Downlink outage probability analysis of UAV base stations

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***Abstract*— Over the previous few years, the use of unmanned aerial vehicles (UAVs) as floating base stations (BSs) has drawn increasing interest. Floating UAV BSs can provide reliable uplink and downlink facilities for ground users, possibly enhancing network ability, eliminating coverage holes in current cellular systems, and addressing the steep rise in communication demands in hotspot fields. Compared to long-term terrain-based BSs deployed at a fixed place, UAVs can quickly alter their roles to provide temporary on-demand service. Unlike terrestrial transmissions, communications to unmanned drones have some benefits, such as line-of-sight (LoS) atmosphere and flexible mobility. Interference will be natural, though. Our UAV communication analysis deals with the effect of interference on UAV communications by considering the probability of LoS and different channel fading for LoS and non-line-of-sight (NLoS) links that are affected by the elevation angle of the communication link. It analyzes the effectiveness of unmanned aerial vehicles (UAVs) acting as wireless base stations providing ground users coverage. The probability of downlink error in ground users is evaluated for variable threshold values, drone altitudes, coverage radii, analysis for all possible main and interference link scenarios and configurations in the presence of an interfering node. Having considered the impacts of transmitting and interfering node parameters on the likelihood of outage, we show the existence of the optimal UAV height minimizing the likelihood of outage.**

Keywords— Unmanned Aerial Vehicle (UAV), Air to Ground (AG), Line of Sight (LOS), Non Line of Sight (NLOS), Outage Probability, Base Station (BS).

I. INTRODUCTION

Due to the enormous use of wireless devices in a variety of implementations, a spectral efficiency and high-speed wireless service are now becoming equally necessary. Nevertheless, owing to the various limitations such as expenses and geographical constraints (e.g. mountains and forests), many areas do not have wireless services or suffer from bad connectivity and service quality [2]. Examples of regions with bad wireless coverage include rural areas and nations (e.g. in Africa) where the construction of a full terrestrial infrastructure is very costly or impracticable. In addition, the current cellular network infrastructure, capability, and coverage will need to be quickly enhanced in order to deal with such a rise in demand during significant government events such as the Olympic Games. UAV-based wireless communication offers an ideal solution for wireless services in such situations. AT & T and Verizon, for instance, intend to use flying drones to provide temporarily improved Internet coverage for the University Football and Super Bowl national championship [1][4].

As an aerial base station, unmanned drones can be used to meet the coverage and frequency demands of wireless customers. They may have line-of-sight (LOS) contacts to terrestrial users owing to the flying nature of UAVs, resulting in enhanced coverage and rate results [3]. Mobile UAVs can smartly relocate and alter their place compared to terrestrial base stations to deliver on-demand coverage for terrestrial users. As a consequence, UAV-dependent aerial base stations can be utilized for temporary occurrences or hotspot regions to increase wireless ability and coverage [5] [8].

One of the primary issues in UAV drone based communications is the three-dimensional deployment of UAVs. The variable altitude of UAVs and their prospective flexibility actually provide extra notches of liberty for effective placement. As a consequence, considerable attention has been paid to ideal deployment of UAVs. Deploying UAVs for coverage and ability maximization, public safety and security, smart cities, caching, and IoT apps is, in reality, a main design factor [6]. The ideal 3D positioning of UAVs is a difficult mission as it relies on many variables, such as placement setting (e.g. geographic region), locations of terrestrial users, and UAV-to-ground channel features, which is itself a function of the altitude of a UAV. Moreover, it becomes more difficult to concurrently deploy various UAVs owing to the effect of inter-cell interference on system efficiency. In reality, as in standard cellular network planning, the placement of UAVs is considerably more difficult than ground base stations. Unlike ground base stations, UAVs must be positioned in a constant 3D space dimension, taking into account the impact of height on the characteristics of the A2G channel [7][10]. In addition, their flight time and energy limitations must also be taken into consideration while deploying UAVs as they directly affect network performance [19].

Recently, the issue of deployment of UAVs in wireless systems has been widely researched in the recent works. For example, various UAVs for energy-efficient information gathering from IoT devices were explored for optimal deployment and mobility [12]. The probability of LoS links between transmitter and receiver reduces at very low altitudes owing to the shadowing impact and subsequently the coverage radius decreases. On the other hand, at very high altitudes, there are high probability LoS connections. However, the path loss increases due to the large distance between transmitter and receiver, and the coverage performance decreases as a consequence. Therefore, to find the ideal UAV altitude, the effect of both range and LoS likelihood should be considered simultaneously [14] [18].

II. SYSTEM MODEL

Consider a geographical location in which certain numbers of UAVs must be placed in order to provide network coverage to terrestrial users within the zone [11]. Each UAV is perceived to have a directional antenna. The drone serves a hexagonal coverage area with Rd radius as illustrated in Figure 1, and any MU is assumed to be within this coverage zone (where users are distributed evenly). The drone's elevation angle to that specific user is described as the internal angle between the surface and the line that binds the mobile user to the drone. The drone is located at h meters from the ground in this model. Under the control of a ground communications system, we will consider the UAV optimizing the drone's height in order to achieve the ideal expected efficiency according to service quality (QoS) constraints [13].

A. Propogation Model

There are few literature studies on characterizing the deployment of air to-ground (ATG) in especially in urban areas where the researchers proposed that ATG communication should takes place in accordance with two primary transmission groups [16]. These groups are extracted statistically where the first group corresponds to receivers endorsing a condition of Line-of-Sight (LoS) or adjacent Line-of-Sight, while the second group generally corresponds to receivers without LAP Line-of-Sight but still getting coverage through strong reflections and diffractions [15].

Radio signals emitted by a LAP base station propagate in free space until they reach the urban environment where the man-made buildings incur shadowing and scattering, resulting in extra losses in the ATG link [8]. We refer to the additive loss incurred on top of the loss of the free space route as the excessive loss of the route, which has a Gaussian distribution, but in this research we are dealing with its mean value (expectation) rather than with its random behavior. Another point is that there is no consideration for the impact of small-scale fluctuations induced by fast modifications in the propagation setting [17].

B. Modeling Line of Sight Probability

Several models for air-to-ground (ATG) channels have been proposed. The UAV-BS transmitted radio signals are largely groups of Line-of-Sight (LoS) or Non-Line-of-Sight (NLoS). The probability that the ground user I would have a LoS link with such a UAV-BS is provided by [9]

$$P_{LoS} = \frac{1}{1 + a\exp(-b(\frac{180}{\pi}tan^{-1}\left(\frac{h}{r_i}\right) - a))}$$

Here a and b are constants which depend on the environment and are assigned, ri specifies the position of the UAV-BS in the horizontal dimension, h denotes the altitude of the UAV-BS. In addition, NLoS likelihood is PNLoS= $1 - \text{PLoS}$. In relation to loss of free space propagation, radio signals are facing losses in the form of shadowing and scattering owing to the metropolitan area [11]. We're dealing with the mean path loss in this job rather than its random conduct. This is because the BS deployment scheduling stage deals with long-term channel differences instead of small-scale differences. The path loss model for LoS and NLoS connections in dB is therefore respectively

$$L_{LoS} = 20\log\left(\frac{4\pi f_c d_i}{c}\right) + \eta_{LoS}$$

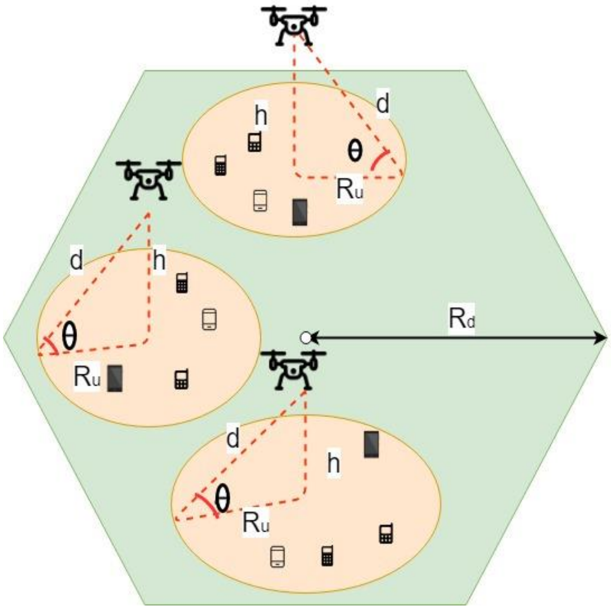

Fig. 1. System model

$$L_{NLoS} = 20\log\left(\frac{4\pi f_c d_i}{c}\right) + \eta_{NLoS}$$

Where fc is the carrier frequency, di is the distance between the UAV-BS and the user i, given by [11]

$$d_i = \sqrt{h^2 + {r_i}^2}$$

In addition, the average extra losses for LoS and NLoS, respectively, are η_ LoS and η_NLoS. We can not determine if the connection is LoS or NLoS in the lack of terrain expertise [12]. The probabilistic mean path loss, which is averaged over the LoS and NLoS circumstances, is therefore considered as

$$L(h, r_i) = L_{LoS}\, X\, P_{LoS} + L_{NLOS}\, X\, P_{NLoS}$$

Line of sight probability P (LoS) can be known as a continuous function of the elevation angle and the parameters of the environment [16]. Plotting this probability for four chosen urban settings like Suburban, Urban, Dense Urban and High Raise Urban in Fig.2

$$L(h, r_i) = 20\log\left(\frac{4\pi f_c}{c}\right) + 20\log\left(\sqrt{h^2 + {r_i}^2}\right) + P(h, r_i)\eta_{LoS} + (1 - P(h, r_i))\eta_{NLoS}$$

Let $A = \eta_{LoS} - \eta_{NLoS}$

$B = 20\log\left(\frac{4\pi f_c}{c}\right) + \eta_{NLoS}$. Then

$$L(h, r_i) = 20\log(\sqrt{h^2 + {r_i}^2}) + A * P(h, r_i) + B$$

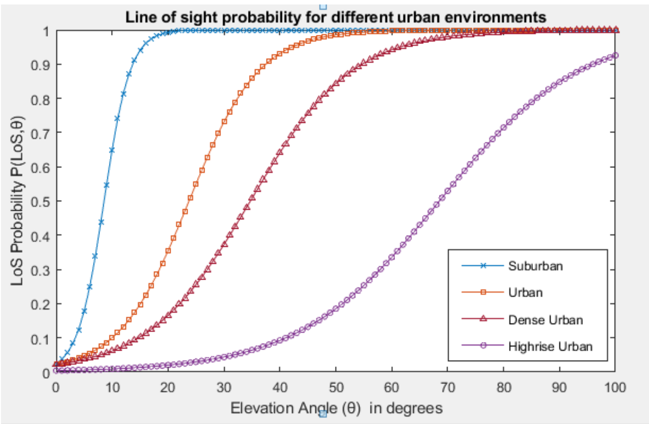

Fig. 2. Variation of line of sight probability with elevation angle for different environments

For a given transmit power P_t, the received power at the user i depends on the path loss experienced by its communication link, and can be written as [14] $P_r = P_t - L(h, r_i)$

C. Modeling Line of Sight Probability

We determine the optimum altitude of UAV for a coverage radius by considering the interference from other UAVs [1]. Due to the use of directional antennas at the UAV we consider the interference received from the nearest UAV k is dominant.

The mean interference power received from the nearest UAV k which is given by

$$I = P_{LoS,k}E[P_{r,k}(LOS)] + P_{NLoS,k}E[P_{r,k}(NLOS)]$$

$$I = P_t\left[10^{\frac{-\mu_{LoS}}{10}}P_{LoS,k} + 10^{\frac{-\mu_{NLoS}}{10}}P_{NLoS,k}\right]\left(\frac{4\pi f_c d_k}{c}\right)^{-n}$$

Where $P_{LoS,k}$ is the line of sight probability for the interference horizontal link distance of the nearest UAV k as d_k.

III. OUTAGE PROBABILITY

Outage probability is defined as the stage where the receiver capacity value falls below the limit (where the energy value refers to the minimum signal to noise ratio (SNR) within a cellular), it can be said that the receiver is outside the BS range in cellular communications. The probability of outage is a significant parameter for Characterizing system results and is described as the likelihood of closing the communication link [4].

The received SINR for a user served by UAV i can be written as:

$$\gamma_i(h, r_i) = \frac{P_{r,i}(h, r_i)}{I_i(h, d_k) + N}$$

Where $P_{r,i}(h, r_i)$ is the received power at the user located at a radius of r when UAV is at a height h and $I_i(h, d_k)$ is the dominant interference power received from the nearest UAV k which is located at a horizontal interference link distance of d_k.

Outage probability $P_{out}(h, r_i)$ here is defined as the probability at which the SNR value falls below a certain specified predefined threshold γ_{th}.

$$P_{out}(h, r_i) = P[\gamma_i(h, r_i) < \gamma_{th}]$$

Here, for a Rayleigh fading channel it follows that

$$P_{out}(h, r_i) = 1 - \exp\left(\frac{-\gamma_{th}}{\gamma(h, r_i)}\right)$$

IV. RESULTS AND DISCUSSIONS

For simulations, we consider the UAV-based communications over 2GHz carrier frequency (fc = 2GHz) in an urban environment with η_{LoS}=1dB and η_NLoS = 20 dB and path loss exponent n = 2. We also consider UAV-BSs that transmit their signals with transmit power Pt = 46 dBm while the noise power is assumed −174 dBm/Hz. Fig 4. Shows the outage probability plot for a SINR threshold of 5dB for a coverage radius of 500 m and interference link distance as 1000 m. we can see that the outage probability first decreases as the height increases up to a certain value of the height, and then increases. This is because the LoS probability of main link increases as the height increases. When the height of UAV is small, as the height increases, the increasing probability of forming LoS main link is more dominant than the increasing main link distance on the outage probability. However, for large height, the LoS probability does not change that much with the height while the link distance becomes longer, so the outage probability increases.

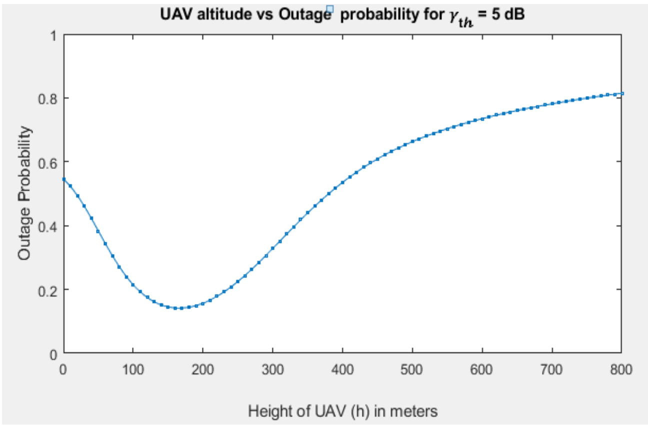

Fig.3. Drone altitude in meters vs. the outage probability for $\gamma_{th} = 5dB$

Fig.4. shows the outage probability plot for a SINR threshold of 10 dB for a fixed coverage radius of 500 m and interference link distance as 1000 m. Outage Probability decreases for smaller heights and increases at larger heights. As we increase the threshold value the outage probability also gets increases. However, there exists an optimum drone altitude at which the average outage probability will be less than at any other altitude. The optimum altitude point which has the lowest outage is around 180-200 m for coverage radius of 500 m.

Fig.5. shows the outage probability variation with respect to coverage radius for a SINR threshold of 5 dB for deployment with multiple drone altitudes and interference link distance as 1000 m. we can notice that as height of UAV raises outage probability also raises. But from outage curves for heights of 100 m and 200 m we can observe that to get a coverage radius of till 400 m optimum altitude point would be around 100 m. (The deployment for h=100 m outperforms

to that of h = 200 m). To get coverage radius more than 400m the optimum altitude point would be around 200 m.

TABLE I. SIMULATION PARAMETERS

Parameter	Value	Description
η_{LoS}	1 dB	Additional path loss to free space for LoS
F	2 GHz	Carrier frequency
N	2	Path loss exponent
η_{NLoS}	20 dB	Additional path loss to free space for NLoS
γ_{th}	5 dB	SINR threshold
N	-174 dBm/Hz	Noise power
Pt	46 dBm	Maximum transmit power of each device

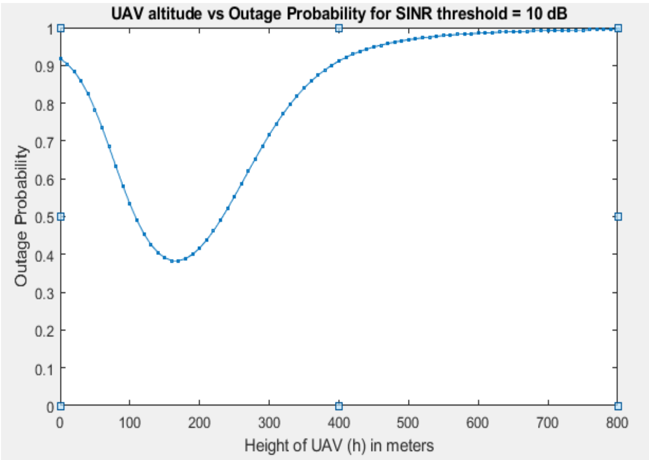

Fig. 4. Drone altitude in meters vs. the outage probability for $\gamma_{th} = 10\ dB$

It is also inferred from Fig.5 that for coverage radius of 500 m the optimum altitude point would be around 200 m. So we obtain low outage for a height of 200m than 100 m for coverage radius of more than 400 m.Outage reaches one for coverage radius more than 1200 m. It can aslo be inferred that link gets failed for a user located at a horizontal distance of more than 1200m from the UAV.

Fig.6. gives the outage probability plot with respect to variable SINR threshold for multiple drone altitudes for a fixed coverage radius of 500 m and interference link distance as 1000 m. It can be seen from Fig. 6 that as the UAV-BSs altitude increases, the outage probability increases due to the increase in path loss. As the height increases outage probability reaches one for lesser threshold value.

A. OUTAGE PROBABILITY ANALYSIS WITH INTERFERENCE LINK DISTANCE

Fig. 7. gives the outage probability plot with respect to UAV height for deployment with different horizontal interference link distances.It can be seen from the Fig.7. that as the horizontal interference link distance increases, outage probability also decreases as the impact of interference link on the communication gets reduced. We can also infer that the optimal height that minimizes $P_{out}(h, r_i)$ increases (shifts towards right) as the distance of interference link d_k increases.

B. Coverage Radius vs Outage Probability

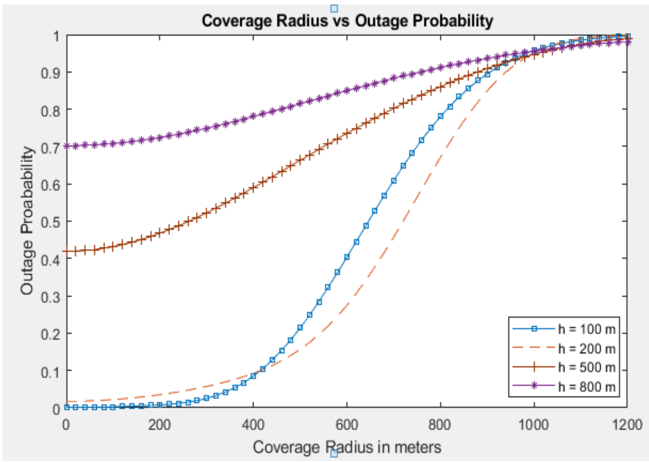

Fig. 5. Coverage radius in meters vs. the outage probability for $\gamma_{th} = 5\ dB$

C. SINR Threshold vs Outage Probability

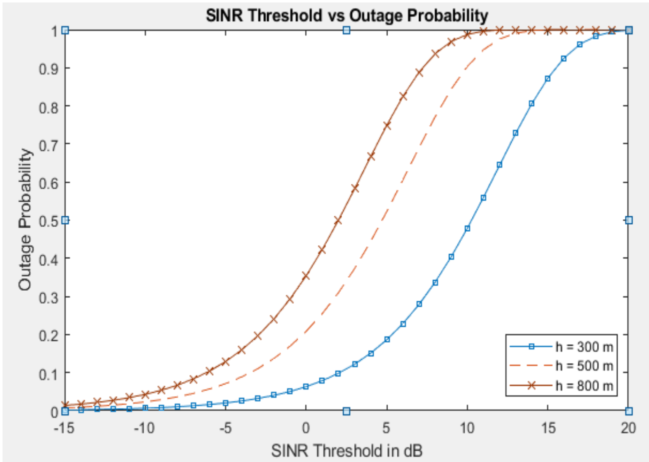

Fig. 6. SINR threshold in dB vs outage probability for multiple drone altitudes

D. OUTAGE CAPACITY

The outage capacity here is defined as the average probability at which the channel capacity will be below a certain level such that the quality constraint cannot be achieved. Here, for a Rayleigh fading channel the outage capacity for a certain threshold C_{th}bits/s/Hz is defined as follows:

$$P_{outC}(h, r_i) = \Pr[\log_2(1 + \gamma(h, r_i)) < C_{th}]$$

$$P_{outC}(h, r_i) = 1 - \exp\left(\frac{2^{C_{th}} - 1}{\gamma(h, r_i)}\right)$$

It can be seen from the Fig. 8. that as the capacity threshold value increases outage probability of capacity increases. When height increases outage reaches maximum for lesser capacity threshold value. From plot it can be inferred that the outage curve for the deployment of h = 200 m outperforms to that of h = 100 m. We observe the same trend as for the previous metrics. This is again due to the optimal altitude point of around 200 m for a coverage radius more than 400 m.

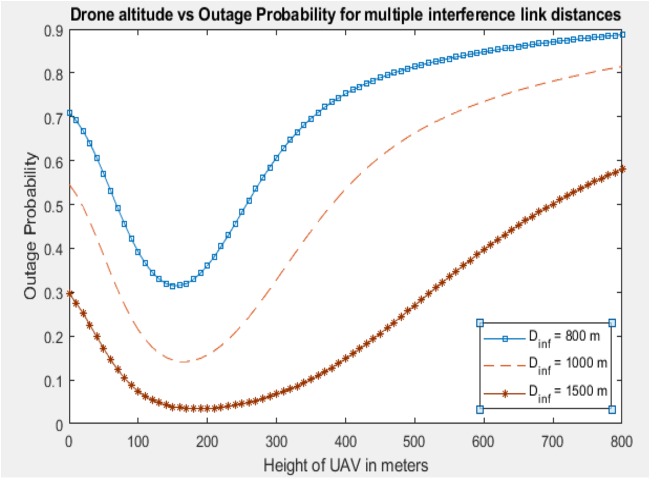

Fig. 7. Drone altitude in meters vs. the outage probability for γ_{th}= 5dB for multiple interference link distances.

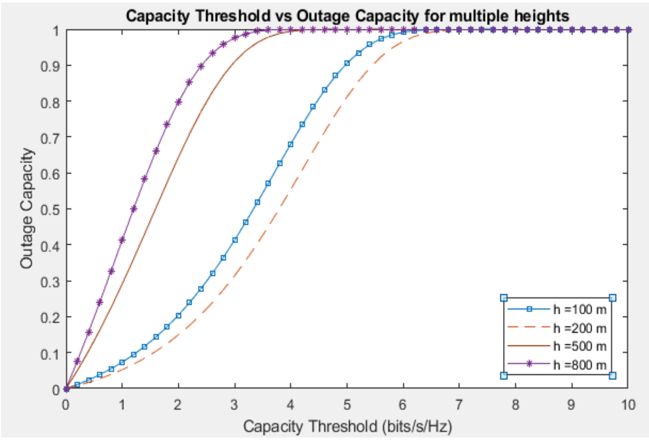

Fig. 8 Capacity threshold vs. the average outage capacity for multiple drone altitudes with fixed cell radius Ro = 500 m

V. Conclusion

This work analyzes the impact on reliable UAV communication of the interfering node. After characterizing the channel model affected by the communication link elevation angle, we determine the probability of interference for all possible main and interference link scenarios. We also show the effects of drone altitude, horizontal and vertical connection distances, coverage radius, and main and Interference communication scenarios. Specifically, we show the existence of the optimal UAV height for different scenarios, which increases as the power of the interference node decreases or the distance of the interference link increases or the coverage radius increases.

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