UAV-BS Integration with Urban Infrastructure: An Energy Efficiency Perspective

Balaji Kirubakaran, Olga Vikhrova, Sergey Andreev, and Jiri Hosek

Abstract

The integration of uncrewed aerial vehicles (UAVs) with fifth-generation (5G) cellular networks has been a prominent research focus in recent years and continues to attract significant interest in the context of sixth-generation (6G) wireless networks. UAVs can serve as aerial wireless platforms to provide on-demand coverage, mobile edge computing, and enhanced sensing and communication services. However, UAV-assisted networks present new opportunities and challenges due to the inherent size, weight, and power constraints of UAVs, their controllable mobility, and the line-of-sight (LoS) characteristics of communication channels. This article discusses these opportunities and challenges from the viewpoint of mobile network operators (MNOs), and offers a novel perspective on efficiently utilizing modern city infrastructures for UAV deployment in typical urban scenarios. In these scenarios, UAV-mounted base stations (UAV-BSs) can significantly improve service continuity and network energy efficiency. We compare system performance in terms of user satisfaction and energy efficiency between conventional UAV deployment, which follows demand dynamics, and an alternative approach where UAVs land on urban infrastructure equipped with charging stations. To identify the preferred UAV locations, while considering the limited availability of such stations and environmental dynamics, we employ a data-driven genetic algorithm. This algorithm closely approximates the true optimal locations subject to a moderate computational budget.

On-Demand Integration with Urban Infrastructure

Inspired by the success of pilot projects on Uncrewed Aerial Vehicle (UAV)-enabled communications, such as AT&T's flying COW and Nokia's F-cell [1], there is a growing interest from mobile network operators (MNOs) in employing UAVs as cost-effective aerial platforms. The shift from the theoretical fundamentals to the practical implementation of 5G+ networks marks a new era of efficient communication, thereby opening avenues into the envisioned domains. However, this transition comes with challenges that demand thorough attention and robust solutions [2].

Cellular networks are experiencing a surge in heterogeneous mobile devices, many demanding high-speed and reliable connections. This scenario presents a significant challenge for MNOs: enhancing and dynamically adapting their network infrastructures to meet these escalating demands. Traditionally, MNOs employed over-provisioning by densifying ground base stations (BSs) in areas with expectedly high demand, particularly in response to the growing need for real-time data transmissions driven by live streaming, interactive online gaming, and autonomous driving. However, this approach has inherent limitations due to the temporary nature of demand peaks in urban and rural areas or during large-scale public events [3]. These limitations result in high capital and operational expenditures as well as unnecessarily high network energy consumption during the periods of low demand. Consequently, MNOs are shifting their focus toward *on-demand* networks that can adapt to varying usage patterns.

UAVs offer a promising solution for on-demand network deployment by serving as advanced airborne relay nodes that significantly alter mobile network design and operation [4]. With UAV-mounted BSs (UAV-BSs), future networks become truly adaptive, versatile, and continuously evolving. The use of these UAV-BSs is pivotal in many urban deployments, where the existing city landscape presents considerable challenges for MNOs with regards to efficient network planning and operation. Wireless UAV-BSs can alleviate these challenges while enhancing signal quality and improving data rates.

However, deploying and managing UAV-BSs in dense and complex urban areas is not straightforward. Challenges include navigating the complex airspace and determining the best UAV-BS positions while respecting their limited battery lifetimes. A large number of prior works discussed these challenges and provided versatile solutions. For example, the study in [5] investigates optimal 3D placement strategies for UAVs to maximize coverage and minimize interference in urban areas. The proposed algorithms dynamically adjust UAV positions based on user demand and environmental conditions. The work in [6] focuses on an important aspect of backhaul optimization for moving UAVs, while the research in [7] compares flying and landed UAV deployments in environments with highly dynamic user demands. The

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more recent works, for example, [8], go beyond the integration of UAVs in cellular networks and discuss the benefits that UAVs can bring to joint communication and sensing applications.

Our research contributes to the topic by examining the dissimilarities between on-demand moving UAV-BS deployments and stationary landed UAV-BS layouts in typical urban environments where demand dynamics and user mobility can be reasonably predicted. We base our assessment on several assumptions regarding the behavior of UEs and traffic fluctuations, while utilizing the information available to MNOs about the environment, such as the anticipated number of UEs, schedules and locations of events. This knowledge enables a proactive deployment of UAVs, which land in strategic locations to meet UE demands while minimizing their energy consumption. To determine the preferred locations for UAV-BSs, we employ a data-driven approach using a genetic algorithm (GA). This method robustly determines the best UAV-BS placements within a given time budget, hence ensuring a timely network response to real-time changes in environmental conditions.

The rest of this article is organized as follows. We explore the UAV-BS integration challenges and elaborate on potential solutions. Following that, we introduce our considered approach for UAV-BS placement using urban infrastructure. We then present our system-level framework, and discuss the results and lessons learned.

UAV-BS Integration Challenges and Solutions

This section addresses the integration of UAV-BSs with urban infrastructure as part of MNO networks, while focusing on key benefits and challenges. It outlines the advantages of using UAV-BSs in various scenarios and the obstacles encountered in their integration, followed by a discussion on potential solutions to these issues.

Attractive Scenarios and Integration Benefits of UAV-BSs

Integrating UAV-BSs with urban infrastructure into MNO networks enhances user Quality of Service (QoS) while cost-effectively improving resilience and operational efficiency. This subsection explores the key benefits and scenarios enabled by this strategic integration.

Expanding Service Coverage: UAV-BSs provide an attractive opportunity to extend network services to remote and geographically challenging areas [9]. This capability is particularly beneficial for ensuring connectivity in rural or underserved regions, where terrestrial network deployment faces significant logistical and financial hurdles. For MNOs, rapidly bridging coverage gaps with UAV-BSs represents a strategic advantage in expanding their service footprint and reaching new customer segments.

Dynamic Capacity Scaling: In response to fluctuating demand, UAV-BSs offer MNOs the flexibility to scale network capacity dynamically. This is particularly valuable during peak load situations or natural disasters where infrastructure is overwhelmed or damaged. UAV-BSs can be deployed promptly to augment the network, thus ensuring uninterrupted service quality and user experience without infrastructure modifications.

Enhanced Network Resilience: UAV-BSs significantly enhance network resilience by offering alternative connectivity means during terrestrial network outages caused by technical malfunctions or maintenance tasks. Their capability of rapid deployment allows for a swift restoration of communication services, while ensuring the continuation of essential transmission links during outages and reinforcing MNO's dedication to reliability.

Smart City and IoT Integration: Integrating UAV-BSs within smart city layouts enhances urban connectivity and supports the deployment of numerous Internet of Things (IoT) applications. From traffic management and public safety monitoring to environmental sensing, UAV-BSs provide the connectivity essential for intelligent urban management systems, thereby promoting operational efficiency and contributing to sustainable city functioning.

Cost-Effective Network Deployment: The use of UAV-BSs offers a cost-effective solution for MNOs to expand their service capabilities. Compared to constructing and maintaining traditional infrastructure, UAV-BSs demand a lower initial investment [1]. They can be redeployed as needed, hence allowing for more efficient use of capital and operational expenses in network expansion and maintenance.

Agile Network Testing and Optimization: UAV-BSs enable MNOs to perform agile and in-depth network testing and optimization. Their mobility allows for detailed network performance assessment across various terrains and conditions, while facilitating precise adjustments to antenna placement, signal strength, and coverage patterns. This capability is essential for maintaining robust network performance.

Challenges and Solutions in UAV-BS Integration with Urban Infrastructure

UAV-BS integration with urban infrastructure presents several challenges. Addressing these issues is crucial for successfully deploying and operating UAV-BSs. Below, we explore these challenging aspects along with potential solutions to overcome them.

Regulatory Compliance: Integrating UAV-BSs into MNO networks faces regulatory hurdles that vary across different regions. This includes navigating complex flight approval processes, adhering to specific altitude restrictions, requiring a human operator's presence during UAV-BS flights [10], collaborating with regulatory bodies to streamline permissions, and developing advanced UAV-BS control systems that ensure compliance with regional regulations. Implementing standardized procedures for UAV-BS operations can also facilitate a more straightforward adaptation to diverse legal frameworks.

Power Management and Energy Efficiency: UAV-BSs are constrained by their battery lifetimes, which restricts the operational duration. This limitation poses a significant challenge for prolonged and sustained use in network operations. Adopting real-time control algorithms that dynamically adjust UAV-BS power consumption based on the current task requirements can improve battery usage [4], thereby extending the operational time of UAV-BSs.

Data Security Protocols: With the capability of UAV-BSs to collect and transmit data comes a heightened risk of data breaches and/or unauthorized access, thus necessitating robust security measures [11]. Implementing stringent security

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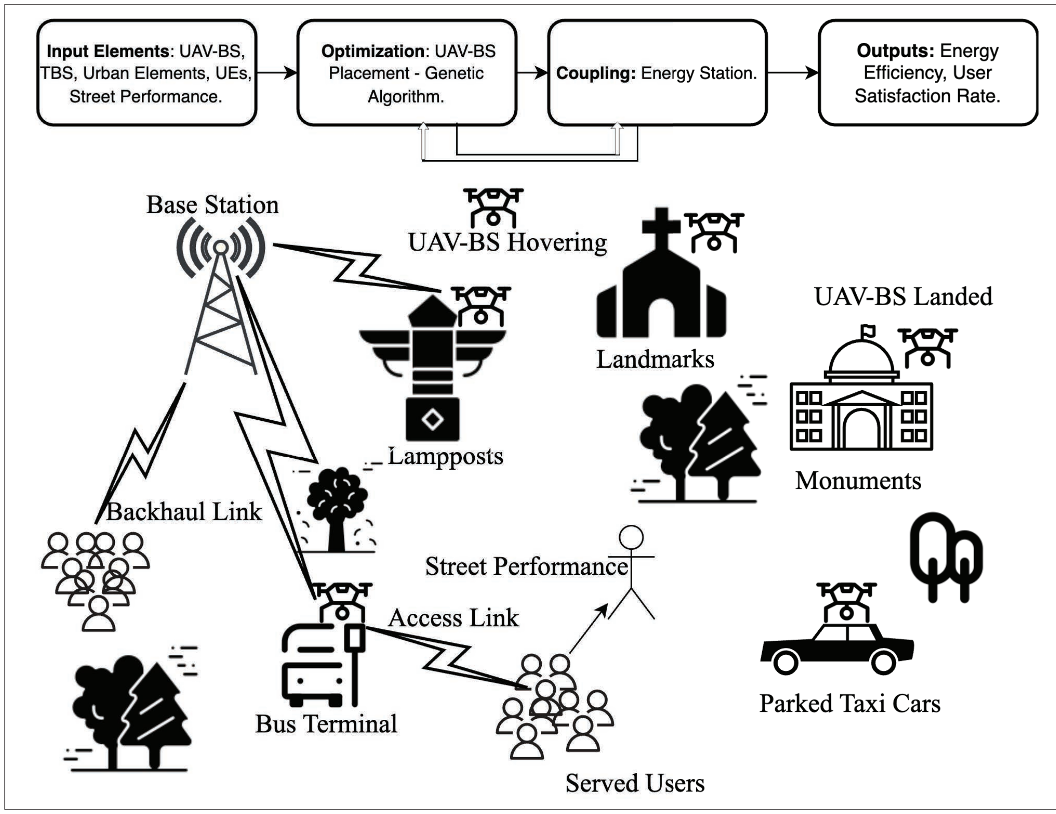

FIGURE 1. Integration of UAV-BSs with Urban Fixtures.

protocols, including encrypted data transmission and secure authentication mechanisms, is essential to protect data integrity and confidentiality in the face of cyber threats.

Spectrum Allocation and Interference Mitigation: Managing radio spectrum efficiently and controlling interference presents a significant challenge in integrating UAV-BSs into MNO deployments. The potential overlap between UAV-BSs operating over terrestrial communication systems [3] can lead to interference, hence affecting service quality. Employing adaptive spectrum management techniques alongside advanced interference cancellation algorithms is instrumental to tackling this issue. Leveraging machine learning methods to dynamically predict and control interference patterns can optimize UAV-BS deployments, consequently ensuring seamless coexistence with terrestrial networks.

Physical Limitations and Environmental Factors: The operational effectiveness of UAV-BSs is limited by their range, flight time, and sensitivity to adverse weather conditions. Enhancing UAV-BS durability through improved materials capable of withstanding various weather conditions and incorporating weather-resistant features can mitigate these issues. Developing UAV-BSs with extended range and battery life also helps overcome these physical limitations.

UAV-BS Positioning via Genetic Algorithm

This section focuses on the methodology behind integrating UAV-BSs with urban infrastructure as illustrated in Fig. 1 to improve network sustainability. In the considered use case, UAV-BSs act as mobile relays connected to the 5G/5G+ macro BS over wireless backhaul links. The deployment of UAV-BSs targets to efficiently accommodate sporadic user demands concentrated in specific areas. The locations of UAV-BSs are reconsidered if the expected system performance deteriorates under their current placement. The performance can be measured in the number of live-streaming UEs whose timely throughput demands are met while the system supports best-effort background traffic.

UAV-BS positions are significant for demanding UEs that require, for example, high-quality live streaming. The challenge lies in determining the preferred location for a certain UAV-BS to land on from the available landmarks and stations, including lampposts, monuments, bus stops, and parked taxi cars, by also taking into account the resulting UAV altitude and quality of the backhaul and access links, availability, accessibility, and stability of the stations. The urban structures available for UAV-BSs can act as a consistent power source and provide the necessary equipment, thereby enabling UAVs to recharge and extend their operational times.

In this work, GA [12] has been selected as a practical solution for the considered UAV-BS placement problem. We compare its performance with another heuristic approach commonly used for the same task, namely, the Particle Swarm Optimization (PSO) algorithm [13], and the true optimal UAV-BS placement obtained via an exhaustive search. Figure 2 demonstrates the UAV-BS positions estimated by selected optimization methods. The performance comparison is discussed further in the following sections.

In general, GA offers a robust method for solving complex optimization and search problems. It can handle diverse data types, constraints, and objective functions, thereby making it highly practical. Its stochastic nature, which involves random operators like mutation and crossover, ensures diversity in the population, hence promoting a broader search and helping to avoid local optima. This approach enhances GA's ability to find global optima, thus providing more reliable solutions to complex problems. The inherent parallelism of GA further contributes to its feasibility by making it well-suited for multi-core and distributed computing environments, hence speeding up the optimization process. Ease of implementation is another practical benefit. The basic operations of selection, crossover, and mutation are straightforward, which renders GA relatively simple to implement and understand. It does not require gradient information or other problem-specific data, thus simplifying its application.

GA operates by initializing a population of possible UAV-BS positions and evaluating each candidate configuration by using a fitness function that calculates the proportion of UEs whose timely throughput demands are satisfied. The best-performing options are then selected for crossover and mutation operations to generate new potential solutions. This iterative process refines the UAV-BS positions, thereby enhancing user satisfaction rates.

In our study, the parameters employed as GA settings include a population size of 150, a crossover probability of 0.8, a mutation probability of 0.2, and a maximum of 100 generations. These values were chosen to balance exploration and exploitation within the solution space, while aiming to ensure robust optimization and acceptable time budget.

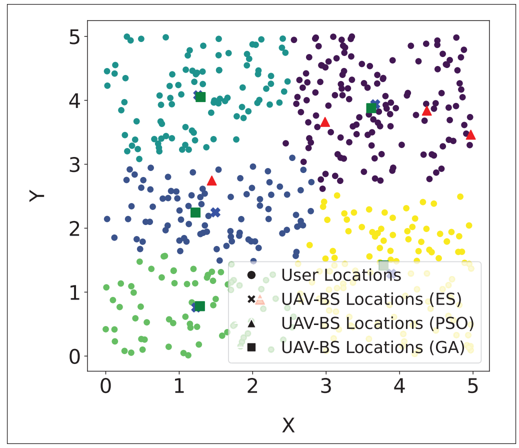

FIGURE 2. UAV-BS placement using the considered Genetic Algorithm (GA), the reference Particle Swarm Optimization (PSO) method [13], and the optimal Exhaustive Search (ES) approach.

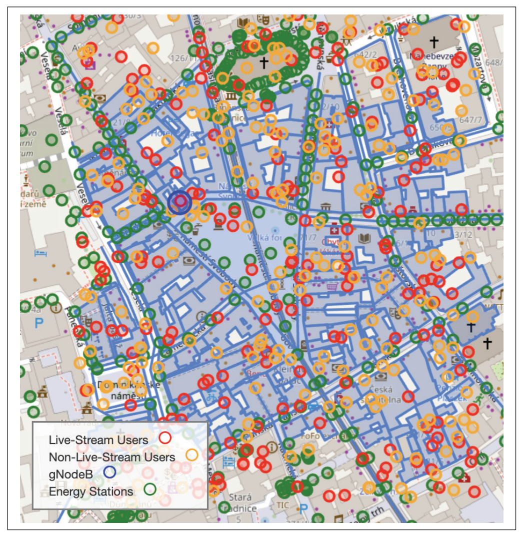

FIGURE 3. Area of Interest: Freedom Square, Brno, CZ.

System-Level Modeling of On-Demand UAV-BS Deployment

This section summarizes our system-level modeling for the on-demand integration of cellular UAV-BSs with urban infrastructure, aimed at enhancing performance in the areas where terrestrial BSs and moving UAV-BSs may face limitations. We rely on simulations to demonstrate that UAV-BSs on top of urban infrastructure can substantially improve network energy efficiency while experiencing marginal user satisfaction loss.

Urban Setup and Deployment Parameters

Area of Interest: For the reference use case, we consider the city center of Brno, Czech Republic, spanning approximately 0.25 square kilometers around Freedom Square. The area is a complex mix of public spaces, narrow streets, and buildings of different types, as illustrated in Fig. 3. This location has high pedestrian traffic during, for instance, the annual Winter Festival, which may create a significant demand for wireless communication services.

We further utilize OpenStreetMap, a free map service that provides detailed maps for a realistic model of the streets and building shapes in the area. We use data from the Brno data portal to add important city features such as landmarks, streetlights, monuments, bus stops, and taxi parking spots. These features play a crucial role in providing a wide range of candidate locations for UAV-BSs to charge, especially important during festivals when the area is crowded.

User Density and Mobility: Utilizing data from the OpenStreetMap and Brno data portal, we simulate the behavior of approximately 5,000 festival attendees, as reported by PredictHQ's event data, to reflect the actual user density and mobility during peak event times. The UEs are categorized into two groups: live-stream users and non-live-stream users. This distinction represents a realistic demand on wireless networks, where live-streaming UEs constitute a significant share of data usage. Our UE mobility model combines a more conventional Manhattan model with a nomadic community-based approach [14], hence aligning with the specific pedestrian dynamics observed in the area. The employed model accurately captures the movement of a group of UEs toward various attractions and live performances commonly occurring at festivals.

Peak Hour Dynamics: In our evaluations, we consider peak festival hours between 7 p.m. and 8 p.m. characterized by significant fluctuations in UE activity. Based on our data, this timeframe typically features around ten events, each having an average duration of 15 minutes. These events typically attract substantial crowds within a 50-meter radius [14]. The observed crowds are nearly static during the performances and then begin to disperse shortly afterwards. This pattern reflects the unique and highly predictable dynamics that can benefit from the landed UAV-BS deployments.

User Traffic: We assume two distinct traffic models. First, we consider users involved in live streaming during the event duration. The traffic of live-streaming users is well approximated by the Gamma distribution [1]. This distribution is important for predictive analysis and proactive UAV-BS placement. Second, we account for users whose network usage pattern is more sporadic and less demanding. These users engage in various activities, from occasional web browsing to social media use. For this group, the Log-normal distribution can be used for traffic generation [1].

Urban Network Deployment: Our deployment model assumes a terrestrial gNB (gNodeB) operating in the sub-6 GHz band and a number of UAV-BSs for seamless connectivity. The location of the gNB is taken from the OpenCellID database. The 3GPP Urban Macro and Micro path-loss models are applied to characterize the capacity of radio links, while considering both LoS and nLoS conditions shaped by urban structures. Such considerations are essential for assessing 5G+ network reliability and performance in dense urban settings. The other parameters related to the UAV-aided deployments of interest, as described in [1], are collected in Table 1.

General Parameters	Selected Values
Area of Interest	Freedom Square, Brno, CZ
Area Size	0.25 km^2 around Freedom Square
Observation Period	1 hour (from 7 p.m. to 8 p.m.)
Channel Bandwidth	100 MHz
Radio Access Network	5G sub-6 GHz
Carrier Frequency	3.5 GHz
Pathloss Model	3GPP UMa and UMi
User Rate Threshold	1.4 Mb/s
BS Scheduler	Proportional-Fair
UE Parameters	
Antenna Height	1.5 m
Transmit Power	23 dBm
Antenna Gain	0 dBi
Noise Figure	7 dB
Macrocell (BS) Parameters	
Antenna Height	30 m
Transmit Power	46 dBm
Antenna Gain	15 dBi
Noise Figure	5 dB
LoS Small-Scale Shadowing	4 dB
NLoS Small-Scale Shadowing	6 dB
Microcell (UAV-BS) Parameters	
Number of UAV-BSs	6, 8, 10, 12
Antenna Height	25 m
Transmit Power	30 dBm
Antenna Gain	5 dBi
Noise Figure	7 dB
LoS Small-Scale Shadowing	4 dB
NLoS Small-Scale Shadowing	7.82 dB
Traffic and User Mobility	
Number of Users	5000
Speed	1.5 km/h
Mobility Model	Nomadic, Community-Based
Traffic Load (Live-Stream)	Gamma (1, 1000000)
Traffic Load (Non-Live-Stream)	Lognorm (4, 0.7)
Number of Active Users	ExtNegBin (10, 0.01, 1, 600)
Genetic Algorithm	
Population Size	150
Crossover Probability	0.8
Mutation Probability	0.2

TABLE 1. Main modeling parameters.

Summary of Conducted System-Level Evaluations

Simulations for Dynamic Network Analysis: Our Python-based framework (The code is available on GitHub: https://github.com/balbal207/UAV-BS-Integration-with-Urban-Infrastructure) is designed to assess the performance of UAV-assisted wireless networks over the peak hour of a festival. The framework enables the evaluation of UE data rates, network energy efficiency, and user satisfaction rates given as a proportion of live-streaming UEs whose achievable data rates exceed a given threshold. These metrics are essential for assessing the system and user performance, as they offer insights into the network's capability to efficiently support user demands and manage energy consumption across different conditions. Together, they provide a comprehensive view of the system-level efficiency.

Scenarios of Interest: We compare and contrast two distinct scenarios to highlight the network performance enhancements with the considered UAV-BS approach.

Scenario 1, Mobile UAV-BSs: In this scenario, users choose to connect either to flying/hovering UAV-BSs or to terrestrial BSs, depending on the signal-to-noise ratio (SNR). The UAV-BSs fly toward a preferred location and may hover over that location until when another location is decided by the macro BS. The adjustments of UAV-BS locations are based on user movements and traffic demand changes.

Scenario 2, Landed UAV-BSs: In this scenario, UAV-BSs are directed to suitable power charging stations within the urban infrastructure to land, charge, and serve users. Meanwhile, by utilizing urban infrastructure, UAV-BSs can considerably reduce energy consumption and extend their active time, thereby ensuring that the network remains functional without interruptions.

Numerical Assessment and Lessons Learned

This section opens a discussion of network performance results obtained for the two considered scenarios and summarizes important implications of these results on further research directions. We examine the benefits of landed UAV-BS deployments in a dynamic environment with high user demands.

Energy Efficiency of UAV-Aided Networks

Figure 4 shows the energy efficiency, which is quantified in Bits per Joule and achieved under different scenarios and system configurations, specifically for various numbers of deployed UAV-BSs. The results demonstrate that deploying additional UAV-BSs in the case of Scenario 2 (landed UAV-BSs) noticeably improves the network energy efficiency, while it does not considerably increase the efficiency in the case of Scenario 1 (mobile UAV-BSs). Importantly, the energy efficiency in Scenario 2 with UAV-BSs landed on the city landmarks and urban infrastructure is almost twice higher than that in the conventional Scenario 1 with highly mobile and adaptive UAV-BS layouts.

For MNOs, this evidence highlights the potential of landed deployments to extend the operational times of UAV-BSs and ensure service continuity. It also helps MNOs avoid network over-provisioning, as the same UAV-BSs can simultaneously serve the UEs and charge their batteries. Such insights are valuable for network planning in urban contexts, particularly when the user demand is sporadic and the city infrastructure is difficult to work with.

User Satisfaction in Urban Settings

Figure 5 illustrates the user satisfaction rates in an urban environment under different UAV-BS deployment strategies. As anticipated, Scenario 1 consistently shows higher user satisfaction than Scenario 2. Notably, the performance disparity widens with the growing number of deployed UAV-BSs. This trend may be attributed to the scarcity of charging stations near high-demand areas, which results in UAV-BSs being positioned in less suitable locations.

However, optimizing the placement of charging stations in urban areas to align with user and network demand dynamics may further enhance user satisfaction while maintaining reduced network energy consumption. This operational trade-off is crucial for supporting network services, particularly in dense urban environments with high user demands. The capability of UAV-BSs to perform continuous service without excessive repositioning and recharging has the potential to improve network sustainability when facing traffic and user dynamics.

Noteworthy, the user satisfaction rate in Fig. 5 changes only marginally as the number of users increases, which highlights the important role of the UAV fleet size. Therefore, it is crucial to jointly optimize the numbers of UAV-BSs and UEs to determine the minimum population of UAV-BSs required to meet the actual user demands. If the number of UAV-BSs increases but remains below a certain lower threshold, the resulting network performance improvements may be insufficient to enhance user satisfaction.

Toward Integrated 6G-Non-Terrestrial Networks

High Altitude Platform Stations (HAPS) [2] have been envisioned as mobile BSs serving different types of users in mega-cells alongside legacy macro-cell and small-cell BSs. HAPS usually reside in the stratosphere at the altitudes of about 20 km, which allows them to operate in tandem with terrestrial BSs or UAV-BSs to support dynamic and unpredictable capacity demand in urban regions.

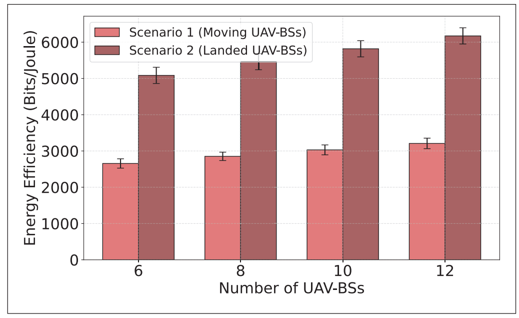

FIGURE 4. Energy efficiency as a function of the number of deployed UAV-BSs.

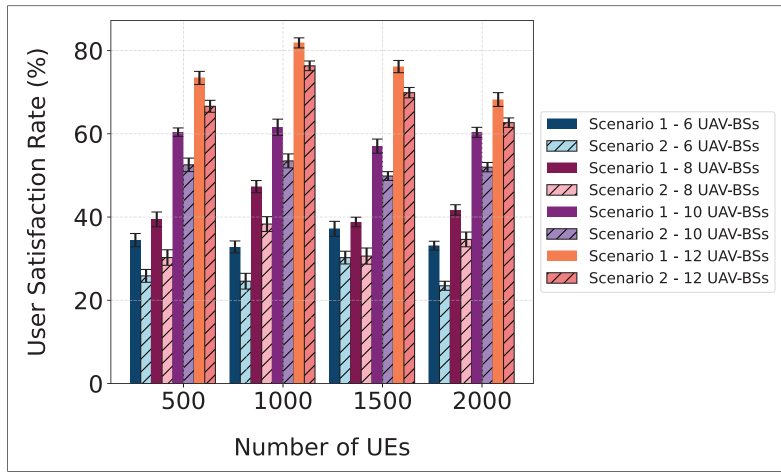

FIGURE 5. User satisfaction rate as a function of the numbers of UAV-BSs and UEs.

The integration of landed UAV-BSs with HAPS becomes a promising approach for 6G networks, particularly in addressing the more stringent user requirements in dense urban environments. This hybrid, semi-static deployment strategy offers significant advantages in terms of sustainability, energy efficiency, and network performance, thereby making it a timely topic with HAPS being one of the top-10 emerging technologies according to the World Economic Forum [15].

The integration of landed UAV-BSs with HAPS has the potential to improve network coverage and capacity in dense urban areas. Accordingly, HAPS provide wide-area coverage, while UAV-BSs fill-in specific gaps and handle high user demands by providing robust service quality and high data rates essential for 6G. This hybrid deployment enhances energy efficiency by employing HAPS for long-term, low-energy coverage, while UAV-BSs are deployed only as needed. This reduces the overall energy consumption, thus aligning with 6G-ready sustainability targets and lowering the environmental impact. Moreover, this approach offers flexibility, where UAV-BSs are promptly repositioned to meet either changing user demands or varying communication conditions at HAPS to ensure a stable backbone. The resultant scalability benefits the network, which can then adapt to the actual environmental conditions and serve emerging applications, hence making it suitable for dynamic 6G requirements.

Conclusion

This study investigates an attractive deployment approach for UAV-aided networks in urban areas that assumes the use of dedicated urban infrastructure potentially equipped with charging stations to land the UAV-BSs on. Such deployments are significantly more energy-efficient, even though they may experience moderate performance deterioration in the user satisfaction rate for highly demanding applications. Our research provides new insights into the placement of UAV-BSs by emphasizing the benefits of integrating them with urban elements and discusses the potential improvements for integrated urban deployments based on a realistic system-level setup. Future efforts are expected to extend these findings by addressing network performance within versatile use cases across diverse urban environments and under more unpredictable demand dynamics.

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