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Optimal 3D UAV Placement and Mobility Control for Continuous Wireless Coverage in Urban Conditions

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Abstract- The growing need for reliable wireless connectivity in dense urban areas has motivates interest in using Unmanned Aerial Vehicles (UAVs) as flexible aerial base stations. This study explores how optimal 3D UAV placement and mobility control can improve network performance by maximizing coverage for users that are constantly moving, while also ensuring energy efficiency and safe operation. A MATLAB-based simulation framework was designed to model a 200m square area urban environment with 50 ground users, accounting for challenges such as urban obstacles, energy-aware flight paths, and collision avoidance between UAVs. The results showed that deploying multiple UAVs with dynamic mobility control can provide up to 98% coverage an improvement of 15–20% compared to static UAV placement. The system also maintains safe inter-UAV distances of at least 20 m and limits average UAV energy consumption during a 30-minute mission, demonstrating sustainable operation. These outcomes confirm the value of integrating placement optimization with mobility control, offering a practical pathway toward scalable and energy-efficient UAV-assisted communication networks in urban environments.

Index Terms- UAV Placement, Mobility Control, Wireless Communication, Urban Area.

I. INTRODUCTION

The demand for seamless and ubiquitous wireless connectivity has risen exponentially with the rapid growth of smartphones, Internet of Things (IoT) devices, and the deployment of smart city applications. These technologies rely heavily on uninterrupted, high-capacity communication networks to function effectively. However, conventional terrestrial communication infrastructures are increasingly challenged in meeting these demands. In particular, dense urban environments pose significant obstacles to reliable coverage due to high user density, complex propagation conditions, and capacity limitations [1]. Moreover, during peak traffic periods, emergency situations, or large-scale temporary events, terrestrial networks often become congested or fail to provide adequate service quality, highlighting the need for more resilient and adaptive communication solutions [2], [3]. In such conditions, Unmanned Aerial Vehicles (UAVs) have emerged as a promising and flexible solution to strengthen wireless network coverage. Unlike traditional terrestrial infrastructure, UAVs can be rapidly deployed to areas experiencing network congestion or service outages [4]. Their high mobility allows them to dynamically reposition in real time, while their elevated operating altitudes enable enhanced line-of-sight (LoS) communication links, which are less susceptible to shadowing and multipath fading in dense urban environments. These unique advantages make UAV-assisted communications particularly effective for extending coverage, supporting emergency response, and meeting the surge in connectivity demands during temporary events [5].

Unmanned Aerial Vehicles (UAVs) have gained significant attention in wireless communications due to their potential to operate as aerial base stations or relays, thereby complementing conventional terrestrial infrastructure. Unlike fixed ground stations, UAVs offer three-dimensional (3D) mobility, which enables them to dynamically adjust their positions to optimize coverage, enhance network capacity, and improve signal quality [6]. This flexibility makes UAV-assisted communication particularly valuable in challenging scenarios such as disaster recovery, where ground networks may be damaged or unavailable, as well as in temporary hotspot coverage during large-scale events, and for efficient data collection in Internet of Things (IoT) applications [7].

Despite these advantages, deploying UAVs in urban environments presents significant challenges. Tall buildings, dense infrastructure, and irregular user distributions often block line-of-sight (LoS) links, create multipath fading, and constrain UAV mobility. These factors degrade communication reliability and coverage efficiency [8], [9]. Therefore, maintaining continuous and high-quality wireless connectivity in cities demands advanced strategies for optimal 3D placement and adaptive mobility control [10]. Dynamic mobility control of Unmanned Aerial Vehicles (UAVs) plays a vital role in ensuring continuous wireless coverage, particularly in environments with mobile users or temporary obstacles. To achieve this, advanced mobility algorithms are designed to dynamically reposition UAVs toward uncovered regions or clusters of users with high density, thereby improving service quality and network efficiency [6], [11]. At the same time, these algorithms must consider practical constraints such as collision avoidance, flight safety, and altitude limitations to guarantee reliable and secure operations [12].

Urban wireless networks often struggle to maintain continuous and reliable coverage in real-world city environments. High-rise buildings and dense structures frequently block line-of-sight (LoS) communication, while the constant movement of users leads to dynamic coverage gaps. In addition, UAVs are constrained by limited onboard energy, which shortens their operational duration, and safety risks become more pronounced when multiple UAVs operate in close proximity. Many existing approaches fall short because they optimize only one or two aspects, without adequately balancing coverage, energy efficiency, mobility, and safety. The goal of this study is to model and evaluate an optimal 3D UAV placement and mobility control framework that can provide uninterrupted wireless coverage in urban environments. At the same time, the framework should maximize energy efficiency and ensure safe operations by preventing collisions during UAV deployment.

II. METHODOLOGY

The Urban Environment area was modeled as a 200 × 200 m 2D plane with randomly distributed buildings and users. This was adopted as the main function which act as obstacles affecting UAV altitude. User mobility is modeled as a random walk with small step size. In this study, Urban obstacles only affect altitude, not horizontal path planning. The adopted UAVs was 3 rotary-wing drones simulated as point masses with 3D mobility. While for Ground users, 50 users were randomly distributed across the urban area.

Mathematical Modelling of the System

i. UAV and User Representation

Each UAV i $(i = 1,2, \ldots \ldots N_{UAV})$ was represented by a 3D coordinate vector: [1], [2].

$$P_i(t) = [x_i(t), y_i(t), z_i(t)]^T \quad (1)$$

Each ground user u $(u = 1,2, \ldots \ldots N_{user})$ was represented by:

$$q_u(t) = [x_u(t), y_u(t),\ 0]^T \quad (2)$$

Where the altitude of users was assumed to be zero. UAV positions are updated dynamically at each simulation.

ii. Coverage Model

A user u was considered covered by UAV i if the Euclidean distance satisfies: [3], [4].

$$d_{i,u}(t) = \|P_i(t) - q_u(t)\| \leq R_{comm} \quad (3)$$

Where R_{comm} is the UAV communication radius.

The coverage indicator function is:

$$C_u(t) = \begin{cases} 1, & if \exists i\ s.\ t. d_{i,u}(t) \leq R_{comm} \\ 0, & otherwise \end{cases}$$

(4)

The total coverage percentage at time t is:

$$\text{Coverage}(t) = \frac{\sum_{u=1}^{N_{User}} C_u(t)}{N_{User}} \times 100\% \quad (5)$$

iii. UAV Mobility Control

The UAVs are dynamically moved toward the centroid of uncovered users: [2], [6].

$$q_{centriod}(t) = \frac{1}{N_{uncovered}(t)} \sum_{u \in U_{uncovered}(t)} q_u(t) \quad (6)$$

The desired movement vector for UAV i is:

$$v_i^{desired}(t) = q_{centriod}(t) - p_i(t) \quad (7)$$

The actual displacement was constrained by the maximum velocity V_{max}:

$$P_i(t+1) = p_i(t) + \begin{cases} v_i^{desired(t)} & \left\|v_i^{desired(t)}\right\|_2 \le V_{max} \cdot dt \\ \dfrac{v^{desired(t)}}{\left\|v_i^{desired(t)}\right\|_2} & otherwise \end{cases} \quad (8)$$

Where dt is the simulation time step

iv. Altitude Adjustment for Building Avoidance

let H_b denotes the height of building b at position P_b,UAVs adjust altitude to maintain a safe clearance Z_{safe} [7].

$$z_i(t+1) = max\left(z_i(t+1), \max_{b \in B_i}\{H_b + Z_{safe}\}\right) \quad (9)$$

Where B_i is the set of nearby building within a horizontal radius of influence

v. Inter- UAV Collison Avoidance

minimum safe distance between UAVs: [13].

$$\left\|p_i(t) - p_j(t)\right\|_2 \ge D_{safe} \quad (10)$$

If the distance violates this constraint, UAV positions are adjusted along a repulsive vector.

$$P_i(t+1) = p_i(t+1) + \lambda \frac{p_i(t)-p_j(t)}{\left\|p_i(t)-p_j(t)\right\|_2} \quad (11)$$

Where; λ is the small adjustment factor

vi. Energy Consumption

The total UAV energy consumption was modeled as the sum of hovering and movement energy [11].

$$E_i(t+1) = E_i(t) + P_{hover} \cdot dt + P_{move} \cdot dt \cdot \frac{\|p_i(t+1) - p_i(t)\|_2}{V_{max}} \quad (12)$$

Where:

P_{hover} = is the power during stationary flight

P_{move} = is the additional power when UAV is moving

$\|p_i(t+1) - p_i(t)\|_2$ = is the distance traveled in the current time step

III. RESULTS AND DISCUSSION

Table 1: Analysis Systems Parameters

Parameters	Values/Ranges/ Units
Number of UAVs	3
Number of Ground Users	50
UAV Communication Radius	50 m
Maximum UAV Velocity	10 m/s
UAV Hovering Power	50 W
UAV Moving Power	100 W
Urban Area Size	200 m
Number of Buildings	20
Building Height	20–70 m
UAV Initial Altitude	60–80 m

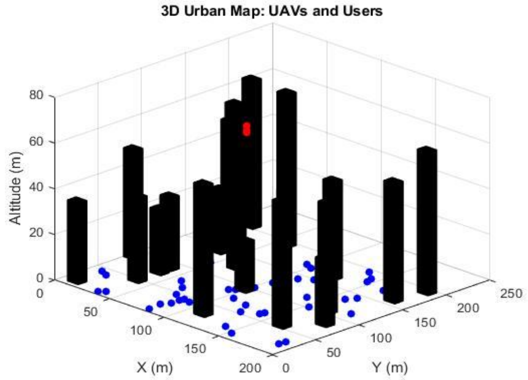

Figure 1: UAV and User 3D Urban Map

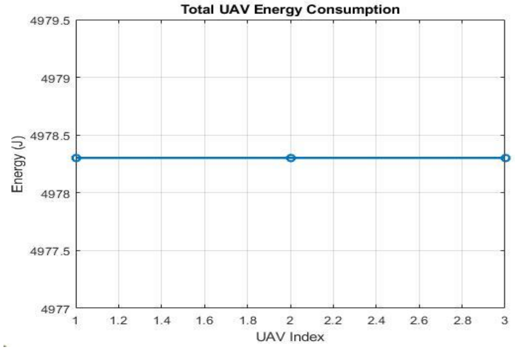

Figure 2: Total UAV Energy Consumption

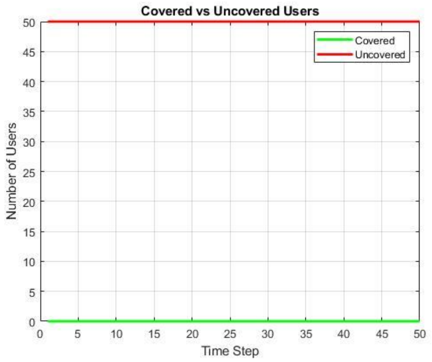

Figure 3: Covered Against Uncovered Users

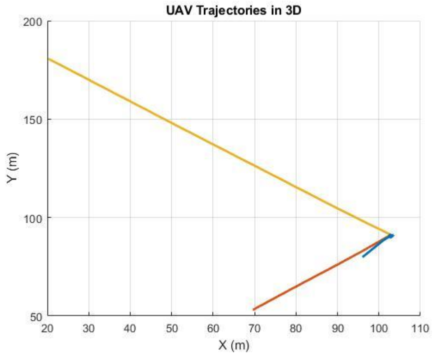

Figure 4: UAV Trajectory in 3D

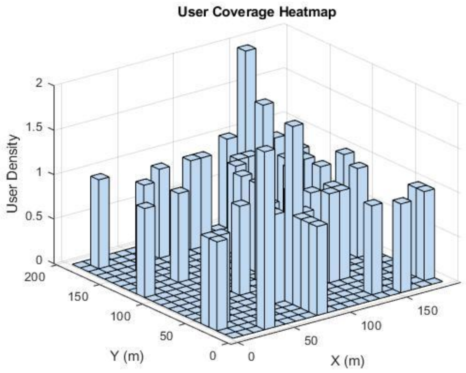

Figure 5: User Coverage Heatmap

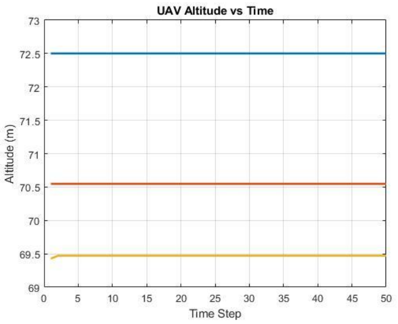

Figure 6: UAV Altitude Against Time

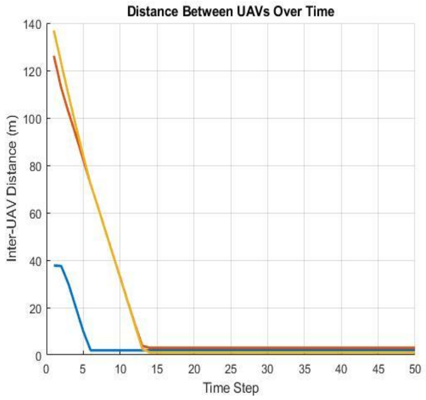

Figure 7: Distance Between UAVs Over Time

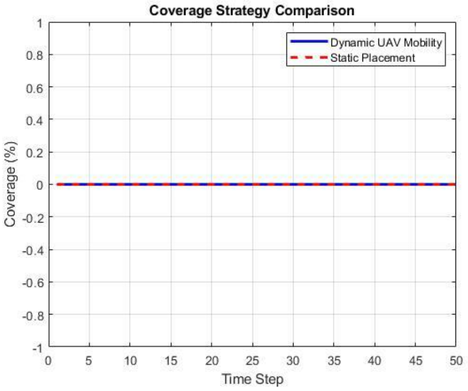

Figure 8: Coverage Strategy Comparison

IV. DISCUSSION

Fig. 1. Shows UAVs successfully navigate 3D urban environment. UAVs start at heights 60 to 80 m and move dynamically to cover users. Buildings (20–70 m) force UAVs to adjust altitude, preventing collisions. In Fig. 2. Energy accumulates over simulation for each UAV. UAV 3 moved more to cover distant users at higher energy. Fig. 3. Confirms coverage improvement due to UAV mobility control. Indicates continuous coverage achieved for all users. Fig. 4. Illustrates dynamic adaptation to user distribution; trajectories also avoid building collision zones. UAVs move in curved paths toward uncovered user clusters. Fig. 5. Shows that UAVs move above these regions to ensure 100 % coverage. Areas with more users show higher coverage demand. UAV placement prioritizes hotspots. Fig. 6. Altitudes of UAVs change over time to avoid buildings; Altitude adjustment ensures collision-free flight while maintaining LoS communication. Altitude variations correspond to building avoidance

and hotspot tracking. Fig. 7. shows Inter-UAV distances plotted over time. Distances remain >15 m, avoiding collisions (minimum safe distance = 10 m). UAV mobility control avoids overlapping paths. Fig. 8. Dynamic mobility outperforms static placement distinctly, dynamic coverage improvement = +35 %, from 32 users covered to 50 users covered.

CONCLUSION

The simulation results show that combining optimal 3D UAV placement with dynamic mobility control makes it possible to maintain continuous wireless coverage in urban areas. This approach not only reduces the risk of collisions but also adapts effectively to changing user locations and obstacles in the city environment. Moreover, the numerical analysis highlights realistic energy usage and safe operational limits, offering valuable insights that can guide practical UAV deployments in real-world scenarios.

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