Service Availability of HAPS considering its elevation angle, density, and altitude

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***Abstract*—We define service area of high altitude platform station (HAPS) in spherical coordination, and using spherical Poisson point process the probability of service availability is derived with respect to the elevation angle, altitude and density of HAPS. It is shown that when elevation angle is high, the probability of service availability is linearly and slowly increased as the density is increased. As the elevation angle is increased the probability of service availability converges to 0. Given that the same density, the higher probability of service availability is achievable if the elevation angle is low and the altitude is high. In order to achieve 99.9% service availability one can carefully consider the deployment of HAPS per unit area in the air, the altitude and the elevation angle of HAPS.**

***Keywords*—Elevation angle, altitude, density, service area, service availability, High Altitude Platform Station (HAPS).**

I. INTRODUCTION

A High Altitude Platform Station (HAPS) is known as one of promising solutions that can enlarge service coverage of current mobile communication systems. It operates in the stratosphere at an altitude of 20~50 km and can stay at a quasi-stationary position providing ubiquitous connectivity. Since it has advantages of easy deployment, rapid applicability and broad coverage, 5G has been treated it as one of important part among non-terrestrial network (NTN). It is also expected a key role in 6G (a.k.a., IMT-2030) to achieve the goal on three dimensional (3D) full coverage provided by integrating terrestrial network with NTN. The World Radiocommunication Conference of 2023 has set agenda item 1.4 to consider the use of HAPS as International Mobile Telecommunication (IMT) Base Station (BS) application below 2.7 GHz on a global or regional basis [1], [2].

There have been many works related to HAPS. 5G-HAPS communication downlink quality is analyzed in term of spectral efficiency and bit error rate with different scenarios such as user's elevation angle, receiver speed and system bandwidth [3]. In [4], path loss is calculated based on the elevation angle between the ground station and the HAPS for different urban scenarios, and the altitude of the HAPS is optimized to provide maximum radio coverage for each urban environment. The performance of the communication system using HAPS affected by the stratosphere winds, which makes HAPS swinging, is analyzed by using beam coverage geometry model in the swing state [5]. [6] studied on coverage and wireless link performance using multiple spot beam cell partition scheme based on scenarios in communication system with HAPS.

In this paper, we evaluate the probability of service availability of HAPS with respect to the elevation angle, altitude and the density of HAPS considering a spherical cap in spherical coordination. The rest of this paper is organized as follows. In Section II, we introduce geometry of HAPS and a typical spherical cap. In Section III, we define the service area of HAPS and derive the probability of service availability using spherical Poisson point process (SPPP). We also show numerical results on the probability of service availability. Conclusion is given in Section IV.

II. SYSTEM MODEL

The geometry of HAPS is depicted in Figure 1. We consider the surface of a sphere in $\mathbb{R}^3$ with the center at the origin $\mathbf{0} \in \mathbb{R}^3$. HAPS are assumed to be located on the surface of a sphere with radius R_H. The surface of a sphere is defined as

$$\mathbb{S}^2_{R_H} = \{x \in \mathbb{R}^3 : \|x\|_2 = R_H\} \tag{1}$$

A point vector $x \in \mathbb{S}^2_{R_H}$ can be given by a pair of azimuthal angles $0 \le \phi \le 2\pi$ and elevation angle $0 \le \theta \le 2\pi$ with a fixed radial distance R_H, in spherical coordination.

Let $\Phi = \{x_1, \cdots, x_N\}$ be a point process that has a finite number elements on the surface of a sphere $\mathbb{S}^2_{R_H}$, called a homogeneous SPPP, provided that the number of points on $\mathbb{S}^2_{R_H}$, $N = \Phi(\mathbb{S}^2_{R_H})$, follows Poisson random variable with mean $4\pi R_H^2 \lambda$ and density λ,

$$\mathbb{P}(N = n) = exp(-4\pi R_H^2 \lambda) \frac{(4\pi R_H^2 \lambda)^n}{n!} \tag{2}$$

where $4\pi R_H^2$ is the surface area of the sphere. For given N, the $\{x_1, \cdots, x_N\}$ forms a binomial Poisson point process (BPP), in which x_1 for $i \in [N]$ is independent and uniformly distributed on the surface of the sphere.

A typical receiver is located at $(0,0,R_E)$ where R_E is the radius of the Earth ($R_E = 6371km$). A HAPS altitude is determined by distance difference between R_E and R_H. The distance between the typical receiver and its corresponding HAPS is defined as r ($R_{min} \le r \le R_{max}$). R_{min} is the smallest r when it is considered the nearest HAPS from the typical receiver, HAPS #1 which is located at the zenith of it. Note that $R_{min} = R_H - R_E$. On the other hand, R_{max} is the largest the r

when it is considered the farest HAPS from the typical receiver, HAPS #3 which is located at the intersection point between the horizontal line at the typical receiver and the HAPS sphere. Note that $R_{max} = \sqrt{R_H^2 - R_E^2}$.

We consider the spherical cap region that includes the typical receiver as the typical spherical cap. The area of the typical spherical cap is given by

$$\mathcal{A} = 2\pi(R_H - R_E)R_H \quad (3)$$

It is noteworthy that only the HAPSs located on the typical spherical cap are visible to the typical receiver. In Figure 1, HAPS #4 cannot be seen by the typical receiver because it is under the horizontal line at the typical receiver.

The elevation angle at the typical receiver θ_t ($0 \le \theta_t \le \frac{\pi}{2}$) is the angle that is formed between the horizontal line at the typical receiver and the line of sight toward HAPS from the typical receiver. It is possible to point out the corresponding HAPS for the typical receiver to communicate by θ_t at the typical spherical cap.

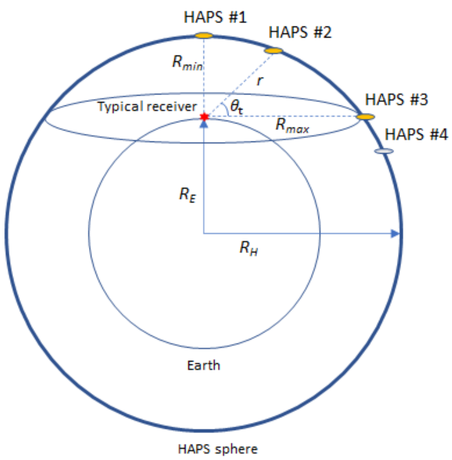

Figure 1. Geometry of HAPS and its receiver on the Earth

III. Evaluation of Servce Availbility and Numerical Results

We define service area as the area where the typical receiver can transmit and receive its data through its corresponding HAPS in the typical spherical cap. The service area $\mathcal{A}_s$ is a spherical cap which is a subset of the typical spherical cap given by

$$\mathcal{A}_s \in \mathcal{A} \text{ where } 0 \le \mathcal{A}_s \le \mathcal{A} \quad (4)$$

Considering the distance r from the typical receiver and its corresponding HAPS, the service area can be given by

$$\mathcal{A}_s(r) = 2\pi R_H\left(R_{min} - \frac{R_H^2 - R_E^2 - r^2}{2R_E}\right) \quad (5)$$

Note that $\mathcal{A}_s(R_{max}) = 2\pi R_H R_{min}$ and $\mathcal{A}_s(R_{min}) = 0$.

The service area can be expressed as the function of the distance r and the elevation angle θ_t as follows:

$$\mathcal{A}_s(r, \theta_t) = 2\pi R_H(R_{min} - r sin\theta_t) \quad (6)$$

We further can express the distance r as the function of elevation angle θ_t and R_H as follows:

$$r = -R_E sin\theta_t + \sqrt{R_H^2 - R_E^2 cos^2\theta_t} \quad (7)$$

Consequently, the service area is given by

$$\mathcal{A}_s(\theta_t) = 2\pi R_H\left(R_{min} - sin\theta_t\left(-R_E sin\theta_t + \sqrt{R_H^2 - R_E^2 cos^2\theta_t}\right)\right) \quad (8)$$

The HAPS service is available if there exist at least one HAPS in the service area of the typical receiver. Without loss of generality, we consider that N HAPS(s) is(are) independent and uniformly distributed over the area of the typical spherical cap as shown in Figure 1. Using SPPP with the probability of service availability is represented as

$$\begin{aligned} Pr\{\text{Service availability}\} &= 1 - Pr\{\text{No HAPS exist within service area}\} \\ &= 1 - \left(1 - \sum_{i=1}^{\infty} Pr\{i\ HAPS(s) \in \mathcal{A}_s(\theta_t)\}\right) \\ &= e^{-\rho\cdot\mathcal{A}_s(\theta_t)} \end{aligned} \quad (9)$$

where $\rho = N/\mathcal{A}$ is the HAPS density in the typical spherical cap.

Finally, the probability of service availability is represented by

$$Pr\{\text{Service availability}\} = e^{-\rho\cdot 2\pi R_H\left(R_{min} - sin\theta_t\left(-R_E sin\theta_t + \sqrt{R_H^2 - R_E^2 cos^2\theta_t}\right)\right)} \quad (10)$$

where described by the function of the elevation angle, R_H, and the density.

The probability of service availability related to the elevation angle of HAPS with different HAPS densities is shown in Figure 2. The HAPS altitude is 20km and the HAPS density varies from 0.0001 to 0.001. Note that $\rho = 0.0001$ means there exist 1 HAPS over every $100km^2$ area in the typical spherical cap. As the elevation angle is increased the probability of service availability converges to 0. In addition, as the density is increased the probability of service availability is also increased. As the density is increased, the required elevation angle for 99.9% service availability goes to high. Using this result, we might find that at a given elevation angle how many HAPS should be placed in order to get the target service availability for HAPS.

Figure 3 shows the probability of service availability related to the HAPS density with different elevation angles of HAPS. The HAPS altitude is 20km. The lower elevation angle is set the more probability of service availability is achievable given that the same HAPS density. It is noteworthy that when the elevation angle is high, the probability of service availability is linearly and slowly increased as the density is increased. On the contrary, when the elevation angle is low, the probability of service availability is converged to 1 rapidly as the density is increased. To achieve 99.9% service availability, one can set the required elevation angle at the given density.

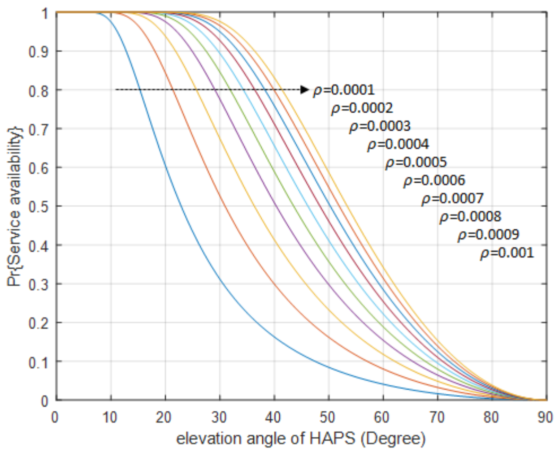

Figure 2. Probability of service availability related to the elevation angle of HAPS with different HAPS densities when the HAPS altitude is 20km

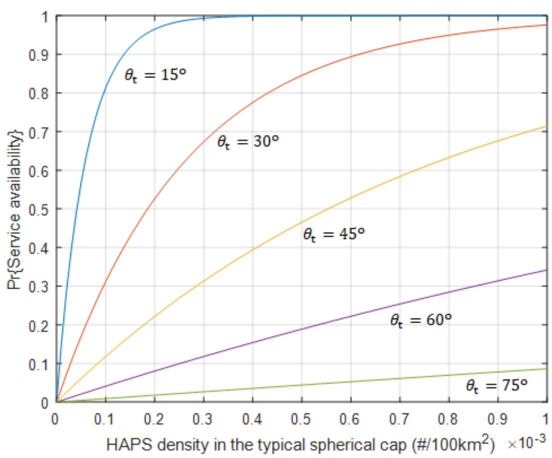

Figure 3. Probability of service availability related to the HAPS density with different elevatoin angles of HAPS when the HAPS altitude is 20km

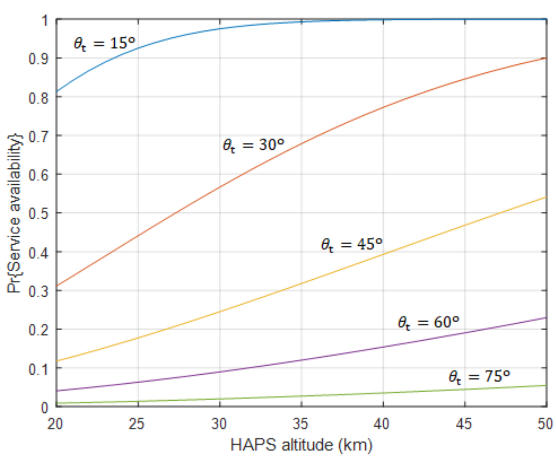

Figure 4. Probability of service availability related the HAPS altitude with different elevation angles @ 1 HAPS over every $100km^2$ area

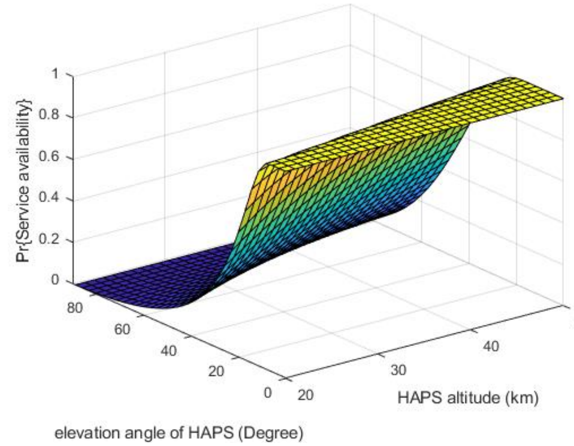

Figure 5. Probability of service availability related to the elevation angle of HAPS and the HAPS altitude @ HAPS over every $100km^2$ area

The probability of service availability related to the HAPS altitude with different elevation angles of HAPS when there exists one HAPS over every $100km^2$ area is shown in Figure 4. The lower elevation angle is set the more probability of service availability is achievable given that the same HAPS altitude. It is noteworthy that when the elevation angle is high, the probability of service availability is linearly and slowly increased as the altitude is increased. When the elevation angle is 30^o, the probability of service availability shows the largest gap as the altitude changes.

Figure 5 shows the probability of service availability related to the HAPS altitude and the elevation angle of HAPS when there exists one HAPS over every $100km^2$ area. Given that the same density, the higher probability of service availability is achievable if the elevation angle is low and the altitude is high. In order to obtain the target service availability, it is possible to find out how we deploy HAPS in the air, that is, the required elevation angle, altitude and density of HAPS. For example, 99.9% service availability is granted with the elevation angle 14.32^o and the altitude 40km when there exists one HAPS over every $100km^2$ area.

IV. Conclusion

In this paper, we evaluated the probability of service availability of HAPS with respect to the elevation angle, the altitude and the density of HAPS when all HAPSs are independent and uniformly distributed over the area of the typical spherical cap, i.e., the spherical cap region that includes the typical receiver. The probability of service availability is investigated by the elevation angle, the altitude and the density of HAPS. Given that the same density, the higher probability of service availability is achievable if the elevation angle is low and the altitude is high. In order to achieve 99.9% service availability one can carefully consider the deployment of HAPS per unit area in the air, the altitude and the elevation angle of HAPS. For the further work, it is required to be studied the effect of HAPS deployment on interference among HAPS to obtain target quality of service (QoS).

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