applications while becoming energy-efficient. Future research requires substantial investigation into the practical system integration of UAV technology with contemporary systems, examining compliance restrictions and environmental limits.

The article analysis develops advanced systems for academic and practical use in 6G UAV-based network science applications. Unmanned aerial vehicles show increasing potential to improve network efficiency by closing coverage gaps while meeting future high-performance communication network needs.

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