Scilab Case Study Project on Unmanned Aerial Vehicle (UAV) - Based Wireless Communication System

Deepan Nagarajan

Government Polytechnic College, Srirangam, Tamilnadu

Wireless Communication System

February 2025

Abstract

The use of flying platforms, such as unmanned aerial vehicles (UAVs), commonly known as drones, is becoming increasingly attractive. With their unique features, including mobility and adjustable altitude, UAVs offer numerous promising applications in modern wireless communication systems. These applications include military, agriculture, cargo delivery, surveillance, monitoring, and search and res- cue operations. Additionally, UAVs can function as flying mobile terminals within cellular networks to improve coverage, capacity, reliability, and energy efficiency. This study aims to evaluate the performance of UAV-based wireless communication systems, focusing on key metrics such as power loss, coverage probability, energy efficiency, and the optimization of UAV height. The study employs a unified mathematical model to analyze the trade-offs between UAV altitude, coverage, and energy consumption. Using SCILAB, simulations are conducted to visualize the relationship between UAV altitude and energy efficiency, providing insights into optimal UAV deployment strategies. The results demonstrate that an optimal altitude exists for maximizing coverage probability and energy efficiency, which varies depending on the coverage area and environmental conditions. The outcomes of this study will

provide valuable guidelines for analyzing, optimizing, and designing UAV-based wireless communication systems.

Index terms: Unmanned aerial vehicle (UAV), Coverage, UAV placement, Power loss, and Energy efficiency.

1 Introduction

A UAV, or Unmanned Aerial Vehicle, in the context of wireless communication, refers to a drone or aircraft that operates without a human pilot onboard and is used to enhance or facilitate wireless communication networks. The integration of UAVs into wireless communication systems is gaining attraction due to their ability to provide flexible, on-demand connectivity. UAVs are particularly useful in scenarios where traditional infrastructure is either unavailable or impractical, such as in rural areas, disaster zones, or during large-scale events. With the advent of 5G and the Internet of Things (IoT), UAVs are expected to play a pivotal role in enabling seamless connectivity for a wide range of applications, including smart cities, precision agriculture, and autonomous vehicles. However, the deployment of UAVs in wireless networks introduces several challenges, such as optimizing energy consumption, managing interference, and ensuring reliable communication in dynamic environments. This study addresses these challenges by focusing on the relationship between UAV altitude and energy efficiency, pro- viding a framework for optimizing UAV deployment in various scenarios.

2 Problem Statement

UAVs deployed for wireless communication face a fundamental trade-off between coverage and energy consumption. At lower altitudes, UAVs can achieve stronger signal strength due to reduced path loss, but this comes at the cost of limited coverage and increased interference from ground obstacles. Conversely, higher altitudes provide broader coverage but suffer from increased path loss, leading to reduced signal quality and higher energy consumption. This trade-off necessitates a careful balance between altitude, coverage, and energy efficiency. Additionally, environmental factors such as urban density, terrain, and weather conditions further complicate UAV deployment. This study aims to address these challenges by determining the optimal UAV altitude that maximizes energy efficiency while maintaining adequate coverage and throughput. The findings will provide valuable insights for network operators seeking to deploy UAVs in diverse environments.

3 System Model

Consider a UAV communications system as shown in Figure. 1. The ground user is located in a circle with radius r and angle α in polar coordinates. The drone is fixed on top of the center of the circle with an altitude of h. The radio signals emitted by a UAV base station propagate in free space until reaching the urban environment where they incur shadowing and scattering caused by the man-made structures, introducing additional loss in the air-to-ground link. We refer to the additive loss incurred on top of the free space path loss as an excessive pathloss. The respective path loss calculation will be discussed in the next section.

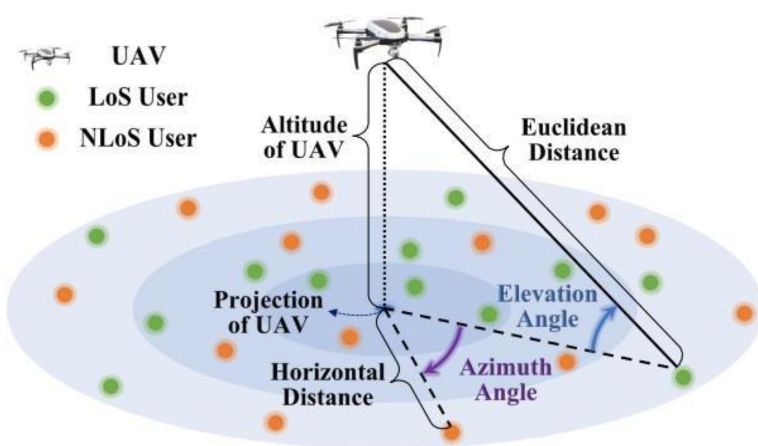

Figure 1: UAV Network Model

3.1 Air-to-Ground Pathloss Model

This section describes the UAV-associated path loss calculations. The path loss for UAV communication depends on the type of environment and the line-of- sight (LoS) probability. To precisely model the propagation conditions for UAV- assisted communication, we have adopted the path-loss model presented in [3], which can be expressed as

$$\mathrm{PL(d)} = \mathrm{P_{LoS} PL_{LoS}} + \mathrm{P_{NLoS} PL_{NLoS}}$$

P_{LOS} and $P_{NLOS} = 1 - P_{LOS}$ are the line-of-sight and non line-of-sight probabilities. PL_{LoS} and PL_{NLoS} are the pathloss respectively. Further, the P_{LOS} can be expressed as

$$P_{LOS} = \frac{1}{1 + \alpha \exp\left(-\beta \left[\frac{180}{\pi} \theta - \alpha\right]\right)},$$

Alternatively the end-to-end path loss can be given as [4]

$$PLd = \frac{A}{1 + \alpha \exp\left(-\beta \left[\frac{180}{\pi} \theta - \alpha\right]\right)} + B$$

where $A = \eta_{LoS} - \eta_{NLoS}$, $B = 20 \log(\frac{d_k 4\pi f_c}{c}) + \eta_{NLoS}$, in which f_c is the carrier frequency, c is the speed of light. The values of α and β are constants that vary depending on the environment, such as rural, suburban, or urban dense areas. Moreover, η_{LoS} and η_{NLoS} are the additional path loss related to environment.

3.2 Coverage Analysis

Coverage analysis of UAV communication is a key aspect of designing efficient and reliable UAV communication systems. It involves evaluating the signal strength and quality of service (QoS) at different locations within the coverage area.

3.2.1 Coverage Area Calculation

When the UAV is at a fixed altitude h and its communication radius is defined, the coverage area is the circular projection of its range onto the ground. The area of the circle is given by

$$A_{Cov} = \pi R^2$$

where, R is the horizontal coverage radius.

Key Parameters for Coverage Analysis:

- UAV Altitude (Height): The altitude of the UAV significantly affects its coverage area and signal quality. Optimal altitude must balance:

  i. Larger coverage at higher altitudes.

  ii. Better signal strength at lower altitudes.

- Transmission Power: Higher transmission power increases coverage but may cause interference and drain energy.

- Environment Type: Coverage varies in rural, urban, or suburban environments due to path loss and obstructions.

3.2.2 Coverage Probability

Coverage probability in UAV networks refers to the probability that a user in the coverage area of a UAV can achieve a signal-to-noise ratio (SNR) above a certain threshold. It depends on factors such as the UAV's height, user distribution, channel conditions, and the network model.

Mathematical Expression:

$$P_{cov} = P(\gamma > \gamma_{th})$$

where, γ is the received SNR, and γ_{th} is the thershold SNR.

3.3 Throughput Analysis:

Throughput is a key performance metric in wireless communication that measures the rate at which data is successfully transmitted from a sender to a receiver over a given time period. It is usually expressed in bits per second (bps), kilobits per second (kbps), or megabits per second (Mbps). Mathematically, throughput (T) is defined as,

$$T = B \log 2 \left(1 + \frac{SNR}{N_0 B}\right)$$

where, B is bandwidth (Hz), N_0 is noise power spectral density (W/Hz).

3.4 Energy Efficiency Analysis:

Energy efficiency (EE) in UAV-based wireless communication is a critical metric that measures how effectively energy is utilized for data transmission. Since UAVs have limited onboard energy, optimizing energy consumption is crucial for extending flight time and ensuring reliable communication. It is defined as the amount of successfully transmitted data per unit of energy consumed.

$$EE = \frac{T}{P_{total}}$$

where, T is throughput defined in (6), P_{total} is the total power consumption (W)

4 Flowchart


Start
Define System Parameters
Generate Random User Positions
For each altitude
Calculate Path Loss
Calculate Coverage Probability
Calculate Throughput
Calculate Energy Efficiency
Plot the Results
End

5 Software used

Operating system: Windows 10

Scilab Version: Scilab 2025.0.0 (64-bit)

Toolbox: Nil

6 Procedure of Execution:

In this case study, we simulate key performance metrics of a wireless network, including user distribution, coverage probability, and energy efficiency. A total of six plots are generated using Scilab, each illustrating different aspects of the system.

To generate the plots, follow these steps in **Scilab**

- **Step 1:** Launch **Scilab** on your computer and open **SciNotes** (the built-in editor).

- **Step 2:** Load the simulation scripts of your choice named

  – “Fig_2_user_distribution_3D.sci”, (3D visualization of user locations)

  – “Fig_3_distribution_covered.sci”, (covered vs. uncovered users)

  – “Fig_4_Power_Loss.sci”, (signal power loss over distance)

  – “Fig_5_coverage_probability. sci”, (coverage vs. transmit power)

  – “Fig_6_data_rate. sci”, (For achievable data rates)

  – “Fig_7_energy efficiency. sci”. (energy efficiency analysis)

- **Step 3:** Run the code.

- **Step 4:** Observe the result. Each plot will display the simulated behavior. To test different scenarios, modify the system parameters (e.g., transmit power, user density) in the respective “sci” file before re-running.

7 Simulation Results and Discussion

In this section, a numerical simulation results obtained using SCILAB is presented. A 3-Dimensional location of the UAV and the ground wireless users are illustrated in Figure.2, where a group of 50 users is randomly deployed in the circular coverage area. Meanwhile, the location of the UAV on top of the user location with respect to height, h.

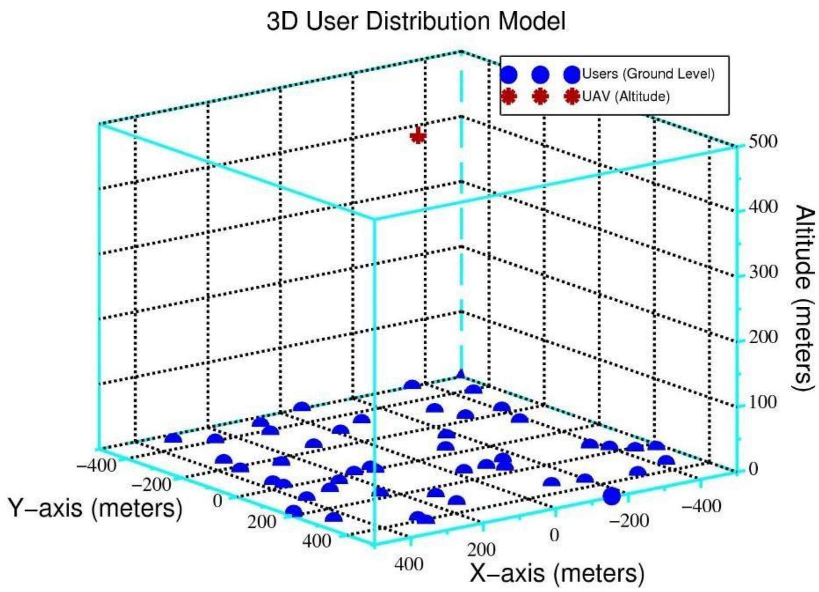

Figure 2: 3-Dimensional user distribution model and the UAV

Figure 3 plot represents a UAV Coverage Simulation, illustrating how a UAV provides communication coverage to ground users at an altitude of 100 meters. The plot ranges from -120 m to 120 m, indicating a 240 m x 240 m area. The UAV is centrally positioned, and users are randomly distributed around it. The UAV provides coverage to most users, but some remain uncovered due to their distance from the UAV. The elliptical shape suggests path loss variations influencing the coverage range. Adjusting the UAV's altitude or position could improve coverage.

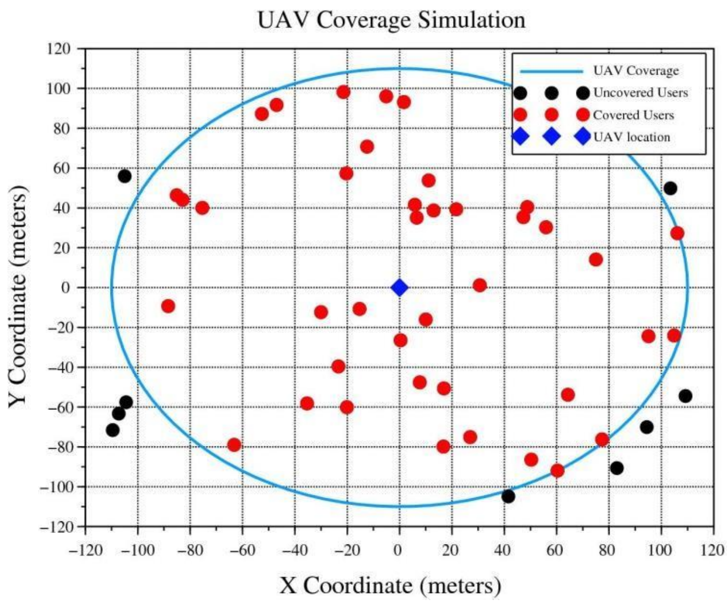

Figure 3: UAV Coverage Area

Figure 4. plot represents the Power Loss vs. UAV altitude relationship for different types of environments: Suburban, Urban, Dense Urban, and Highrise Urban. Initially, in all scenarios, the power loss decreases sharply as altitude increases, later, after reaching a minimum height, the power loss gradually increases. This indicates that low-altitude UAVs face higher interference, while signal propagation is best at an optimal altitude. An optimal UAV altitude exists (200m in suburban, 300-400m in urban areas) where power loss is minimized. dense urban and highrise urban environments have higher power loss due to obstacles and multipath effects. Deploying UAVs too low results in high attenuation, while too high leads to increased free-space path loss.

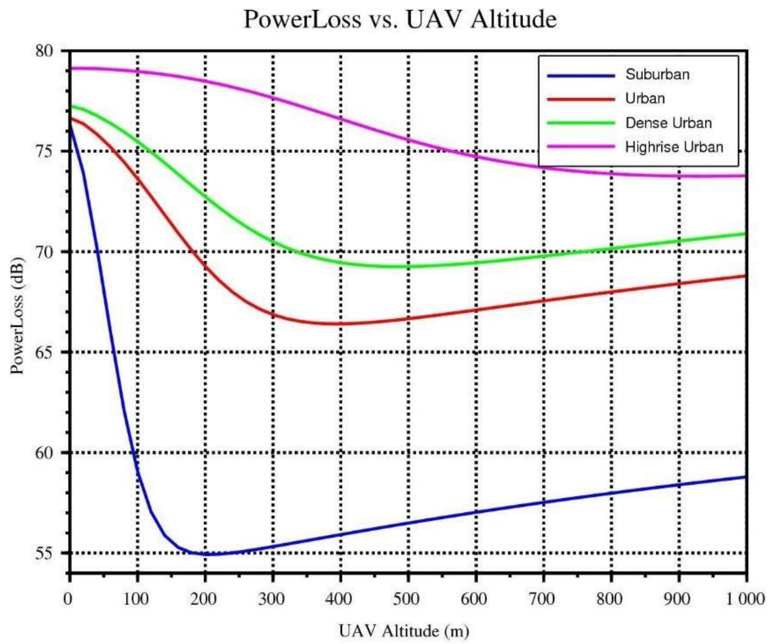

Figure 4: The total power loss vs. the altitude h for static UAV.

Figure 5. plots the coverage probability versus UAV altitude for different coverage area. from the plot it is observed that, for each area, there is a specific UAV height (optimal height) where the coverage probability is maximized. This is because a lower UAV altitude causes limited coverage due to the smaller footprint, while a higher altitude introduces signal degradation due to increased path loss. Further, as the area increases (from 500 to 2000), the maximum achievable coverage probability decreases. This is because covering a larger area requires a higher UAV altitude, which results in increased path loss, reduced received signal strength, and hence lower coverage probability. For very low altitudes,

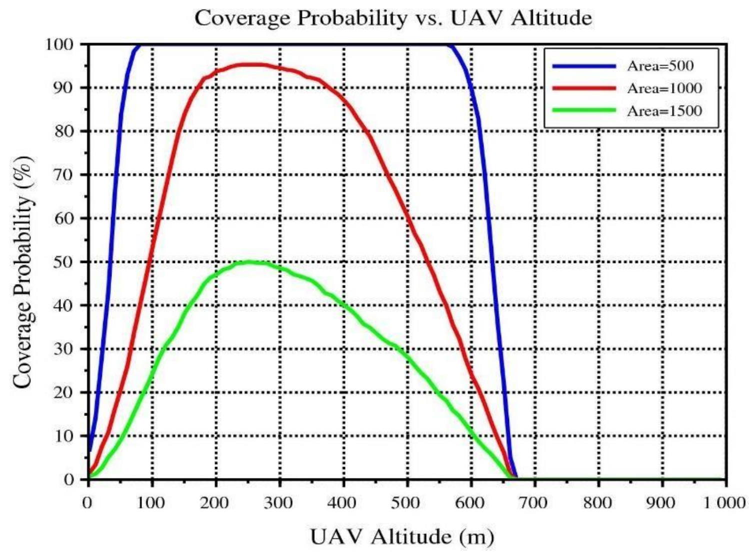

Figure 5: UAV coverage probability versus the altitude h for static UAV.

the coverage probability drops sharply because the UAV cannot cover the area effectively. For very high altitudes, the probability drops due to signal degradation, even though the UAV theoretically has a larger footprint. Hence, there is always a trade-off between UAV altitude and coverage efficiency. Operating at the optimal height for a specific area ensures maximum coverage probability.

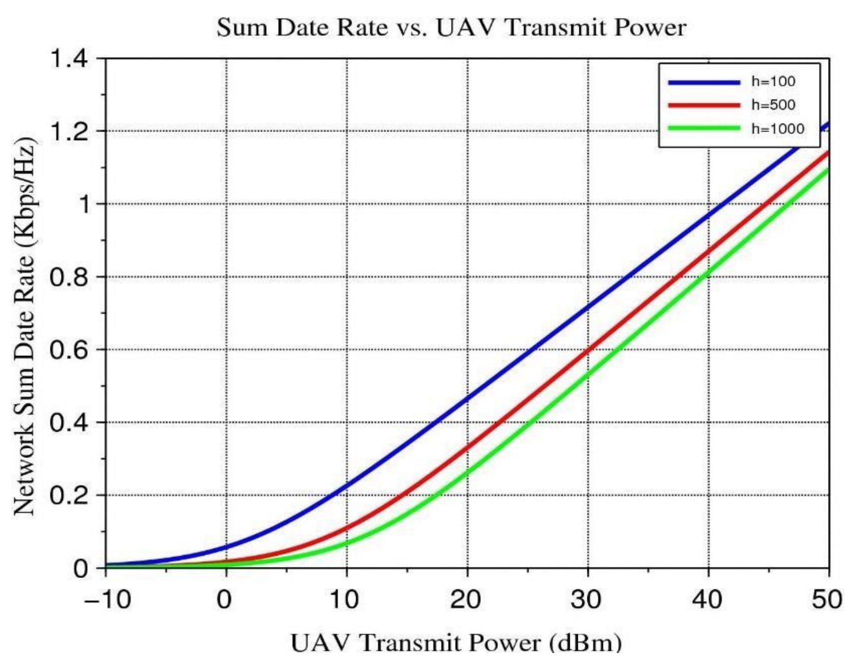

Figure 6: Sum throughput vs the transmit power of the

UAV.

Figure.6 plot represents the data rate vs. UAV transmit Power for different UAV altitudes. It shows how the network sum data rate (throughput) varies as the UAV's transmit power increases. As UAV transmit power increases, the network sum data rate also increases. This is expected since higher power improves signal strength and SINR. At higher altitudes, UAV signals suffer from greater free-space path loss, reducing received power at the users. The reduced SINR (Signal-to-Interference-plus-Noise Ratio) lowers the achievable data rate.

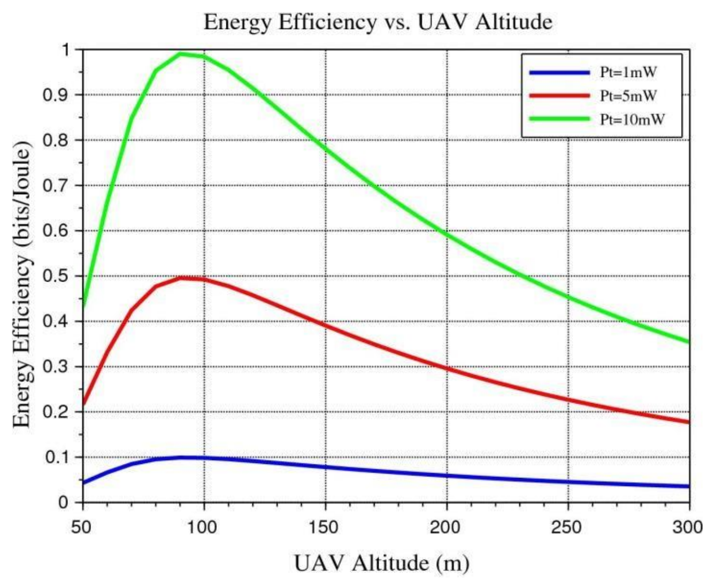

Figure 7: Energy efficiency vs UAV altitude h with different transmit power Pt

Figure 7, plot illustrates how energy efficiency (bits/Joule) varies with UAV altitude for different UAV transmit power levels. For all transmit power levels, energy efficiency first increases as the UAV gains altitude, beyond a certain altitude, efficiency starts decreasing. This is due to the trade-off between signal coverage and increasing path loss. Hence, balancing UAV altitude and transmit power is crucial for maximizing energy efficiency in UAV-based communications.

Conclusion:

This study presents a comprehensive analysis of the impact of UAV altitude on energy efficiency in wireless communication systems. By optimizing the altitude, network operators can enhance system performance while minimizing energy consumption.

8 References

[1] A. Al-Hourani, S. Kandeepan, S. Lardner, Optimal lap altitude for maximum coverage, IEEE Wireless Communications Letters 3 (6) (2014) 569–572.

[2] Y. Chen, W. Feng, G. Zheng, Optimum placement of uav as relays, IEEE Communications Letters 22 (2) (2017) 248–251.

[3] Yang, Shengzhi, Yansha Deng, Xuanxuan Tang, Yuan Ding, and Jianming Zhou. "Energy efficiency optimization for UAV-assisted backscatter communications." IEEE Communications Letters 23, no. 11 (2019): 2041-2045.