Enhancing Wireless Connectivity through Bayesian-optimized UAV-BS Positioning and Charging

Balaji Kirubakaran[0000−0002−2234−140X]1,2 and Jiri Hosek[0000−0002−8382−9185]1,2

[1] Department of Telecommunications, Brno University of Technology, Brno, Czech Republic
[2] Unit of Electrical Engineering, Tampere University, Tampere, Finland
`balaji.kirubakaran@vut.cz`

Abstract. Enhancing wireless network coverage in densely populated urban environments, such as those in India and China, poses a significant challenge due to high-rise buildings and intricate topographical features obstructing signal propagation. To augment network coverage in challenging areas, our paper proposes the utilization of Unmanned Aerial Vehicles Base Stations (UAV-BSs) as dynamic relays. By employing Bayesian optimization, we strategically position UAV-BSs to extend signal coverage to regions inadequately served by traditional cellular infrastructure. An essential contribution of our approach lies in integrating diverse urban elements for UAV-BS recharging, encompassing the utilization of transformer lines, adapting customized balconies, and exploiting cellular infrastructure rooftops. These various recharging mechanisms considerably extend the operational duration of UAV-BSs. Through extensive simulations, we demonstrate that our approach ensures a remarkable percentage increase in UAV-BS operating time and significantly enhances network connectivity for areas with high user density and demand. Further underscoring the practicality of our solution in addressing the complex challenges of urban wireless communication, this research represents a significant advancement in UAV-BS-assisted network enhancement, offering a scalable and efficient solution for densely populated urban areas.

Keywords: Bayesian Optimization · Wireless Connectivity · Unmanned Aerial Vehicles · Urban Communications · Recharging

1 Introduction

The digital era has witnessed a seamless transition of traditional board games like chess to online platforms, as exemplified by Chess.com. While these platforms have globalized the game, connecting players worldwide, they face a significant challenge in ensuring stable internet connectivity, particularly in densely populated urban areas of countries like India and China [1]. This issue impacts high-profile chess professionals, including World Chess Champion Ding Liren [2] and India's Grandmaster Vidit Gujarathi [3], who often experience disruptions during online competitions.

Reliable internet is essential for online gaming and vital communication in sectors such as politics and business. Events like the Chess Olympiad, with international participants and audiences, underscore the critical need for improved and reliable internet services. Traditional cellular infrastructure in complex urban areas often struggles to provide consistent signal quality [4]. To address this, Unmanned Aerial Vehicles Base Stations (UAV-BSs) have emerged as a dynamic solution to enhance network coverage.

UAV-BSs offer several advantages over traditional communication infrastructure. Their mobility provides targeted coverage in areas where traditional networks are weak or non-existent [5, 6]. Furthermore, their aerial positioning can overcome obstacles like tall buildings, which typically hinder signal propagation. However, using UAV-BSs effectively necessitates precise positioning to maximize coverage and minimize signal degradation. Improper placement can lead to inadequate service, highlighting the need for an accurate and reliable method for UAV-BS deployment.

This paper explores using Bayesian Optimization (BO) for optimal UAV-BS positioning, which has shown promise over conventional positioning techniques [7, 8]. BO's data-driven approach allows for more accurate placement of UAV-BSs, considering various environmental factors to ensure optimal network performance. Additionally, we introduce an energy management system that integrates urban infrastructure elements, such as cellular infrastructure rooftops and transformer lines, for UAV-BS recharging. This system extends the operational duration of UAV-BSs and reduces the need for frequent landings for recharging, thereby ensuring a more consistent and reliable network service.

Our results demonstrate the effectiveness of BO in UAV-BS positioning, with significant improvements in network coverage, particularly for high-demand users in densely populated areas. Integrating energy harvesting methods further enhances UAV-BS endurance by approximately good, compared to traditional charging methods. These contributions offer a comprehensive solution to urban wireless communication challenges, underscoring the potential of UAV-BSs in transforming network infrastructures in densely populated settings.

The remainder of the paper is organized as follows: Section 1, the Introduction, outlines the current challenges and the need for research in this area. Section 2, the System Model, describes the proposed UAV-BS-supported connectivity model. Section 3, Problem Formulation, defines the specific problems the UAV-BS system aims to solve. Section 4, Bayesian Optimization for UAV-BS Positioning in Urban Landscapes, explains how Bayesian optimization determines optimal UAV-BS locations. Section 5, Recharging Strategy, introduces the strategies for energy harvesting and maintaining UAV-BS endurance. Section 6, Simulation Results and Discussion, presents the findings from the simulations. The paper concludes with Section 9, Conclusions and Future Work, which summarizes the study's contributions and outlines avenues for further research.

2 System Model

Our system model, illustrated in Figure 1, encompasses diverse connectivity needs in an urban network environment. The critical elements of our model include UAV-BSs, ground base stations (GBSs), and charging stations (CS). Customized users in the model subscribe to premium services, primarily receiving enhanced connectivity from UAV-BSs. These users are guaranteed improved network access, which is particularly beneficial in areas where ground stations are less effective. Sports users represent a priority group needing high-speed, real-time data for activities like live streaming and online gaming, where constant connectivity is essential. Additionally, the model serves common users through the standard GBSs, catering to the general population's everyday internet needs. Combining UAV-BSs and GBSs ensures a balanced network where high-demand and regular users receive appropriate service levels. Mobile users are spatially distributed and are assigned specific coordinates (x_i, y_i, z_i), with the z-axis typically representing street-level altitude. The UAV-BSs, capable of adaptive movement, have coordinates (x_j, y_j, z_j), which allow them to adjust their positioning dynamically to provide optimal coverage based on user demand and network conditions. The GBSs are fixed infrastructure components with coordinates (x_b, y_b, z_b).

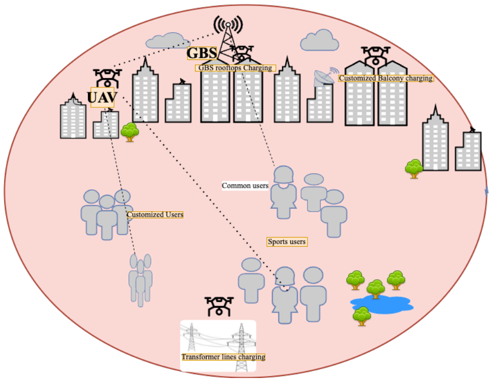

Fig. 1. System model.

Each mobile user and UAV-BS is equipped with a single antenna to facilitate efficient network management and user connectivity. The connectivity strategy ensures that customized and sports users are linked to the nearest UAV-BSs, while GBSs serve common users. This strategic linkage, a crucial part of our network's operational framework, optimises connectivity based on user needs and locations.

The network's communication operates in two distinct phases: the front-haul, involving direct links between user devices and UAV-BSs or GBSs, and the backhaul, where UAV-BSs relay data to GBSs. The distance between a user device and a base station, a key factor for signal propagation and path loss calculation, is denoted as $d_{i,j}$ and is calculated using the Euclidean formula. The Euclidean distance between a user device i and a base station j is denoted by $d_{i,j}$ and is a vital factor for calculating signal propagation and path loss:

$$d_{i,j} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2}. \quad (1)$$

2.1 Path Loss Models

Adhering to the 3GPP TR 38.901 model [10] for sub-6GHz bands, the path loss between user i and UAV-BS j, designated as L_{ij}, is formulated as:

$$L_{ij} = 32.4 + 20\log_{10}(d_{ij}) + 20\log_{10}(f) + G(z_j - z_i), \quad (2)$$

where d_{ij} is the distance between the user and the UAV-BS, f is the carrier frequency, and $G(z_j - z_i)$ is the height gain factor accounting for the altitude difference between the UAV-BS and the user.

Simultaneously, for UAV-BS i interfacing with a GBS j, the associated path loss L_{ij} is:

$$L_{ij} = 32.4 + 20\log_{10}(d_{ij}) + 20\log_{10}(f) + \alpha, \tag{3}$$

with d_{ij} as the distance between the UAV-BS and the GBS, and α representing additional attenuation factors specific to the UAV-BS link. These factors include atmospheric absorption and additional losses due to the UAV-BS operational environment.

Turning our focus to the GBS-user link, the path loss L_{ij} is articulated as:

$$L_{ij} = 128.1 + 37.6\log_{10}(d_{ij}). \tag{4}$$

where d_{ij} is the distance between the user and the GBS.

2.2 Signal-to-Noise Ratio (SNR)

The Signal-to-Noise Ratio (SNR) governs the quality of the established communication link. The SNR for both UAV-BS-to-user and GBS-to-user links is calculated using the same formula, ensuring a uniform approach to assessing communication quality across the network. For a communication link between a user i and either a UAV-BS j or a GBS, the SNR, denoted as γ_{ij}, is computed as:

$$\gamma_{ij} = \frac{P_{ij}G_{ij}}{\sigma^2 L_{ij}}. \tag{5}$$

In this equation, P_{ij} represents the transmit power from the BS (either UAV-BS or GBS) to the user, G_{ij} denotes the channel gain, σ^2 is the noise power, and L_{ij} signifies the path loss, which is determined by the specific link type (UAV-BS to user or GBS to user).

2.3 Achievable Data Rate

The achievable data rate, a crucial metric in communication systems, measures the maximum data transmitted over a network within a specific time frame. The data rate for a user linked to either a UAV-BS or a GBS is derived from the SNR values using the formula:

$$D_i = B\log_2(1+\gamma). \tag{6}$$

In this expression, D_i is the data rate for user i, and B is the channel bandwidth, representing the frequency range available for communication. The γ term denotes the SNR, a key link quality indicator that influences data rate. Depending on the user's connection to a UAV-BS or GBS, γ is represented as γ_{ij}. The SNR's role is critical in determining the communication link's effectiveness and the achievable data rate.

3 Problem Formulation

In addressing the challenge of optimally positioning a fleet of UAV-BSs, our focus is maximizing the SNR for ground communication systems and effectively managing the energy aspects of these UAV-BSs. The objective is to strategically position UAV-BSs in three-dimensional space to enhance the quality of communication for ground users and ensure the operational sustainability of the UAV-BS fleet through efficient energy management strategies.

3.1 Objective Function

Our objective is to compute the optimal 3D coordinates for each UAV-BS to maximize the collective SNR for all users:

$$\max_{\mathbf{x}_j,\mathbf{y}_j,\mathbf{z}_j} \sum_{u\in\mathcal{U}} \gamma_{ij}, \tag{7}$$

where γ_{ij} represents the SNR between UAV-BS j and user i, and $(\mathbf{x}_j,\mathbf{y}_j,\mathbf{z}_j)$ indicates the position of the UAV-BS.

3.2 Constraints

The placement of UAV-BSs is subject to several constraints:

- The UAV-BSs must remain within a predefined geofenced region:

$$x_{v_{\min}} \leq x_v \leq x_{v_{\max}},$$

$$y_{v_{\min}} \leq y_v \leq y_{v_{\max}},$$

$$z_{v_{\min}} \leq z_v \leq z_{v_{\max}}.$$

- The UAV-BSs must comply with altitude regulations:

$$z_{\min} \leq z_v \leq z_{\max}.$$

- The transmit power and antenna gains must be within the UAV-BSs' and users' capabilities:

$$P_{uv_{\min}} \leq P_{uv} \leq P_{uv_{\max}},$$

$$G_{uv_{\min}} \leq G_{uv} \leq G_{uv_{\max}}.$$

3.3 Energy Management

The UAVs are equipped with energy-harvesting technologies crucial for their prolonged operation. The equation represents the energy balance for a UAV-BS:

$$E(t) = E_0 + \int_0^t (P_{in}(t') - P_{out}(t'))\, dt'. \tag{8}$$

where $E(t)$ denotes the available energy at time t, E_0 is the initial energy level, $P_{in}(t')$ represents the power input from recharging technologies, and $P_{out}(t')$ indicates the power consumption of the UAV-BS operations [11].

In managing the energy consumption of UAV-BSs, our approach goes beyond mere charging. We employ a comprehensive energy management strategy encompassing energy harvesting technologies, efficient operational power usage, and strategic recharging planning. This approach ensures that the UAV-BSs maintain an optimal energy balance, enabling them to stay operational for extended periods while providing uninterrupted service.

4 Bayesian Optimization for UAV Positioning in Urban Landscapes

In urban environments, optimizing the positioning of UAV-BSs is crucial for enhancing SNR and managing energy efficiency. Our approach employs BO integrated with GPs to model and optimize this relationship effectively. The primary objective is to iteratively fine-tune UAV-BS positions to balance immediate SNR improvements and long-term operational sustainability, focusing particularly on energy consumption and recharging.

BO, a robust technique for optimizing complex functions, is adept at handling the challenging nature of UAV-BS positioning in urban settings. In this context, BO [12] utilizes GPs to model the SNR as a function of UAV-BS locations and the associated energy consumption. This dual modelling captures urban wireless networks' intricate dynamics, where communication quality and energy efficiency are paramount.

The SNR and energy consumption at a given UAV-BS position (x_j, y_j, z_j) are represented by functions $f(x_j, y_j, z_j)$ and $e(x_j, y_j, z_j)$, respectively. These functions are modeled using GPs with designated mean functions $\mu_f(x)$, $\mu_e(x)$ and covariance functions $k_f(x,x')$, $k_e(x,x')$.

An extended acquisition function is formulated to balance these two critical aspects:

$$\alpha'(x) = w_1 \cdot EI_{SNR}(x) - w_2 \cdot EI_{energy}(x). \tag{9}$$

Here, w_1 and w_2 are the weights balancing the trade-off between maximizing SNR and minimizing energy consumption.

The optimization process iterates by predicting SNR and energy consumption for potential UAV-BS positions, evaluating the acquisition function to identify the optimal position, and deploying the UAV-BS. The actual SNR and energy consumption measurements update the GP model, continuously refining our understanding and predictions.

The process concludes when predefined criteria are met, incorporating energy considerations such as remaining battery life or specific energy consumption thresholds alongside the SNR targets. This comprehensive approach ensures that UAV-BSs are optimally positioned for communication efficacy and operate within sustainable energy parameters, addressing the unique challenges of urban wireless networks.

Algorithm 1 Bayesian Optimization for UAV Positioning with Energy Consideration

```
• Initial data $D = \{(x_1, y_1, z_1, f_1, e_1), \ldots, (x_n, y_n, z_n, f_n, e_n)\}$
• Optimal UAV position $(x^*, y^*, z^*)$
• Initialize GP with $D$
• For $t = 1$ to $T$:
    • Predict the mean $\mu$ and variance $\sigma^2$ of the SNR and energy consumption over the region using GP.
    • Compute extended acquisition function $\alpha'(x,y,z) = w_1 \cdot EI_{SNR}(x,y,z) - w_2 \cdot EI_{energy}(x,y,z)$.
    • $(x_t, y_t, z_t) \leftarrow \text{argmax } \alpha'$ over the region.
    • Deploy UAV to $(x_t, y_t, z_t)$ and observe actual SNR and energy consumption, $f_t, e_t$.
    • Update $D$ with $D = D \cup \{(x_t, y_t, z_t, f_t, e_t)\}$
    • Update the GP with $D$.
• return $(x^*, y^*, z^*)$ where $(x^*, y^*, z^*)$ optimizes $f$ and $e$ in $D$
```

5 Recharging Strategy

Densely populated urban environments, particularly those in India and China, pose unique challenges for wireless communication, especially for UAV-BSs. The high concentration of buildings in these regions often obstructs line-of-sight signals, which are crucial for stable connectivity. The diverse topography and architectural features provide obstacles and opportunities for UAV-BS deployment and recharging. Moreover, cities in these countries, characterized by high user density and network congestion, demand adaptive network management strategies.

Addressing the significant challenge of limited UAV-BS battery life [13], our approach leverages existing urban structures, such as balconies and transformer lines, for efficient UAV-BS recharging, turning these infrastructural characteristics into strategic advantages for maintaining continuous UAV-BS operations.

A key component of our recharging strategy involves the utilization of customized balconies as wireless charging stations. In our UAV-BS model for urban areas in India and China, UAVs primarily hover to provide optimal connectivity to users. When recharging is required, they autonomously navigate to the nearest balcony equipped with a wireless charging station. This approach minimizes network disruption by eliminating the need for UAV-BSs to land for recharging, ensuring continuous coverage and service provision.

5.1 Customized Balconies as Recharging Points

A key component of our recharging strategy involves the utilization of customized balconies as wireless charging stations. In our UAV-BS model for urban areas in India and China, UAVs primarily hover to provide optimal connectivity to users. When recharging is required, they autonomously navigate to the nearest balcony equipped with a wireless charging station. This approach minimizes network disruption by eliminating the need for UAV-BSs to land for recharging, ensuring continuous coverage and service provision.

Advantages

- Location Diversity: Balconies, abundant in urban areas, provide multiple docking points across various locations.
- Safety: Elevating the docking station reduces the risk of theft or vandalism.
- Ease of Retrofit: Minimal modifications are needed to install recharging pads on balconies.

Implementation Operators can collaborate with building owners or residents to lease balcony spaces. The selected balconies can then be equipped with:

- Wireless Charging Pads: Minimizing physical connection requirements.
- Weatherproofing: Ensuring the charging dock remains operational regardless of weather conditions.
- Secure Locking Mechanisms: To securely dock the UAV-BSs and protect against potential theft.

Operational Considerations

- Regulatory Alignment and Safety Compliance: Installations must strictly adhere to local electrical and aviation safety regulations. This includes implementing rigorous safety measures, such as regular maintenance and using weatherproof materials to handle the variability of outdoor conditions.
- Strategic Charging Scheduling: Develop an intelligent scheduling system that directs UAV-BSs to docking stations based on optimal times for energy consumption and minimal disturbance to residents. This system would consider the UAV-BS battery life and peak electricity demand times to enhance operational efficiency and community harmony.

5.2 Transformer Lines for High-Capacity Charging

Transformer lines, a fundamental component of urban electrical infrastructure, present a unique opportunity for high-capacity charging solutions, especially in densely populated areas of India and China. These lines, commonly routed close to or alongside buildings, offer accessible points for innovative power applications. We can create efficient charging stations for UAV-BSs by utilising these transformer lines. The proximity of these lines to urban structures makes them ideal for establishing high-capacity charging points, providing a continuous and reliable power source for UAV-BSs. This integration into the existing power network is a strategic approach to enhance the operational endurance of UAV-BSs, which is crucial for maintaining uninterrupted wireless communications in complex urban environments.

Advantages

- High-Power Charging: Direct access to the power grid ensures UAV-BSs get recharged faster.
- Scalability: Multiple UAV-BSs can be charged simultaneously, making them suitable for large fleet operators.

Implementation An elaborate setup is necessary to ensure safety and efficiency:

- Isolation Transformers: These can protect the UAV-BSs from power surges.
- Smart Grid Integration: Enables operators to tap into the grid during off-peak hours, ensuring cost-effectiveness.
- Automated Scheduling System: For operators to efficiently manage the recharging of multiple UAV-BSs based on battery levels, priority tasks, and grid load.

Operational Considerations

- Dynamic Charging Management: Operators can deploy software solutions to dynamically direct UAV-BSs to the nearest available charging point, considering the current battery status, operational urgency, and grid load.
- Safety and Regulatory Concerns: Due to the potential hazards associated with electricity, especially in high-density urban settings, all installations must adhere strictly to safety regulations. Regular maintenance and inspections are vital.

5.3 Telecommunication Base Station Integration

Due to the mobile connectivity boom, India and China's ubiquitous telecommunications towers and base stations are prime candidates for integrating UAV-BS charging systems. Their strategic location, elevation, and existing electrical infrastructure make them ideal.

Advantages

- Elevated Positioning: Ensures UAV-BSs are away from pedestrian traffic and reduces chances of mishaps.
- Existing Infrastructure: Power systems already in place can be co-utilized, reducing implementation costs.
- Coverage: Given the widespread distribution of telecom towers, they offer vast geographical coverage.

Implementation Utilizing base station equipment for UAV-BS recharging requires:

- Charging Pads: UAV-BS compatible charging pads are installed at base stations.
- Dual-Purpose Antenna Structures: Redesign or modify antenna supporting structures to include docking platforms.
- Power Management Systems: Integrated systems that can alternate or prioritize between telecom equipment and UAV-BS charging based on demand.

Operational Considerations

- Scheduling and Prioritization: With a diverse array of charging options, UAV-BSs, guided by an intelligent management system, should select optimal recharging locations based on urgency, proximity, and power availability.
- Safety and Compliance: Charging integration, especially at telecommunication base stations, necessitates adherence to strict safety and electromagnetic interference regulations. Ensuring UAV-BS operations do not interfere with telecommunication signals is paramount.

6 Simulation Results and Discussions

The simulation environment was developed in Python, utilizing scientific libraries such as `numpy` for array operations, `matplotlib` for data visualization, and `scipy.optimize` for numerical optimization. The spatial variations in signal transmission were modelled using `GaussianProcessRegressor` from `sklearn.gaussian_process` with a `Matern` kernel, while the `BayesianOptimization` package optimized UAV placement. Details on library versions and computing environment specifics are outlined to ensure reproducibility. The parameters set for the simulation are displayed in Table 1.

Table 1. Simulation Parameters

Parameter	**Value**	**Description**
Area	500m × 500m	Square area for simulation
f_t (Hz)	3.5×10^9	The carrier frequency (3.5 GHz for 5G sub-6GHz) both GBS and UAV-BS
$U1$	100	Number of Common Users
$V1$	50	Number of Customized Users
$S1$	50	Number of Sports Users
p_t (dBm)	20	Transmit power for the GBS and UAV-BS
σ^2 (dBm)	-94	Noise power for the GBS and UAV-BS
σ_{shadow} (dB)	8	Shadowing standard deviation
init_points	5	Number of initial random points
n_iter	100	Number of optimization iterations
N	1	Number of UAV-BS
N	1	Number of GBS
h (m)	20 to 80	Altitude of the UAV-BS
$h1$ (m)	1.5	Altitude of the Mobile Users
$h1$ (m)	30	Altitude of the GBS
BW (Hz)	100×10^6	Total bandwidth of the System

User distribution, including Customized users and sports enthusiasts, was implemented using a uniform random distribution method across the simulation area. The UAV-BS and BS placement followed the BO algorithm in Section 4, which was designed to maximize coverage and UAV energy efficiency.

The path loss was calculated using the specified version of the 3GPP TR 38.901 model [14] for 5G Sub-6GHz bands, incorporating frequency, distance, and height variables. Shadowing was modelled using a log-normal distribution in line with urban environmental conditions. SNR for each user group was computed considering path loss, transmit power, antenna gain, and noise power, with values presented in dB for clarity.

The SNR, a crucial determinant of user experience in UAV-enabled communication networks, is quantified using CDF plots in Fig. 2, highlighting the service quality by depicting probable SNR levels for users.

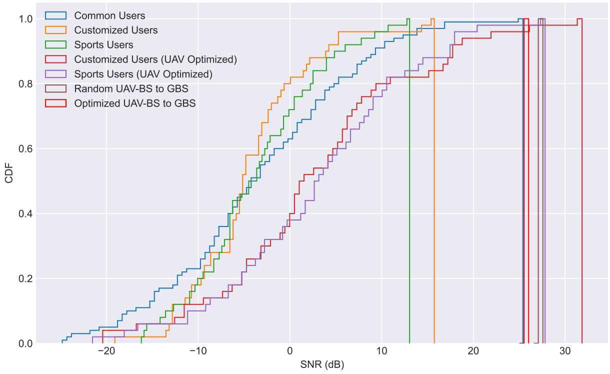

Fig. 2. CDF of SNR for Normal scenario.

UAV-BSs are strategically positioned through BO, maximizing coverage while conserving energy. This optimization, reflected in Fig. 3, prolongs the UAV-BS operational period before the need for recharging and underlines the enhanced communication quality by comparing the SNR distributions across standard and optimized deployments.

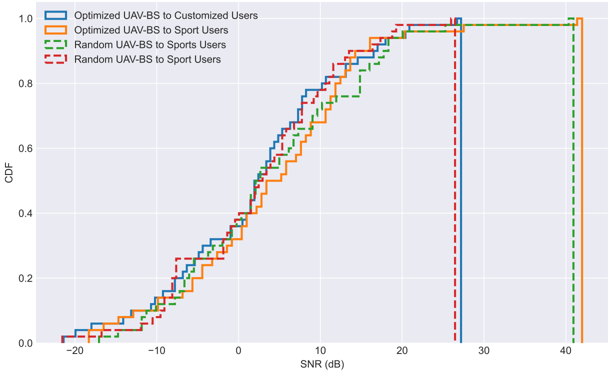

Fig. 3. CDF of SNR for Optimized Scenario.

By balancing coverage with energy constraints, UAV-BS positioning was refined using BO, incorporating GP. This approach strategically determined the UAV locations that maximize service duration before recharging, as evidenced by the distribution plots in Fig. 4.

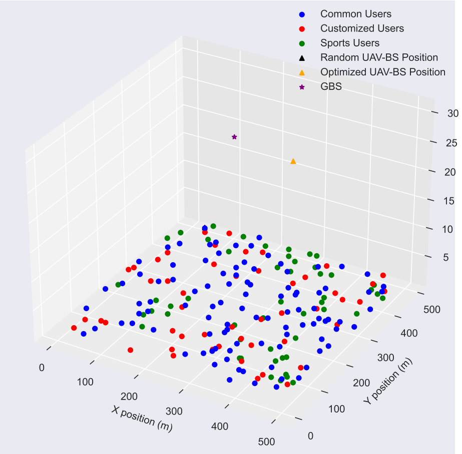

Fig. 4. 3D Scatter plot of user distribution and Optimized UAV-BS placement.

At an optimal 20-meter altitude, UAV-BSs maintained operational status for approximately 48 minutes at this altitude, a finding depicted in Fig. 5. The same figure also highlights the SNR disparities between Customized and sports user groups, validating the positioning strategy's success in prioritizing high-importance communication channels.

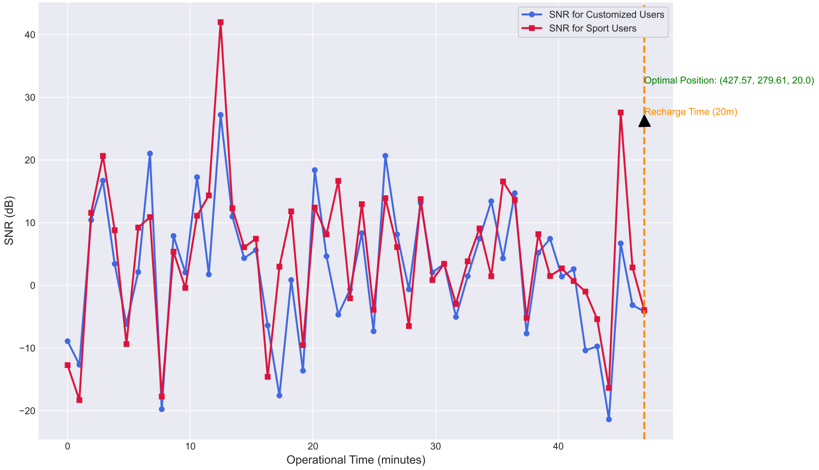

Fig. 5. SNR comparison for Customized versus sports users over operational time before UAV-BS recharge.

The comparative analysis of SNR among different user groups further indicates that UAV-BS-based systems offer a notable advantage over conventional fixed base stations. This is primarily due to their direct line-of-sight connectivity, which mitigates path loss and fortifies signal integrity. Despite the limitations imposed by current battery technologies, the need for early recharge highlights the scope for innovative power solutions to extend UAV operational periods. Maintaining adequate SNR levels until recharge indicates operational efficiency and the potential for expanding operational limits with advancements in energy harvesting techniques.

The trade-off between coverage span and recharge frequency has been managed effectively, with BO proving to be a powerful tool in sustaining service quality. This is particularly relevant in urban and emergency response scenarios, where the expeditious and reliable deployment of communication services is critical. The insights gained from this study have significant implications for the strategic employment of UAV-BSs in future wireless communication infrastructures.

7 Conclusions and Future Work

This study has explored the deployment of UAV-BSs as dynamic relays in urban settings, emphasizing their role in enhancing wireless connectivity, particularly in densely populated areas and during special events. A significant focus was placed on using Bayesian Optimization (BO) for optimal positioning of UAV-BSs. Our findings suggest that BO offers a superior approach in this context due to its efficiency in managing complex, dynamic environments and its ability to achieve optimal solutions with fewer iterations than other optimization techniques. This aspect is critical in urban scenarios where environmental variables and user demands constantly change. Introducing urban recharging is a promising step towards overcoming the energy constraints of UAV-BSs.

Our future work will refine the UAV-based communication system to adapt to dynamic urban environments. Real-time positioning adjustments using advanced algorithms will be explored to cater to changing user demands. Machine learning models will be investigated to predict and optimize energy consumption and recharging cycles. The feasibility of alternative energy sources, like solar power, will be examined to extend UAV-BS operational times further. Field trials will be conducted to validate the proposed system in real-world scenarios, ensuring that the enhanced model is not only theoretically sound but also practically viable.

Bibliography

[1] Dayal, S.: Online education and its effect on teachers during COVID-19—A case study from India. In: PLoS ONE. vol. 18, no. 3, e0282287. Public Library of Science, San Francisco, CA, USA (2023).

[2] Barden, L.: Chess world champion Ding Liren back in action in Wenzhou after long absence. The Guardian, [Online; accessed 7 November 2023]. Available at: `https://www.theguardian.com/sport/2023/sep/22//chess-world-champion-ding-liren-back-in-//action-in-wenzhou-after-long-absence`

[3] Naik, S.: Team captain Vidit Gujrathi looks back at India's dramatic shared title at the Online Chess Olympiad. Indian Express. [Online] Available: `https://indianexpress.com/article/sports/che//ss/team-captain-vidit-gujrathi-indias-dramatic-//shared-title-online-chess-olympiad-6582088/`. Accessed on: November 7, 2023.

[4] Zhu, Q., Zheng, J., Jamalipour, A.: Coverage Performance Analysis of a Cache-Enabled UAV Base Station Assisted Cellular Network. IEEE Trans. Wirel. Commun. (2023)

[5] Mohsan, S.A.H., Khan, M.A., Noor, F., Ullah, I., Alsharif, M.H.: Towards the unmanned aerial vehicles (UAVs): A comprehensive review. Drones **6**(6), 147 (2022)

[6] Tafintsev, N., Moltchanov, D., Chiumento, A., Valkama, M., Andreev, S.: Airborne Integrated Access and Backhaul Systems: Learning-Aided Modeling and Optimization. IEEE Trans. Veh. Technol. pp. 1–14 (2023). `https://doi.org/10.1109/TVT.2023.3293171`

[7] Kirubakaran, B., Hosek, J.: Optimizing Tethered UAV Deployment for On-Demand Connectivity in Disaster Scenarios. In: Proceedings of the IEEE 97th Vehicular Technology Conference (VTC2023-Spring), pp. 1–6. IEEE (2023). `https://doi.org/10.1109/VTC2023-Spring57618.2023.10199492`

[8] Benzaghta, M., Geraci, G., Lopez-Perez, D., Valcarce, A.: Designing Cellular Networks for UAV Corridors via Bayesian Optimization. arXiv preprint arXiv:2308.05052 (2023)

[9] Matracia, M., Kishk, M.A., Alouini, M.-S.: UAV-Aided Post-Disaster Cellular Networks: A Novel Stochastic Geometry Approach. IEEE Trans. Veh. Technol. (2023)

[10] Jia, X., Liu, P., Qi, W., Liu, S., Huang, Y., Zheng, W., Pan, M., You, X.: Link-level simulator for 5G localization. IEEE Trans. Wireless Commun. (2023)

[11] Zeng, Y., Guvenc, I., Zhang, R., Geraci, G., Matolak, D.W.: UAV Communications for 5G and Beyond. John Wiley & Sons (2020)

[12] Garnett, R.: Bayesian optimization. Cambridge University Press (2023)

[13] B. Kirubakaran and J. Hosek, ”Extending UAV's Operational Time through Laser Beam Charging: System Model Analysis,” in *2022 45th International Conference on Telecommunications and Signal Processing (TSP)*, 2022, pp. 322–328, doi: 10.1109/TSP55681.2022.9851242.

[14] Q. Zhu, X. Wang, B. Hua, K. Mao, S. Jiang, and M. Yao, “3GPP TR 38.901 Channel Model,” *1-35*, 2020. [Online]. Available: `https://doi.org/10.1002/9781119471509.w5GRef048`.