

Optimizing Tethered HAP Networks Configuration Using Genetic Algorithms

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Abstract—A tethered High altitude platform station (tHAPS) is a network node that operates in the aeronautical layer at an altitude of around 100 to 150 meters, playing a crucial role in providing communication services. It is linked to the ground through a tether. According to ITU recommendations [1], a tHAPS should have a wide coverage area with a radius of approximately 20 km. A network of multiple tHAPS can extend this coverage to serve an entire country. In this article, we discuss the scenario where multiple tHAPS are distributed across an area, each covering a circular region beneath them. We analyze the reliability of such a system and use a modified Genetic Algorithm (GA) to determine the optimal arrangement of tHAPS for a given region.

Index Terms—Genetic Algorithm, Tethered High-Altitude Platform, Reliability.

I. INTRODUCTION

A tethered High Altitude Platform Station (tHAP) is utilized to cover an area for communication, reconnaissance, sensing, and other purposes [2]. tHAPs have a higher failure rate as compared to unmanned aerial vehicles (UAVs), with failure rates reaching up to once every 1,000 hours [3][4]. This impacts the reliability of the tHAP networks [5]. tHAPs have several advantages when compared to terrestrial stations or satellite stations. tHAPs have an intermediate geographical range between that of terrestrial stations and a satellite stations. Deployment time for one tHAP is tens of minutes. They can be operated for long duration and can return to ground easily. Furthermore they have a secure and efficient back-haul, since tHAPs are connected to the core network via wire. tHAPs are also extensively used in the case of disaster situation in the concerned region due to the easy deployment.

Components of a tHAP are shown in Fig. 1. A tHAP consists of a flying platform connected to the Ground Control Station (GCS) via a tether. The GCS houses a system for diagnostics and control of the tHAP from the ground. The tether includes a fluoroplastic sheath, 2 high-voltage high-frequency copper wires, a Kevlar bundle wrapped in a thin fluoroplastic sheath, and an optical cable with four fiber-optic cores. The main purpose of the tether is to ensure the transmission of electrical energy from the ground source unit

to the on-board converter-receiver of the tHAP. An additional purpose of the tether is to implement a high-speed noise-resistant data transmission link between the GCS and the high-altitude flying platform. The navigation and stabilization system comprises of on-board sensors, on-ground anchor points, etc., that measures various parameters for navigation, and the circuits that stabilize the platform based on these parameters. The main power source is located on the ground. The intelligent winch is responsible for controlling the tension of the tether.

tHAPs have been previously proposed for transmitting radio frequency signals from ground stations over distances spanning several hundred kilometers. The main issue with tHAPs is ensuring reliable operation over extended durations without failure. With this concern in mind, Vishnevsky et al. [6] and Rykov et al. [7] studied the reliability of a flight module in a tethered high-altitude telecommunication platform using the k-out-of-n: F model.

High-altitude modules of tHAPs operate in a dynamic environment that can be both regular and random in nature. The frequency of these changes can be either commensurate with, or significantly higher or lower than the system failure rate. In [8], Rykov and Nghia investigated the influence of environmental changes on the stationary reliability of technical systems, as well as on the distribution of their time to failure.

Determining the optimal arrangement of tHAPs in a network to ensure reliability through redundancy is a combinatorial problem with a vast solution space. Traditional optimization techniques struggle to explore this space efficiently, especially as the number of tHAPs and potential arrangements grows. GAs, however, are well-suited for exploring large, complex spaces by generating and evolving a diverse set of potential solutions through crossover, mutation, and selection. The underlying situation is a variation of the lamp location problem discussed by Feng et al. [9]. On the similar line, we have also employed a Genetic Algorithm (GA) in tHAPS to determine the optimal arrangements of tHAPS for a given region.

A GA is a meta-heuristic inspired by the process of natural selection. In GA, we have a population of chromosomes which

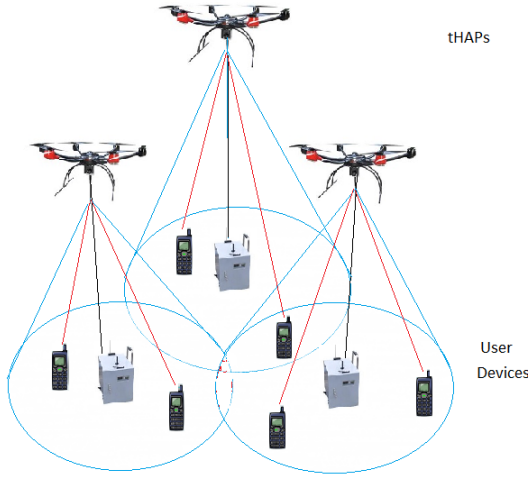


Fig. 1: Architecture of tHAPs network

serves as the foundation for generating new chromosomes through two primary methods:

- 1) **Mutation:** One chromosome is taken and its parameters are partially changed by a small amount depending on a probability.
- 2) **Cross-breeding:** Two chromosomes are taken and their genes are arranged along a random direction and then we form a new chromosome by taking genes from each of the two chromosomes.

Upon the addition of these newly generated chromosomes to the existing population, each chromosome undergoes an evaluation process based on a scoring system. Following this assessment, chromosomes with lower scores are identified and subsequently removed from the population [10].

In the satellite-aerial-terrestrial (SAT) network, the tHAPs are assumed to be at a fixed altitude, and the ground is considered level. Consequently, each HAP covers a circular area on the ground with the same radius.

To summarize this article, the potential tHAP system model is described in Section II, followed by the analysis in Section III. The suggested model's results are presented in Section IV. Finally, Section V concludes with suggestions for further research.

II. MODEL DESCRIPTION

The proposed model depicts a scenario where multiple tHAPs are dispersed throughout a specific region within an aerial network. tHAPs are connected with each other through wireless connection. The objective is to determine the optimal number of HAPs for a particular given region. To achieve this goal, we have employed a modified genetic algorithm.

In this genetic algorithm, chromosomes represent potential configurations of tHAPs, where each gene corresponds to a specific tHAP. Each gene comprises two components: a location coordinate and a weight. The weight component is inspired by the genetic principle of dominance, where a dominant gene suppresses the expression of a recessive gene.

In the proposed model, if two tHAPs are positioned too closely to each other, we deactivate the tHAP with the lower weight, thereby ensuring that only the tHAP with the higher weight remains active. The final arrangement of tHAPs in our solution consists exclusively of these active genes, collectively forming an optimized tHAP network configuration.

This approach enables us to maintain an efficient distribution of tHAPs, minimizing overlap and redundancy while maximizing coverage and performance. By integrating genetic principles, we enhance the algorithm's capability to identify optimal solutions for intricate network layouts.

Algorithm 1 explains the process briefly.

Algorithm 1 Algorithm to determine pattern from chromosome

```

genes ← sort_by_weight_desc(chromosome.genes)
i ← 0
while i < len(genes) do
    gene ← genes[i]
    dist ← min_dist_between(gene, genes[:i])
    if dist < min_dist then
        gene.active ← false
    else
        gene.active ← true
    end if
end while

```

III. METHODOLOGY

The score function for the GA is composed of two factors: a reliability score and a tHAP cost. The reliability score reflects the overall reliability of the system. To determine this, the service area is divided into several subsets based on the coverage circles of the active tHAPs. We assume each subset is independent and calculate the overall reliability by taking the weighted average of the reliability scores of each subset.

Let $\sigma(m)$ be the fraction of service area under a multiplicity of m . Therefore, the reliability score S_R is given by

$$S_R = \sum_{m=0}^{m_{max}} \sigma(m) * (1 - (1 - R)^m), \quad (1)$$

where $0 < R < 1$ is the reliability constant representing the reliability of one tHAP and m_{max} is the maximum multiplicity attained.

The tHAP cost C_G is determined by the number of tHAPs. If the number of HAPs increases in the pattern the score will decrease. The score function is given by

$$S = M_R * S_R - M_G * C_G, \quad (2)$$

where M_R and M_G are the weights related to reliability score and weight of tHAP cost.

Pareto dominance: A solution A dominates a solution B if the factors of score of A is better than or equal to that of B , but they are not equal. For example, $(S_R = 0.9, C_G = 10)$ dominates $(S_R = 0.8, C_G = 11)$. $(S_R = 0.8, C_G = 11)$ does

not dominates ($S_R = 0.9, C_G = 10$). ($S_R = 0.9, C_G = 10$) dominates ($S_R = 0.8, C_G = 10$). ($S_R = 0.9, C_G = 10$) does not dominates ($S_R = 0.9, C_G = 10$).

A solution A is Pareto optimal if there is no other solution that dominates A . Pareto Front is the collection of all pareto optimal solutions.

In this case one of the factors of the score C_G is discrete. Therefore, the pareto optimal solution can be obtained by fixing C_G and maximizing S_R . Using this we can approximate the pareto front.

The relation between the effective multiplicity (m_{eff}) of tHAPs and reliability score function is given as follows:

$$S_R = 1 - (1 - R)^{m_{eff}}, \quad (3)$$

or

$$m_{eff} = \frac{\log(1 - S_R)}{\log(1 - R)}, \quad (4)$$

where R is the reliability of a tHAP [4].

IV. RESULTS

The assumptions for the numerical simulations are as follows:

- 1) The service area is a square of radius 10 km.
- 2) The radius of tHAP's coverage is 3 km.
- 3) Minimum distance between tHAPs is 1 km.
- 4) $R = 0.99$.
- 5) $M_R = 1000$.
- 6) $M_G = 0.25$.

The reliability of tHAP $R = 0.99$ has been referred from the earlier research work on tHAP [4]. The outcome of the simulation, as illustrated in Fig. 2, achieves $S = 997.0111$ with $S_R = 0.9997611$ and $C_G = 11$. Notably, the experiment has been conducted considering the pattern of 11 tHAPs.

Fig. 3 shows the relation between S_R and R for the optimal solution. The value of S_R increases with respect to R for different values of m .

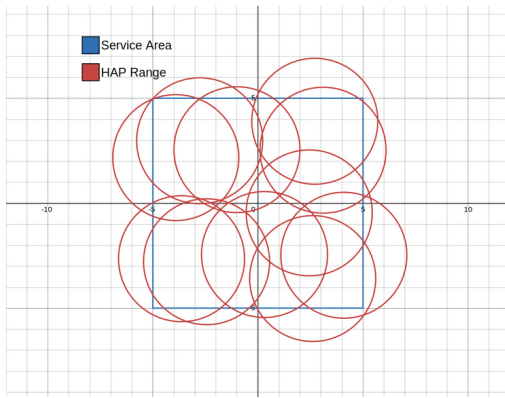


Fig. 2: Simulation result of HAP range for a given service area

Fig. 4 shows the approximated result for our model's Pareto front for different values of tHAP's coverage area radius. We take the values of radius as 2 km, 3 km and 3.5 km. As it

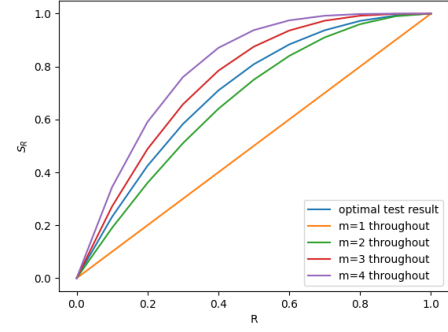


Fig. 3: S_R vs R for various cases including optimal test result

is a saturating curve, we instead plot the effective multiplicity (m_{eff}) against C_G , as shown in Fig. 5. As can be seen from the figure there could be a linear relation between m_{eff} and C_G given by

$$m_{eff} = K * C_G + m_0. \quad (5)$$

where K and m_0 are constants that determine the linear relationship.

The reason behind this can be attributed to the optimal solutions primarily residing within the designated region. Consequently, each tHAP contributes to the multiplicity, leading to a linear relationship between them.

In Fig. 6, we present a graphical representation of K as a function of R . It becomes evident that as R increases, there is a corresponding decrease in K . Additionally, Fig. 7 provides a visual depiction of the behavior of m_0 . No linear relationship can be found in this behaviour. Fig. 8 shows the percentage of area which is covered by a given multiplicity. This was found by using the red circles in the 2 to divide the service area into subsets and then calculating the multiplicity for each subset. Here, multiplicity 2 covers the maximum percentage area being 51.1%.

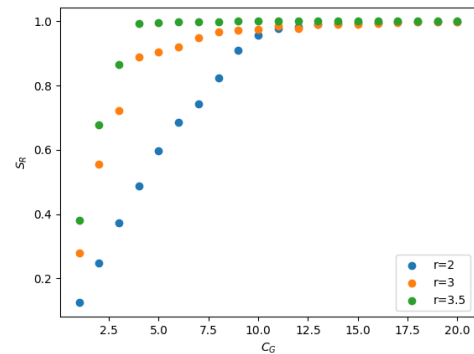


Fig. 4: S_R vs C_G for the Pareto front for various values of the radius (r) of tHAP's coverage in km

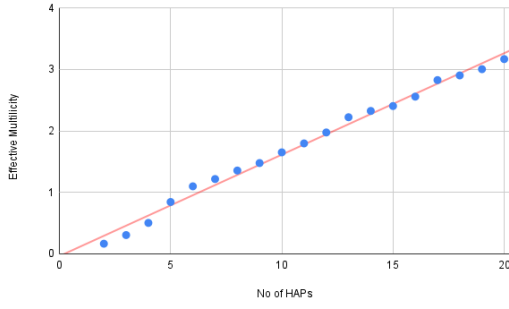


Fig. 5: m_{eff} vs C_G for the Pareto front

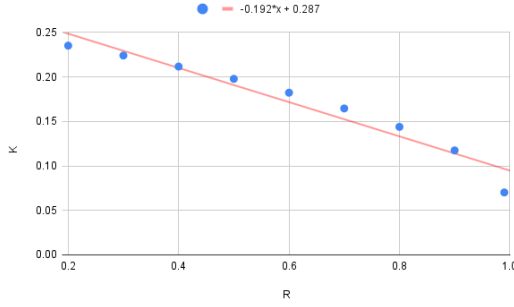


Fig. 6: Behavior of K vs reliability R

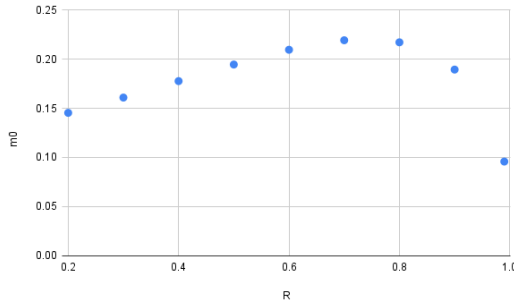


Fig. 7: Behavior of multiplicity m_0 vs reliability R

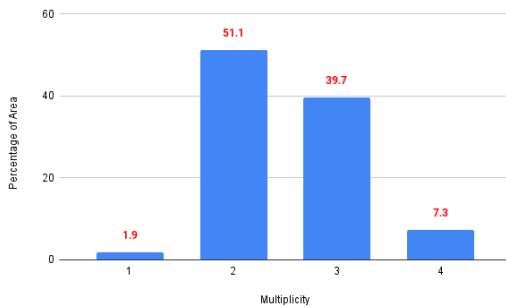


Fig. 8: Percentage of area with given Multiplicity

V. CONCLUSIONS & FUTURE DIRECTIONS

In this article, we explore a scenario where multiple tHAPS are distributed across a region, each covering a circular area

beneath them. We analyze the reliability of this system and employ a GA to determine the optimal arrangement of tHAPS for a given region. Our results indicate that with a multiplicity of two, the tHAPS achieve maximum coverage of the region. However, as the multiplicity increases, the coverage percentage decreases. This study demonstrates that with proper optimization, a strategic deployment of tHAPS can achieve highly reliable coverage in a designated service area. In summary, the results demonstrate that while redundancy is key for reliability, optimal deployment that considers coordination and interference is essential for effective coverage. Adding more tHAPS can inadvertently reduce coverage, emphasizing the importance of strategic positioning.

In future, the work can be extended by applying different heuristic algorithm and considering a different area of coverage.

ACKNOWLEDGEMENT

Dharmaraja Selvamuthu, Dimitry Kozyrev and Vladimir Vishnevsky thank the financial support of DST-RSF research project no. 22-49-02023 (RSF) and research project no. 64800 (DST).

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