

Optimizing Disaster Response with tHAPs: Modeling and Coverage Analysis for Crisis Zones

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Abstract—In the 6G era, aerial base stations will significantly enhance cellular network coverage and capacity. Tethered High Altitude Platforms (tHAPs) present an effective solution to extend coverage in crisis zones, particularly when ground infrastructure is unavailable or damaged. This paper provides a comprehensive modeling and coverage analysis of tHAP systems, incorporating the hovering region, signal propagation based on the Hata model, and detailed link budget analysis for both uplink and downlink scenarios. Key parameters such as tether length, transmit power, antenna gains, and path loss are considered in the model. Simulation results demonstrate how varying tether lengths impact path loss, cell radius, and coverage probability. For example, increasing tether length from 100 m to 250 m at operating frequency of 1 GHz expands coverage but also increases the path loss by 13 dB. We also demonstrate that this increased path loss can be balanced with transmit power i.e., by increasing the transmit power from 43 dBm to 49 dBm improves signal strength by 10 dB. These results indicate that increasing the altitude of the tHAP enhances the coverage area, though it also leads to higher path loss. This trade-off between tether length and path loss is critical for optimizing the deployment of tHAP systems in crisis zones which is the focus of the paper.

Index Terms—Aerial Platforms, Tethering, Modeling, HAP-to-ground communication, Coverage Analysis

I. INTRODUCTION

Airborne base stations are a promising solution for providing wide cellular coverage from high altitudes. They can improve network capacity in remote areas or areas affected by disasters. However, these platforms face challenges due to limited battery life, which limits their flight time. As a result, they need to return to ground stations for recharging. This causes temporary service interruptions and affects the performance of airborne cellular networks [1].

To overcome these limitations, we propose a novel solution utilizing tethered high altitude platforms (tHAPs) for the deployment of cellular networks. Unlike traditional aerial platforms, tHAPs are connected to ground stations via tethers that provide a continuous power supply, enabling prolonged operation that can last for several days without the need for recharging. This stable power source reduces downtime and ensures uninterrupted service. tHAPs are particularly well suited for disaster response scenarios, where they can deliver critical communication services when conventional ground-based infrastructure is compromised or destroyed. In events such as earthquakes, hurricanes, or floods, traditional cellular networks are often severely damaged, leaving affected

areas isolated and hindering emergency response efforts. By providing a flexible, resilient communication solution, tHAPs can restore connectivity in these challenging environments, as summarized in Table I. This paper explores the potential of tHAPs in optimizing wireless communication networks for crisis zones, offering a detailed analysis of their performance, coverage, and impact in urban disaster scenarios.

TABLE I: Advantages of tHAPs for Emergency Communication in Disaster Areas.

Key Advantage	Description
Rapid Deployment	tHAPs can be swiftly deployed, ensuring immediate communication coverage in disaster-affected regions.
Wide Coverage Area	Positioned at high altitudes, tHAPs can provide extensive coverage, including hard-to-reach urban and rural zones.
Continuous Power Supply	The tether provides a constant power source, enabling tHAPs to operate for extended periods without need to recharge.
Reliable Connectivity	tHAPs offer stable, secure backhaul connections to the core network, ensuring uninterrupted critical communications.
Scalable and Flexible	tHAPs can be integrated into existing networks or set up independently, offering adaptability for various deployment scenarios.
Resilient to Ground Disruptions	Even in the event of ground infrastructure failure, tHAPs remain operational, providing continuous communication services.

A. Background and Motivation

Despite the extensive body of research on HAPs [2], [3] and tHAPs [4], several critical areas remain underexplored, particularly in the context of disaster response and recovery. Although existing studies [5], [6] have demonstrated the feasibility and advantages of tHAPs in various communication scenarios, there is a lack of a comprehensive analysis of the trade-offs between the length of the tether, the altitude, and path loss, particularly in urban environments where obstacles can significantly affect signal propagation. Moreover, while the Hata model has been widely used for the prediction of path loss in terrestrial networks, its application in the context of tHAPs has not been thoroughly investigated. Specifically, more detailed studies are needed that incorporate the Hata model into tHAP coverage analysis, particularly in uplink and downlink scenarios. Such studies would provide valuable

information on optimizing tHAP deployments for maximum coverage and reliability. Furthermore, the impact of varying tether lengths on coverage probability and received signal strength, particularly in disaster-stricken areas, has not been adequately addressed in the literature. Understanding these dynamics is crucial for designing tHAP systems that can effectively support emergency communication networks.

This paper aims to fill these research gaps by providing a detailed mathematical analysis of tHAP deployment. It incorporates the Hata model for calculating path loss and looks at how tether length affects coverage area and signal strength. The goal is to help improve tHAP systems for better performance in both urban and disaster-prone areas. The novelty of this research lies in its comprehensive analysis of how tether length, altitude, and path loss affect tHAP performance, especially in crisis zones where ground based infrastructure has been compromised. By applying the Hata model to tHAP scenarios, this study offers new insights into optimizing coverage area by balancing path loss and received signal strength, addressing gaps in current research.

B. Contributions

The key contributions of this paper are:

- 1) A comprehensive mathematical model for tHAPs and ground terminal which includes coverage analysis, path loss calculation, and signal propagation dynamics is developed. Hata model is used for the prediction of path loss in urban and disaster-prone environments, focusing on both uplink and downlink scenarios between ground stations and tHAPs.
- 2) A detailed analysis of the trade-offs between tether length, path loss, and user density is performed providing insights into how these factors affect coverage probability and received signal strength.
- 3) Next, numerical simulations are provided to evaluate the coverage probability, path loss, and received signal strength of tHAPs, specifically examining the impact of varying tether lengths and user density in different operational scenarios.

C. Paper Organization

The rest of the paper is organized as follows. Section II introduces the system model used for analytical and simulation work. The focus of Section III is on the modeling and coverage analysis of tethered aerial platforms. Next, numerical results are discussed in Section IV and conclusions are drawn in Section V.

II. SYSTEM MODEL

In the proposed system, we consider a disaster area A_0 where all terrestrial base stations within this region have failed, leaving the area without any functional communication infrastructure. However, some terrestrial base stations outside this disaster area remain operational and are available for connection. The system model is depicted in Fig. 1. The system consists of three main components: tHAP, the tether,

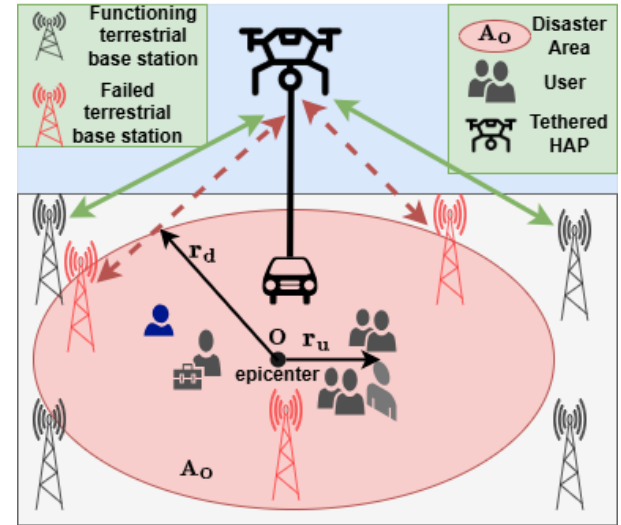


Fig. 1: Modeling and coverage analysis for crisis communication in a disaster area using tHAPs.

and the ground station (GS). Unlike traditional setups, the GS is mounted on a vehicle, allowing for rapid and flexible deployment in disaster scenarios. The GS is strategically positioned to achieve two critical objectives: (i) establishing a reliable connection with the functioning terrestrial base stations outside the disaster area, and (ii) ensuring a stable energy supply via connection to the vehicle's power source, such as a generator or battery system.

The tether, extending from the GS, serves a dual purpose. It provides a continuous power supply to the tHAP, allowing it to maintain extended flight times without the need for frequent landings. Additionally, the tether ensures the tHAP remains within a designated hovering region, defined by a truncated hemisphere with a radius equivalent to the tether length. This region is carefully selected to maximize coverage within the disaster area A_0 . Equipped with antennas and processing units, the tHAP establishes communication links with the functioning base stations outside A_0 and relays signals to the affected users within the disaster zone. The GS is responsible for dynamically managing the tether, adjusting its length as needed to maintain optimal tension and ensure the tHAP remains stable and well-positioned.

III. MODELING AND COVERAGE ANALYSIS

In this section, we develop a mathematical model for the proposed tHAP system's deployment and analyze its coverage capabilities. The analysis includes determining the hovering region of the tHAP, modeling the signal propagation using the Hata model, and performing link budget analysis to calculate the optimum tether length for a given coverage area as depicted in Fig. 2. Coverage area can be expanded by increasing the tether length but it comes at a cost of increased path loss as discussed below.

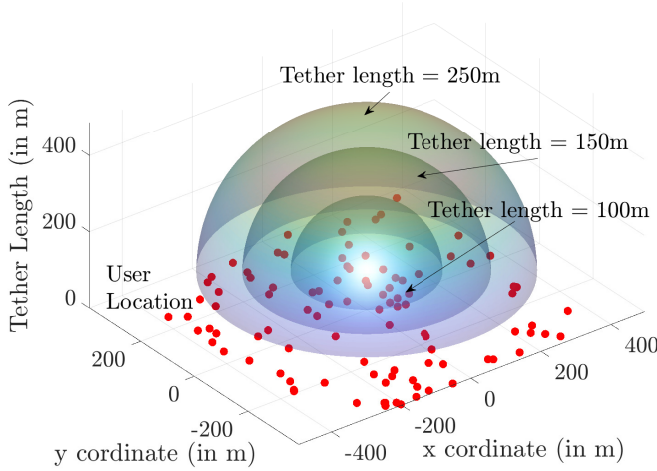


Fig. 2: Tether length versus coverage area.

A. Hovering Region

The hovering region of the tHAP is defined by the length of the tether and the location of the GS. Assuming the GS is positioned at coordinates $(0, 0, 0)$, and the tether length is L , the tHAP can hover within a truncated hemisphere of radius L centered at the GS [7]. The height of the tHAP above the GS is constrained by the heights of surrounding buildings.

The region can be mathematically expressed as [8]:

$$\mathcal{H} = \{(x, y, z) \in \mathbb{R}^3 \mid \sqrt{x^2 + y^2 + z^2} \leq L \text{ and } z \geq 0\} \quad (1)$$

B. Signal Propagation Model using Hata Model

To model the signal propagation from the tHAP to ground mobile station, Hata model is used [9] [10]. The received power P_r at a ground terminal located at $(x, y, 0)$ from the tHAP at (x_t, y_t, z_t) is given by:

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi d} \right)^2 \quad (2)$$

where:

- P_t is the transmitted power from the tHAP.
- G_t and G_r are the antenna gains of the tHAP and the ground mobile station, respectively.
- λ is the wavelength of the signal.
- $d = \sqrt{(x - x_t)^2 + (y - y_t)^2 + z_t^2}$ is the distance between the tHAP and the ground terminal.

The path loss PL in dB is given by [11]

$$PL = 69.55 + 26.16 \log_{10}(f) - 13.82 \log_{10}(h_b) - a(h_m) + (44.9 - 6.55 \log_{10}(h_b)) \log_{10}(d) \quad (3)$$

where:

- f is the frequency.
- h_b is the height of the tHAP antenna in meters.
- h_m is the height of the mobile station antenna in meters.
- d is the distance between the tHAP and the mobile station in kilometers.
- $a(h_m)$ is the correction factor for the mobile station antenna height, which is given by:

$$a(h_m) = (1.1 \log_{10}(f) - 0.7)h_m - (1.56 \log_{10}(f) - 0.8). \quad (4)$$

C. Link Budget Analysis

The link budget accounts for all gains and losses in the signal path, and it is essential for determining the feasibility of the communication link.

1) Uplink (Ground Terminal to tHAP)

The received power $P_{r,up}$ at the tHAP from the ground terminal can be calculated using:

$$P_{r,up} = P_{t,gs} + G_{t,gs} + G_{r,tHAP} - PL_{up} - L_{misc} \quad (5)$$

where:

- $P_{t,gs}$ is the transmit power of the ground station.
- $G_{t,gs}$ and $G_{r,tHAP}$ are the antenna gains of the ground station and the tHAP, respectively.
- PL_{up} is the path loss for the uplink, calculated using the Hata model.
- L_{misc} represents miscellaneous losses including connector losses, fading margin, etc.

2) Downlink (tHAP to Ground Terminal)

Similarly, the received power $P_{r,down}$ at the ground station from the tHAP is given by:

$$P_{r,down} = P_{t,tHAP} + G_{t,tHAP} + G_{r,gs} - PL_{down} - L_{misc} \quad (6)$$

where:

- $P_{t,tHAP}$ is the transmit power of the tHAP.
- $G_{t,tHAP}$ and $G_{r,gs}$ are the antenna gains of the tHAP and the ground terminal, respectively.
- PL_{down} is the path loss for the downlink, also calculated using the Hata model.

Using (5) and (6), received power signal strength in both direction is determined and the lesser of the two is used for determining the coverage probability.

D. Coverage Probability Analysis

The coverage probability is the likelihood that the received signal power exceeds a certain threshold P_{th} . For both uplink and downlink scenarios, this can be expressed as:

$$\mathbb{P}(P_r \geq P_{th}) = \mathbb{P}(P_t + G_t + G_r - PL - L_{misc} \geq P_{th}). \quad (7)$$

Rearranging the terms, the coverage probability can be determined by evaluating the probability that the path loss and other losses do not exceed the difference between transmit power and threshold:

$$\mathbb{P}(PL \leq P_t + G_t + G_r - P_{th} - L_{misc}). \quad (8)$$

Also, using (2) we have,

$$\mathbb{P}(P_r \geq P_{th}) = \mathbb{P}\left(P_t G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2 \geq P_{th}\right). \quad (9)$$

Simplifying the above expression, we get:

$$\mathbb{P}(P_r \geq P_{th}) = \mathbb{P}\left(d \leq \frac{\lambda}{4\pi} \sqrt{\frac{P_t G_t G_r}{P_{th}}}\right). \quad (10)$$

Let the maximum coverage distance i.e. cell radius be d_{max} :

$$d_{max} = \frac{\lambda}{4\pi} \sqrt{\frac{P_t G_t G_r}{P_{th}}}. \quad (11)$$

The coverage probability can then be expressed as the probability that a user lies within this distance from the tHAP:

$$\mathbb{P}(d \leq d_{max}) = \frac{\text{Volume of sphere of radius } d_{max}}{\text{Volume of hovering region}}. \quad (12)$$

For a truncated hemisphere, the volume is given by:

$$V_H = \frac{2}{3}\pi L^3. \quad (13)$$

Thus, the coverage probability becomes:

$$\mathbb{P}(d \leq d_{max}) = \frac{\frac{4}{3}\pi d_{max}^3}{\frac{2}{3}\pi L^3} = \frac{2d_{max}^3}{L^3}. \quad (14)$$

IV. NUMERICAL RESULTS

In this section, the effect of varying the tether length and its impact on path loss and received signal strength for a tHAP system at different altitudes and transmit powers is analyzed. The study is conducted using tHAP transmit powers of 43 dBm and 49 dBm, with an antenna gain of 17 dBi. The receiver sensitivity is set to -114 dBm, accounting for a connector loss of 3 dB, an interface margin of 2 dB, and a fading margin of 5 dB. The altitudes considered are 100 meters, 150 meters, and 250 meters. For the user terminal, the transmit power is 33 dBm, with an antenna gain of 0 dBi, receiver sensitivity of -110 dBm, no connector loss, and a body loss of 3 dB. The antenna height of the user terminal is 1.5 meters. The various simulation parameters used are given in Table II [12].

TABLE II: Simulation Parameters

Parameter	Value (tHAP)	User Terminal
Transmit Power	43 dBm, 49 dBm	33 dBm
Frequency	1 GHz, 1.5 GHz	-
Antenna Gain	17 dBi	0 dBi
Receiver Sensitivity	-114 dBm	-110 dBm
Connector Loss	3 dB	0 dB
Interface Margin	2 dB	-
Fading Margin	5 dB	-
Altitude (distance)	100m, 150m, 250m	-
Body Loss	-	3 dB

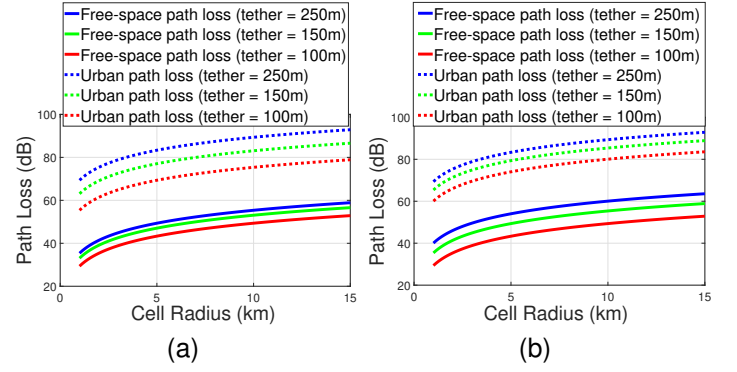


Fig. 3: Path Loss versus Cell Radius for different tether lengths of 100 m, 150 m and 250 m (a) Operating frequency 1 GHz (b) Operating frequency 1.5 GHz.

A. Path Loss Analysis

Fig. 3 presents the values of path loss and cell radius at different altitudes and transmit frequencies. As expected, the path loss increases as the user moves farther from the center of the coverage area. At a lower altitude (100 meters) and a transmit frequency of 1 GHz, the path loss is relatively moderate within a cell radius of approximately 7.2 km. However, as the tether length (and therefore the distance between the tHAP and the user) increases, the path loss increases significantly. For a transmit frequency of 1.5 GHz the path loss further increases. Here also increasing the tether length (altitude) reduces the signal strength due to higher path loss.

Remark 1. Increasing the altitude of the tHAP system at a fixed transmit frequency results in higher path loss values. For instance, at a fixed radius of 10 km and transmit frequency of 1 GHz, the urban path loss values are 75 dB, 83 dB, and 88 dB at altitudes of 100 m, 150 m, and 250 m, respectively as shown in Fig. 3 (a).

Remark 2. Increasing the transmit frequency to 1.5 GHz results in higher path loss values at fixed heights. For instance, at a fixed radius of 10 km and transmit frequency of 1.5 GHz, the urban path loss values are 80 dB, 86.004 dB, and 90 dB at altitudes of 100 m, 150 m, and 250 m, respectively as shown in Fig. 3 (b).

B. Received Signal Strength Analysis

Fig. 4 illustrates the received signal strength versus cell radius at different tether lengths and transmit powers. The received signal strength diminishes with increasing distance from the tHAP, as expected. As shown in Fig. 4 (a), at an altitude of 100 meters with a transmit power of 43 dBm, the urban received signal strength is -24 dBm for a cell radius of 10 km. When the tether length is increased to 250 meters, the urban received signal strength degrades to -40 dBm for a cell radius of 10 km at transmit power 43 dBm. However, when the transmit power is increased to 49 dBm for a tether length of 100 meters, the urban received signal strength improves

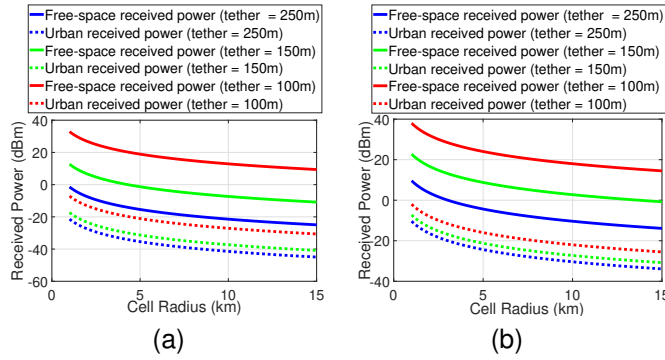


Fig. 4: Received signal strength versus Cell Radius for different tether lengths of 100 m, 150 m and 250 m (a) With transmit power 43 dBm (b) With transmit power 49 dBm.

to -21 dBm and hence, the coverage area expands, but the signal strength at the edge of the cell becomes weaker due to increased path loss. Similarly, when the transmit power is increased to 49 dBm for a tether length of 250 meters, the urban received signal strength improves to -30 dBm as shown in Fig. 4 (b).

Remark 3. Higher altitudes and tether lengths lead to larger coverage areas but at the cost of reduced received signal strength at greater distances. This trade-off must be carefully managed to maintain adequate coverage while minimizing the risk of signal degradation.

C. Coverage Probability and User Density Analysis

To gain insights into the interaction between user density, tether length, and transmit power, we analyze the total number of covered users as a function of user density in Fig. 5. While higher tether lengths expand the coverage area, the coverage probability decreases due to increased path loss. For instance, at a user density of 100 users/km², the total number of covered users for tether lengths of 100 m, 150 m, and 250 m are approximately 1200, 1100, and 900, respectively, for a transmit power of 43 dBm. Increasing the transmit power to 49 dBm significantly improves the number of covered users, especially for higher tether lengths. For the same user density of 100 users/km², the total number of covered users increases to 1400, 1350, and 1200 for tether lengths of 100 m, 150 m, and 250 m, respectively.

At lower user densities the difference in total covered users across tether lengths is negligible. However, as user density increases, the differences become more pronounced, with shorter tether lengths outperforming longer ones in terms of total users covered. Overall, tether length must balance the trade-off between expanding the coverage area and maintaining a high signal strength. Shorter tether lengths provide better signal quality but cover smaller areas, while longer tether lengths expand coverage at the cost of reduced signal strength. Higher transmit power effectively mitigates the increased path loss

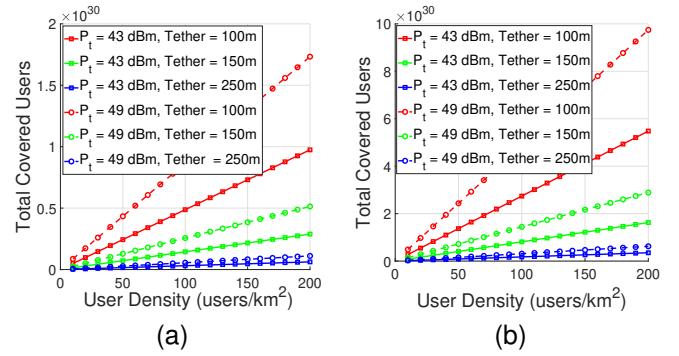


Fig. 5: Trade off between user density vs. total covered users for different tether lengths and transmit powers (a) Operating frequency 1 GHz (b) Operating frequency 1.5 GHz.

associated with longer tether lengths, making it a critical factor for extending coverage in disaster scenarios.

V. CONCLUSION AND FUTURE WORK

This paper presented a detailed mathematical framework and numerical results for analyzing tethered high altitude platform deployments by considering the trade-offs between tether length, path loss, and received signal strength, for effective and reliable communication system design. The analysis indicated that increasing tether length (and hence altitude) can extend the coverage area of the tethered balloon system, but this comes with the trade-off of increased path loss and reduced received signal strength at greater distances. Deploying the system at a higher altitude allows for a larger coverage area, but the power budget must be carefully managed to ensure that the signal strength remains above the threshold required for reliable communication.

For practical deployment, the choice of tether length should balance the desired coverage area with the need to maintain sufficient signal strength across the coverage region. Additionally, higher transmit power can help mitigate the effects of path loss, but this also requires careful consideration of energy consumption and interference management which is the future scope of this work.

ACKNOWLEDGEMENT

This work was supported in part by DST-RSF research project no. 22-49-02023 (RSF) and research project no. 64800 (DST) and in part by the Science and Engineering Research Board, India, under grant CRG/2023/005421.

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