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Unmanned Aerial Vehicles Base Station Performance Analysis In Wireless Communications

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ABSTRACT

Unmanned aerial vehicles (UAVs) are becoming increasingly popular for a variety of applications, including wireless communication. manoeuvrability, low cost, and Line of sight (LOS) communication make UAVs a promising candidate for future wireless communication networks. This paper reviews the classification of UAVs, and their use cases in wireless communication, and UAV channel modeling. Begins by exploring the primary types of UAV channel fading: large-scale fading and small-scale fading, then reviews the UAV channel characteristics and categories . Finally, this paper discusses the performance evaluation of UAV base stations regarding UAV coverage probability, optimal altitude, ideal elevation angle, and minimum transmission power. Our findings demonstrate that several factors, including the height and density of buildings, coverage radius, UAV altitude, and necessary network throughput, impact the optimal altitude, elevation angle, and minimum transmission power.

Keywords: unmanned aerial vehicles, path loss, channel modeling, UAV base station.

تحليل أداء المحطات القاعدية الطائرة بدون طيار في الاتصالات اللاسلكية

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ملخـــــــص البحـــــــث

أصبحت المركبات الطائرة بدون طيار تحظى بشعبية متزايدة لتعدد استخداماتها في العديد من التطبيقات، بما في ذلك الاتصالات اللاسلكية. و بفضل قدرتها على المناورة، التكلفة المنخفضة، وقدرتها على الاتصالات عبر خط البصر، اصبحت الطائرات بدون طيار مرشحا مستقبليا واعدا لشبكات الاتصالات الاسلكية. تستعرض هذه الورقة تصنيف الطائرات بدون طيار، وحالات استخدامها في الاتصالات اللاسلكية، ونمذجة قنواتها. تبدأ الورقة بمناقشة النوعين الرئيسيين لتلاشي قنوات الطائرات بدون طيار: التلاشي واسع النطاق والتلاشي صغير النطاق، ثم تستعرض خصائص وفئات قنوات الطائرات بدون طيار، مع التركيز على قنوات جو–جو وجو–أرض. أخيرًا، تناقش هذه الورقة تحليل أداء المحطات الطائرة بدون طيار من حيث احتمالية تغطية الطائرات بدون طيار، والارتفاع الأمثل، وزاوية الارتفاع المثلى، والحد الأدنى لقدرة الإرسال. تُظهر نتائجنا أن نوع البيئة يؤثر على ارتفاع انتشار الطائرات بدون طيار،حيث ان ارتفاع معامل فقد المسار سيؤدي الي انخفاض احتمالية التغطية . علاوة على ذلك، نستنتج أن هناك مجموعة متنوعة من العوامل، مثل ارتفاع المباني وكثافتها، ونصف قطر التغطية، وارتفاع الطائرات بدون طيار، والإنتاجية المطلوبة للشبكة، ستؤثر على الارتفاع المثالي، وزاوية المثلى للارتفاع، والحد الأدنى لقوة الإرسال.

الكلمات الدالة: الطائرات بدون طيار، فقد المسار, تضمين القناة ، المحطات القاعدية الطائرة بدون طيار .

1. INTRODUCTION

The dramatically rising demand for higher transmission rates for wireless access has been incessantly growing, fueled by the rapid proliferation of highly capable mobile devices such as smartphones, tablets, and advanced IoT devices [1]. In return, the capacity and coverage of existing wireless.

cellular networks have been extensively strained, which led to the emergence of a plethora of wireless technologies that seek to overcome these challenges [1], one of these technologies is unmanned aerial vehicles (UAVs). The rapid development of UAV technology in recent years has enabled a widespread deployment of drones in a variety of applications, from goods delivery and environmental monitoring to rescue operations and communications networking, which is considered one of the most important emerging applications for UAVs.

In general, the terms "UAV" and "drone" can be used to refer to any type of flying, unmanned aircraft, or robot that can be remotely controlled from the ground without a human pilot aboard and has multipurpose functions [2]. which can be used as aerial base stations or flying relay nodes,to improve wireless networks' capacity, coverage, dependability, and energy of wireless networks also it can be used as aerial user equipment. Benefiting from the high maneuverability, sufficient flexibility, ease of deployment, and lower operating and maintenance costs the UAV can be quickly deployed to provide wireless services for some hotspots and in case of terrestrial base station (BS) failure. Even though, compared to fixed infrastructure-based communications, location flexibility offers significant performance improvements. These benefits, meanwhile, also present several difficulties [3]. To use UAVs effectively for any wireless networking applications, it is important to take into account their capabilities and flying altitudes.

1.1 Classification of UAVs

Depending on the application and goals one can choose different types of UAVs while taking into account their capabilities (e.g., sensors, size, weight, battery life, etc.) and their flight abilities (e.g., altitude, ability to hover, etc.) [2]. It’s important to use an

appropriate type of UAV that can meet various requirements imposed by the desired quality-of-service (QoS), environmental conditions,, and local regulations [1].

There are two basic classifications for UAVs one is based on the flight altitude of the UAVs and the other depends on the wing type. According to their altitudes, UAVs can be categorized into:

- low-altitude platforms (LAPs)
- high-altitude platforms (HAPs).

LAPs are usually small-sized UAVs that can fly at low altitudes ranging from tens of meters up to a few kilometers, LAPs can move rapidly and are very flexible in their deployment [1,2], but they have a smaller coverage area and shorter endurance times.

The majority of UAVs that have recently been considered for end-user and commercial applications, are basically LAPs [4]. HAPs are larger and more capable UAVs that are used to fly at high altitudes (usually exceeding 17 km), HAPs are frequently utilized for long-term missions and are semi-stationary in nature. In general, HAP systems are often recommended for providing wide-scale wireless coverage for large geographic areas [4].

Depending upon wing type UAV can be either:

- fixed-wing
- rotatory wing

The fixed-wing generates lift using wings with forward airspeed. It needs a runway for taking off and landing and forward speed needs to be maintained, while the rotary wing generates lift using blades revolving around a rotor shaft. It can hover and move in any direction. A rotary-wing UAV's mechanism is based on vertical takeoff and landing, and it usually has a lower payload, lower speed, and shorter range compared to fixed-wing UAVs. Figure (2), describes the UAV Classification.

1.2 Uav Use Cases In Wireless Communication

UAVs, in all of their types and sizes, provide ample opportunities for wireless communica- -tion applications. Across these application domains, we can see three primary communication roles for UAVs [2]:

1) As Aerial Base Station: in this use case, the UAV itself is used as a provider of wireless communication services as a mobile BS which can be deployed in case of any partial or complete failure of the existing infrastructure caused by natural disasters or if there is a significant traffic load [2,4].

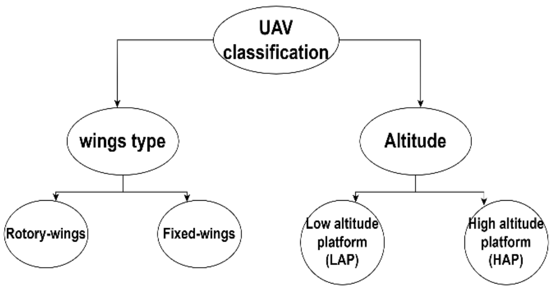

Fig 1. CLASSIFICATION OF UAVS.

2) As Flying Relay Node: in this use case, the UAVs act as relay stations that provide a relaying link between a transmitter and a receiver. In particular, the use of UAV relays is suitable for expanding the coverage of a ground network or for overcoming obstacles.
3) As Aerial User Equipment: in this case UAVs act as flying user equipment (UE) of the wireless network. that can be used for any delivery services for information collection, or as remote sensing nodes in hard-to-reach areas [2,4].

1.3 Uav Channel Modeling

Compared to terrestrial radio channels, aerial radio channels exhibit many different characteristics. For example, when the heights of the transmitter and receiver are at a medium height or above, the direct LOS signal path between them is less likely to be obstructed by other objects in the propagation environment, additionally due to the absence of surrounding objects aloft in the sky, radio waves experience less scattering when they propagate. As a result, the number of multipath components tends to be less for aerial wireless channels, and in general, it decreases with the height of the antenna aloft in the air [2] we can roughly divide the airborne communication channel fading into two types:

- Large-scale fading, arising from path loss of signal as a function of distance and shadowing by large objects such as buildings and hills.
- Small-scale fading, resulting from the constructive and destructive interference of the multiple signal paths between the transmitter and receiver. Multipath fading can also arise from the aircraft itself, while these are typically weak and have a very small relative delay [5].

A-Large-Scale Propagation Channel Models

Large-scale fading is used to describe the signal level at the receiver after traveling over a large area and experiencing shadowing by large objects such as buildings and hills. This type of fading can be approximated using numerous models, in this section, we briefly address the main three of these models:

1) Free-Space Path Loss Model

The free space path loss is the loss in signal strength in terms of radio energy when it travels between two antennas through free space, and it is valid only when there is an unobstructed LOS (Line-Of-Sight) path between the transmitter and the receiver and no objects in the first Fresnel zone. [5]

The free-space path loss denoted by PL is defined as:

$$PL = \frac{1}{G_t G_r}\left(\frac{4\pi d}{\lambda}\right)^2 \quad (1)$$

where ***d*** denotes the horizontal distance between the transmitter and the receiver, $G_t\ and\ G_r$ are the transmitter and receiver antenna gain.

2) Two-Ray Model

In an aerial wireless channel, in addition to the direct path, there may exist other paths between a transmitter and a receiver, particularly when a UAV is flying at a low height. In such cases, the free-space path loss may not be accurate when used alone. A two-ray model that considers both the direct path and a ground-reflected path between a transmitter and a receiver turns out to be a useful model for aerial wireless channel modeling spatially in rural environments and over sea surfaces [2].

For large d, the received signal power can be approximately calculated as follows [2]:

$$P_2 \approx P_t\left(\frac{\lambda}{4\pi}\right)^2 \left\|\frac{\sqrt{G_{t,0}G_{r,0}}}{d_0} + \frac{\Gamma\sqrt{G_{t,1}G_{r,1}}}{d_1}e^{-j\Delta\emptyset}\right\|^2$$
$$\approx P_t\left(\frac{\lambda}{4\pi}\right)^2 \frac{G_t G_r}{d^2}\left(\frac{4\pi h_t h_r}{\lambda d}\right)^2$$
$$\approx P_t G_t G_r {h_t}^2 {h_r}^2 d^{-4} \quad (2)$$

Where P_t is the UAV's transmit power, $G_{t,0}$ and $G_{r,0}$ are the antenna field radiation patterns of the transmit and receive antennas in the LOS direction, respectively, $G_{t,1}$ and $G_{r,1}$ are the antenna field radiation patterns of the transmit and receive antennas along the direction of the ground reflection path, respectively, and *r* is the reflection coefficient for the ground is approximately ≈ -1, and the phase difference between the two received signal components is denoted by$\Delta\emptyset$, The propagation distances of the LOS path and the ground-reflected path are denoted by $d_0$and d_1. h_t and h_r are the heights of the transmitter and the receiver, respectively as in Figure (3).

The two-ray path loss, when d $\gg h_t, h_r$ denoted by:

$$PL_{2ray} \approx \frac{d^4}{G_t G_r {h_t}^2 {h_r}^2} \quad (3)$$

As we see in (3) at large values of d, the two-ray path loss increases with the distance raised to the fourth power. In contrast, the free-space path loss increases with the distance raised to the second power only, we can also observe that the two-ray path loss does not depend on the carrier frequency [2].

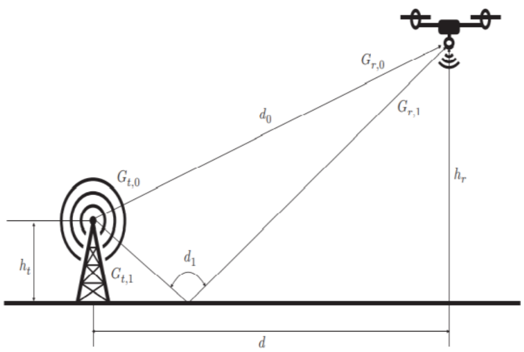

Fig 2. The flat-earth two-ray model.

3) Log-Distance Path Loss Model

In aerial wireless channel modeling the log-distance model has been widely used which is considered a fundamental essence of the large-scale channel effects of radio propagation is that the path loss increases exponentially with distance. The rate at which the path loss increases with distance is called the path loss exponent. Log-distance path loss models are still much simplified from real propagation environments, but they capture the essence of the large-scale channel effects of radio propagation [2].

The basic form of the log-distance path loss model can be expressed by [7].

$$L(d)[dB] = L(d_0) + 10n log\left(\frac{d}{d_0}\right) + x, \quad for\ d \geq d_0 \quad (4)$$

where $L(d_0)$ is the free space path loss at distance d_0 which is the close-in reference distance, n is the path loss exponent depends on the propagation environment, d is the distance between the transmitter and receiver. x is a zero-mean log-normal distribution random variable (in dB) with standard deviation $\boldsymbol{\sigma}$ where the values of $\boldsymbol{\sigma}$ tend to be smaller in aerial wireless channels, and decreases with increasing antenna height, this variable is used only when there is a shadowing effect where shadowing is the random attenuation due to blockage from objects in the signal path, giving rise to random variations of the received power at a given distance [6]. If there is no shadowing effect, then this variable is zero, which is why it is also referred to as the log-normal shadowing model [4].

B-Small-Scale channel Propagation

Small-scale fading, or often simply fading, is the rapid variation of the received signal level over time, frequency, and space in the short term. Fading is caused by multipath signal propagation leading to the subsequent arrival of multipath components (MPC) with varying phases. Relative phase differences of these components can cause constructive and destructive interference. The speed of the TX/RX and surrounding objects causes changes in MPCs [7].

Compared with mobile wireless channels, UAV air-to-ground channels will often be more dispersive, incur larger terrestrial shadowing attenuations, and change more rapidly [5]. The UAV channels can be characterized as a linear time-variant channel, this time variation arises because either the transmitter or the receiver is moving, and therefore the location of reflectors in the transmission path, which gives rise to multipath, will change over time.

To characterize the small-scale fading, statistical models have been used to describe the empirical fading distribution of the amplitude of the received signal along the radio propagation channel, e.g., Nakagami model, Rayleigh model, Rician model, etc. The probability density function (PDF) is generally employed to give a quantitative analysis of this kind of fading distribution [3].

The Rician model has been widely used for aerial channel modeling due to the high likelihood of LOS [2]. The statistical time-varying envelope of a narrowband channel, or the envelope of a multipath component in a wideband channel, in the Rician model in which random independent reflected and scattered paths are superimposed on a stationary nonfading component (such as the LOS component). [1] is given by:

$$f_{|h|} = \frac{x}{\sigma^2} e^{-\frac{x^2+A^2}{2\sigma^2}} I_0\left(\frac{Ax}{\sigma^2}\right), \quad x \geq 0 \tag{5}$$

Where x is Gaussian random variables with mean zero and variance σ^2, $2\sigma^2$is the average power in the Nonline-of-sight(NLOS) multipath components, and A^2 is the power in the LOS component. The function I_0 is the modified Bessel function of 0^{th} order.

In the case of the NLOS scenario Rayleigh fading model is preferred, and it can be expressed as follows:

$$f_{|h|} = \frac{x}{\sigma^2} e^{\frac{-x^2}{2\sigma^2}}, \quad x \geq 0 \tag{6}$$

1.4 Uav Communication Channel Characteristics

Compared to a terrestrial deployed communication system, where only ground-to-ground communication links are involved and only users are mobile, UAVs' air-ground linkages communication channel characteristics are significantly different. In UAV-assisted communication, the user and the deployed BS are both mobile, so even a slight movement can have a significant impact on the air-to-ground channel characteristics [4]. One of the most important characteristics of the UAV communication channel is the LOS and NLOS probability.

- LOS and NLOS probability

One of the important factors in characterizing the UAV communication channels and forming channel models is the line-of-sight probability, where the links between a UAV and a ground device can be either LOS or NLOS depending on the locations of the UAV and the ground device as well as the type of propagation environment (such as, rural, suburban, urban, high-rise urban), density and height of buildings, and elevation angle between UAV and ground device [5].
A common probabilistic LOS model that captures the probability of having an LOS connection between the aerial base station and ground users as a function of elevation angle which is given by [5]:

$$P_{Los} = \frac{1}{1 + C\, exp(-B[\theta - C])} \tag{7}$$

where C and B are constant values that depend on the environment (rural, urban, dense urban, or others) and θ is the elevation angle in degrees.

- Atmosphere and rain attenuation

When studying UAVs channel there's an additional loss that we should take into account. Attenuation is caused by Atmospheric Gases where the gaseous molecules, such as oxygen and water vapor, contribute to some extent to signal attenuation. The attenuation may be modeled by additional path loss factors that are additive in decibel units. Rain attenuation is where the rain affects the propagation of electromagnetic waves, as the raindrop absorbs some of the signal strength depending on the rainfall rate, and the size and shape of the raindrops [2].

- Airframe shadowing

In aerial wireless channels, there is a unique shadowing phenomenon known as "airframe shadowing," which is defined as the obstruction of the line of sight (LOS) path by the aircraft body, which may occur during aircraft maneuvers [2]. This shadowing can cause significant attenuation of the signal, which can disrupt communication links and reduce the performance of sensors and other equipment on the UAVs.

1.5 Uavs Communication Channel Categories

The aerial wireless channels are divided into three categories air–to-ground (ATG) channel, air–to-air (ATA) channel, and ground-to-ground (GTG) channel. In this paper, we will focus on ATA and ATG channel models because there is enough study on GTG channels.

A. AIR-TO-AIR Channel

The ATA channel characterization is particularly essential in multi–UAV networks and aerial wireless sensor network applications, where the characteristics of the ATA channel rely on the UAV altitude and relative velocity [10]. Usually, air-to-air communication links experience a dominant LOS where there is no obstacle in the air, although there may be some multipath fading from ground reflections, its impact is not as significant as in UAV-to-ground or ground-to-ground channels [4].
The free-space path loss model is the simplest and most commonly used model for air-to-air (ATA) communication links, assuming a line-of-sight (LOS) path between the transmitter (Tx) and receiver (Rx). This assumption is valid in many cases, such as when two UAVs are communicating with each other in a open, unobstructed environment [12].
Since most path loss models are based on path loss exponent (PLE) and shadowing factor (SF), for better simulation, an ATA channel model is suggested in [11] where a ray-tracing simulation for UAV ATA channel modeling at 2.4 GHz was carried out at various heights over the sea and the land. To model the path loss, they run simulations using a fixed transmitter and a circularly flying receiver at a distance of 3 km and a radius of 100m. They derive the log-distance path loss model depending on the environment type, and use Rician fading to describe the small-scale fading, using the least squared error (LSE) fit:

$$PL(dB) = \alpha(dB) + n10\log(d), \quad (8)$$

where *d* is the Tx-Rx distance in meters, *PL* is the path loss for distance *d, n* refers to the path loss exponent which depends upon the environment and α refers to the intercept that the LSE fit makes with the Y-axis [11].

B. AIR-TO-GROUND CHANNELS

ATG channels are defined as the wireless communication links between an aircraft in the air and a base station on the ground. ATG channels are highly dependent on the altitude, type of the UAV, the elevation angle, and the type of the propagation environment, where because the air has distinctive channel characteristics, such as three-dimensional (3D) space and time-variability, ATG channels are considered much more complex than current ground communication channels. Therefore, finding a generic channel model for UAV-to-ground communications needs comprehensive simulations and measurements in various environments [1].

Air-to-ground in different scenarios:

1) ATG Channels in Rural and Over-Water Areas: Because of the prevalence of the surface reflection and dominance LOS components, the log-distance or two-ray models are most commonly utilized in UAV operations over deserts or seas. The stochastic Rician fading model is another popular model that includes two components: a random distributed component with specific statistical distributions and a deterministic LOS component. The Rician factors of UAV-ground channels in rural and over-water areas vary greatly, depending on the environment around the ground terminals [9].

2) *Low Altitude ATG Channels in Cellular Networks*

Cellular networks can be considered as a prospective candidate to facilitate UAV applications in civil and commercial domains. Widely deployed cellular infrastructure can be utilized to provide reliable ATG channels and hence, cut the cost of investing in additional ground infrastructure and spectrum allocation. However, since cellular–connected UAVs depend on the cellular network and cellular infrastructure can collapse due to natural disasters, a viable fail–safe mechanism is needed. Other challenges, such as down–tilted base station antennas, neighboring cell interference, handover performance, multiple access, UAV mobility, and link security, also need to be addressed thoroughly before the widespread implementation of UAV networks connected to the cellular networks [10].

3)ATG Channels In Urban Areas

In urban areas, where many objects affect the propagation path the probability of line of sight is very low so open-area models as in rural areas and over-sea models are not suited for urban areas.

1.6 Uav Base Station Performance Analysis

This section discusses the efficient deployment of low-altitude UAV base stations to achieve a good performance in terms of flight, focusing on the downlink coverage probability, the optimal altitude, and elevation angle to find the best possible coverage, and we investigate the variation effect on UAV performance in two scenarios both vertical and horizontal aspect. Finally, the minimum required to transmit power for a single UAV is a guideline for power minimization.

A. COVERAGE PROBABILITY

The coverage probability for a ground user, located at a distance $r \leq h.\tan\left(\frac{\theta_B}{2}\right)$ from the projection of a stationary low-altitude aerial platform UAV as a function of the UAV's altitude h and the antenna gain G_{3dB} on the desired area [13] is given by:

$$P_{cov} = P_{Los}.Q\left(\frac{P_{min} + L_{dB} - P_t - G_{3dB} + u_{Los}}{\sigma_{Los}}\right) + P_{NLos}.Q\left(\frac{P_{min} + L_{dB} - P_t - G_{3dB} + u_{NLos}}{\sigma_{NLos}}\right)$$

(14)

Where P_t is the UAV's transmit power, $N(u_{Los}, \sigma_{Los})$ and $N(u_{NLos}, \sigma_{NLos})$ are shadow fading with normal distribution in dB scale for *LOS* and *NLOS* links. where the

variance depends on the elevation angle and type of the environment as follows:

$$\sigma_{Los}(\theta) = k_1 \exp(-k_2\theta) \tag{15}$$

$$\sigma_{NLos} = g_1 \exp(-g_2\theta) \tag{16}$$

$P_{min}$is calculated as:

$$P_{min} = 10\log(\beta N + \beta\bar{I}) \tag{17}$$

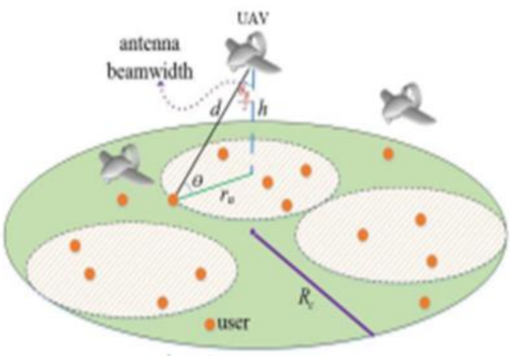

Fig 3. System model. [13]

P_{min} is the minimum received power requirement (in dB) for a successful detection, N is the noise power, and β is the signal-to-interference-plus-noise-ratio (SINR) threshold. $\bar{I}$ is the mean interference power received from the nearest UAV which is given by:

$$\bar{I} = P_t g(\emptyset)[10^{\frac{-u_{Los}}{10}} P_{Los} + 10^{\frac{-u_{NLos}}{10}} P_{NLos}] \left(\frac{4\pi f_c d}{c}\right)^{-n} \tag{18}$$

L_{dB} is the path loss for the air-to-ground communication is:

$$L_{dB} = 10nlog\left(\frac{4\pi f_c d}{c}\right) \tag{19}$$

d is the distance between the UAV and a ground user which equal to $d = \sqrt{h^2 + r^2}$, as in Figure (4), and $n \geq 2$ is the path loss exponent. This model considers the LOS and non-line-of-sight (NLOS) links between the UAV and the ground users separately. Each link has a specific probability of occurrence which depends on the elevation angle, environment, and relative location of the UAV and the users [13].

where $\theta = sin^{-1}\left(\frac{h}{d}\right)$ is the elevation angle between the UAV and the user. k1,k_2,g_1, and g_2 are constant values which depend on the environments. Finally, the LOS probability is given by:

$$P_{Los} = \alpha\left(\frac{180}{\pi}\theta - 15\right)^{\gamma} \tag{20}$$

where α and γ are constant values reflecting the environmental impact. Note that, the NLOS probability $P_{Nlos} = 1 - P_{Los}$.

B. Optimal Altitude And Elevation Angle For Maximum Coverage

In this section, we aim to find the optimum altitude by providing a mathematical model capable of predicting the optimum elevation angle of a LAP based on the statistical parameters of the underlying urban environment. Then from the optimal altitude, we compute the maximum coverage radius. After that to analyze the effect of the LAP's altitude on the provided service, firstly we define the service threshold in terms of the maximum allowable path loss PL_{max}. Then we calculate the path loss versus elevation angle at a specific UAV height, to compute the optimum elevation angle.

$$arg \max_{\theta} PL(R,\theta) = \left\{\theta_{opt}: \frac{\pi \tan(\theta_{opt})}{9\ln(10)} + \frac{abAe^{(-b[\theta_{opt}-a])}}{\left[1+ae^{(-b[\theta_{opt}-a])}\right]^2} = 0\right\} \quad (21)$$

$$A = \eta_{LOS} - \eta_{Nlos} \quad (22)$$

Where η_{LOS} and η_{Nlos} are the mean excess path loss in the case of LOS and NLOS respectively After solving (20), numerically we found that the values of optimal elevation angle corresponding to suburban, urban, and dense urban environments are 20.53, 42.44, and 53.06 degrees respectively.

Then, from the optimum elevation angle presented above, the maximum coverage radius R_{max} at the maximum allowable path loss L_{th} is given by [15]:

$$R_{max} = \cos(\theta_{opt}).10^{0.05\left(L_{th}-\frac{A}{1+a\exp\left(-b(\theta_{opt}-a)\right)}-B\right)} \quad (23)$$

Then from R_{max} and θ_{opt} presented above, the optimal altitude h_{opt} is given by

$$h_{opt} = R_{max}.\tan(\theta_{opt}) \quad (24)$$

The next table shows the values of optimum altitude and maximum coverage radius at different maximum allowable path losses in urban environments.

Table 1. Optimum altitude and maximum coverage at different maximum allowable path losses.

maximum allowable path loss in dB L_{th}	optimum altitude in m h_{opt}	maximum coverage in m R_{max}
90	204.4373	223.585
100	646.874	707.0379
110	2044.373	2235.85
120	4075.411	10882.9

Table (1) shows that the maximum coverage and optimum height rise with an increase in the maximum permissible path loss, providing the UAV with more maneuvering space. It is evident that if the UAV is deployed at the ideal height, it offers all ground users the maximum signal-to-noise ratio. For the users, this translates to a minimum path loss.

Next, we try to find the optimum elevation angle at a certain UAV height by computing the UAV path loss for each elevation angle from 10 < θ < 90 as follows [14]:

$$PL(R,\theta) = \frac{A}{1+ae^{(-b(\theta-a))}} + 20\log(R.\sec(\theta)) + B \quad (25)$$

Where *R* is the ground distance between the UAV and the user, θ is the elevation angle

$$B = 20log\left(\frac{4\pi f}{c}\right) + \eta_{NLos} \quad (26)$$

C. Variation Effect On Uav Performance

Variations can significantly impact the performance and stability of Unmanned Aerial Vehicles (UAVs). where it could reduce stability and controllability, degrade navigation accuracy, and reduce mission effectiveness. There are two types of variations: vertical, and horizontal variation. The vertical variation is the altitude variation, where the minimum exactable altitude variation for UAVs depends on several factors, including the type of UAV, the payload, and the weather conditions.

Horizontal variation, also known as lateral drift or crosswind, can significantly impact the performance and stability of UAVs. It occurs when the UAV's path deviates from its desired course due to the influence of wind or other external forces.

A very small variation is called vibration, which refers to the unwanted shaking or oscillation of Unmanned Aerial Vehicles during flight. It can be caused by various factors, including the spinning of motors, wind gusts, and mechanical faults. Rotary-wing aircraft have higher vibration levels than fixed-wing aircraft due to their lift being generated by one or more high-speed rotors. Sensitive onboard sensors (cameras, GPS) can be affected by vibrations, which can translate into shaky, blurry footage, compromising mission objectives. The vibrations can be mitigated by multiple methods, one such method involves using mounts or isolators. A rubber or gel mount that absorbs vibrations through it's material properties.

D. Minimum Transmit Power

Finding the minimum transmit power required provides very useful guidelines for power minimization Considering the essential limit of available onboard energy of UAVs, which is one of the main concerns in designing UAV networks. In this part, the target area is considered to have a fixed radius of R_c, where the goal is to find the optimal altitude with the minimum required transmit power of drone small cells (DSCs) to cover the target area [16].

The minimum required transmit power is equal to:

$$p_{t,min}(dB) = \bar{L}\left(R_c, \hat{h}_{opt}\right) + \gamma_{th} N \tag{27}$$

Where N is the noise power, γ_{th} is signal to noise ratio (SNR) threshold. $\bar{L}$ is the average path loss as a function of the UAV altitude and the coverage radius becomes

$$\bar{L}(R, h) = P(Los).L_{Los} + P(NLos).L_{NLos} \tag{28}$$

P(Los) is the probability of having LOS connections at an elevation angle of θ is computed as in (3-2) which is equal to:

$$P(Los) = \frac{1}{1 + \alpha exp(-\beta\left[\frac{180}{\pi}\theta - \alpha\right])} \tag{29}$$

As we know *P(NLos)=1-P(Los)*

the path losses for LOS and NLOS connections are equal to:

$$L_{Los}(dB) = 20\log\left(\frac{4\pi f_c d}{c}\right) + \varepsilon_{Los} \tag{30}$$

$$L_{NLos}(dB) = 20\log\left(\frac{4\pi f_c d}{c}\right) + \varepsilon_{NLos} \tag{31}$$

Where ε_{Los} and ε_{NLos} are the average additional loss to the free space propagation loss which depends on the environment, f_c is the carrier frequency, d is the distance between the UAV and ground receiver, $d = \sqrt{h^2 + R^2}$, and R is the radius of ground users from a point corresponding to the projection of DSC onto the ground.

2. RESULTS AND DISCUSSION

To analyze the performance of UAV base stations, simulations were carried out using MATLAB. In the simulation buildings were randomly generated and distributed. UAV base stations were deployed at various altitudes.

A- LOS AND NLOS PROBABILITY

In this subsection, the impact of Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) conditions on UAV communication performance is analyzed. where the LOS probability is calculated based on the environment model and UAV-UE elevation angle.

To study the LOS probability between the aerial base station and ground user Figure (4) shows the LOS probability for three kinds of environments (suburban, urban, dense urban) versus the elevation angle. We found that the value of LOS probability increases as the elevation angle increase where it has a very low probability at low angles but rises in a fast way after 5 degree in suburb environment and 20 degree in urban and dense urban environments, this is due to the fact that as the UAV gets higher, its elevation angle increases and becomes less likely to be blocked by obstacles on the ground. The nurtures of the environments also play fundamental rowels where in suburban environments, the buildings are typically shorter and farther apart, whereas urban and dense urban environments are typically more densely built up, with taller buildings and more obstacles, which are more likely to cause signal scattering and attenuation. causing a low probability of a clear line-of-sight (LOS) path, for example a 50% LOS probability is attained at an elevation angle of approximately 10° in suburban areas, compared to 25, and 30 degrees in dense urban environments.

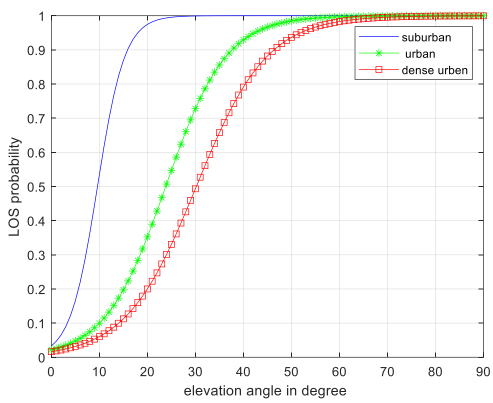

Fig 4. LOS probability as a function of elevation angle.

B- COVERAGE PROBABILITY

This subsection evaluates the coverage performance of UAV base stations through system-level. System simulations are carried out to validate the analysis and study the impact of key parameters on real coverage behavior. The simulations investigate how the probability of coverage varies with UAV altitude, antenna beam width, and environment type. The optimal altitude to maximize coverage under various operational conditions is also established.

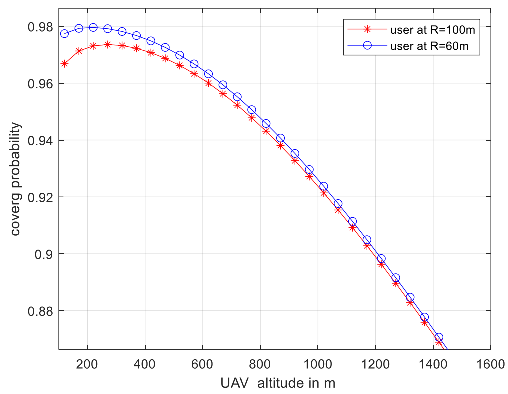

Fig 5. The coverage probability for a ground user versus UAV height in urban environments. at R= 60, 100m.

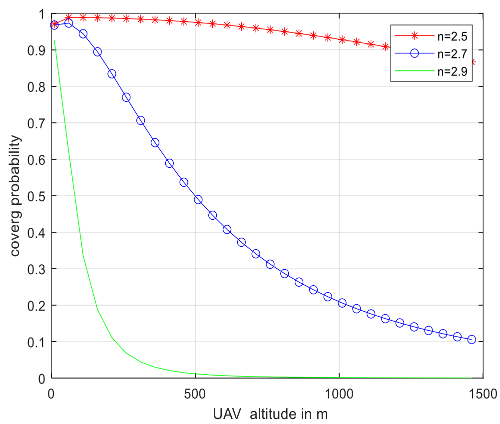

Fig 6. Coverage probability at different path loss exponents in urban environments at (R=10m).

In Figures (5,6) for coverage probability to a ground user versus UAV height in urban environments, at R= 60, 100m, we consider the UAV-based communications over 2 GHz carrier frequency (f_c = 2 GHz) in an urban environment (with α = 0.6, γ = 0.11, k1 = 10.39, k2 = 0.05, g1 = 29.06, g2 = 0.03, u_{Los}= 1 dB, u_{NLos} = 20 dB), and n = 2.5. The Transmitting power P_t = 35 dBm, the main lobe gain θ_B = 80°, R is chosen equal to 100 and 60 to satisfy: $r \leq h.\tan(\frac{\theta_B}{2})$ where h (1) =120m.

we observe that changing the UAV's altitude affects the coverage probability for a ground user at 60m, and 100m away from the projection of the UAV. As a result, the coverage probability increases until it reaches h=220,270 m respectively, because of the increase of the LOS probability where these heights are considered the optimal altitude for these conditions. After that the coverage probability begins decreasing as the UAV heights increase, that's because the distance between the UAV and the user extends leading to a rise in the pathloss beyond the optimal altitude. We notice also that the difference in coverage probability between the user at 60 and 100 m away from the UAV becomes unnoticeable at high altitudes because the difference between the two positions is small compared to the UAV highs.
In figure (6) we observe that when changing the pathloss exponent the coverage probability decreases with increasing the pathloss exponent where at n=2.9 the UAV altitude should be less than 100m to have a coverage probability above 0.5, while when n=2.7 the UAV altitude could retch 500m for the coverage probability to drop to 0.2, that's because the pathloss exponent is a function of the propagation environment, and a higher pathloss exponent means that the received signal power decreases more rapidly with distance which makes it more difficult to achieve a given signal-to-noise ratio (SINR) threshold. Therefore,a higher pathloss exponent leads to a lower coverage probability. So, in an urban environment with a high pathloss exponent, UAVs need to be deployed at lower altitudes to achieve a good coverage probability, while in a rural environment with a low pathloss exponent, UAVs can be deployed at higher altitudes to achieve a good coverage probability.

C- Optimal Altitude And Elevation Angle For Maximum Coverage

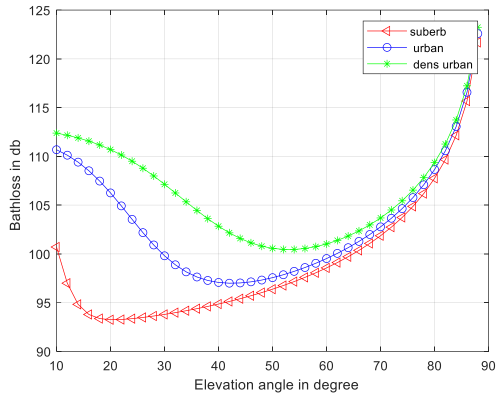

Fig 7. Path loss versus elevation angle in three different environments when h=100m.

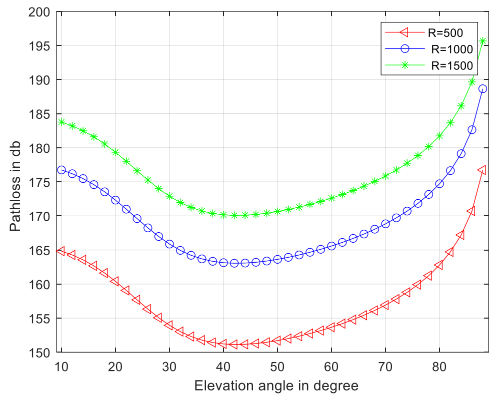

Fig 8 . The path loss versus elevation angle in different coverage radius.

This subsection performs analysis and simulations to determine the ideal altitude and elevation angle settings for UAV base stations to maximize coverage area. Various altitude and angle combinations are tested to identify the settings providing maximum coverage footprint while meeting a predetermined signal quality threshold. System simulations are then carried out considering different propagation environments.
In Figure (7) illustrates the relationship between path loss and elevation angle for UAV-based communications over 2 GHz carrier frequency in three different environments suburban, urban, and dense urban, where UAV height

h=100m, and the user is 500m away from the UAV's projection. We found that the number of local minimum path losses as a function of elevation angle is not greater than one which considered the optimum elevation angle at this altitude, and it is equal to 22,44 and 56 degrees corresponding to suburban, urban, and dense urban environments respectively with path loss equal to 93.24,96.66 and 100.45 dB respectively, This indicates that within a specific coverage radius, there is an elevation angle at each UAV altitude that makes best performance in terms of communication link reliability.

Figure (8) by using the same simulation, shows the relationship between path loss and elevation angle for three different coverage radii 500,100,1500m in an urban environment. we can see that optimum elevation angle is 43 degrees for each of the three radiuses; but the path loss values are different which equal 151 dB, 163 dB, and 170 dB respectively. we can assume that the optimum elevation angle with minimum path loss required to achieve an LOS link with a device or sensor will increase as the coverage radius increases. This is because the device or sensor will be further away from the UAV, and therefore the signal will have to travel a longer distance causing the path loss to increase. We therefore draw the conclusion that the optimal elevation angle will vary depending on several factors, including the height and density of the buildings, the coverage radius, the UAV altitude, and the intended network throughput. When designing a UAV-based network, it is important to consider these factors to ensure that the network operates reliably and efficiently.

D- Variation Effect On Uav Performance

This subsection analyzes how the performance of UAV base stations is impacted by variations in deployment parameters through extensive system-level simulations. Performance stability and sensitivity to changes are important considerations in UAV network planning and operation. This subsection first evaluates the effect of altitude fluctuations by testing a range of UAV heights around the optimal values determined previously. After that, the impact of coverage radius variations is also studied.

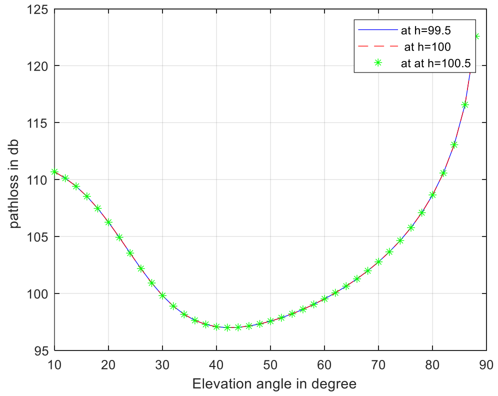

Fig 9. Path loss versus elevation angle in an urban environment when R=500m.

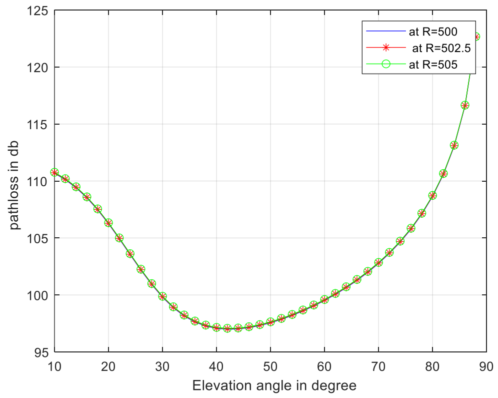

Fig 10. path loss versus elevation angle in an urban environment at h=100m.

Figures (9,10) show the variation effect on path loss versus elevation angle we assume that the UAV has the same conditions in Figure (7,8) where the only variable parameter is the UAV altitude by changing h from 100 to 100.5m and 99.5, thus the variation of UAV altitude is considered 0.5% of the actual altitude which is equal to 0.5m. As we can see from Figure (9) The impact of altitude variations (up to 0.5 meters) on path loss is negligible. This means that vertical variations have little or no effect on UAV performance when they are less than 0.5% of the UAV's altitude. This may be further validated by conducting real-world experiments and simulating the propagation of radio waves in various environments. However, it is important to be aware that this approximation may not be valid in all cases. For example, if the UAV is flying close to the ground, then even a slight altitude variations can have a significant impact on the path loss. Additionally, if the surrounding environment is complex, such as in an urban area with tall buildings, then small altitude variations can also have a more significant impact on path loss. Also, from Figure (10) we notice that when changing the user position from 500 to 502.5m or to 505 m the path loss and optimum elevation angles remain the same in all three different positions. This means that when the user changes its position (horizontal variation) by 0.5% or less, it doesn't affect the UAV performance and can be neglected because the horizontal distance between the UAV and the ground user is significantly greater than the altitude, this knowledge can be used to simplify the design and analysis of UAV-based communication systems.

E- MINIMUM TRANSMIT POWER

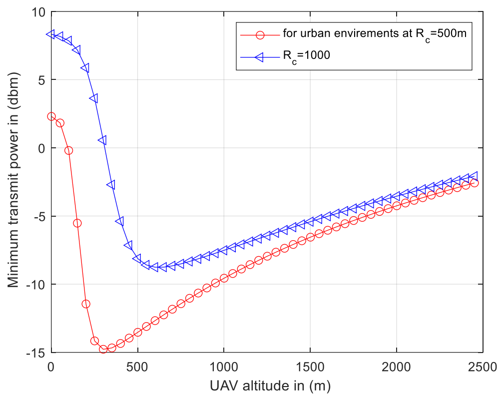

Fig 11. Minimum transmit power versus UAV altitude.

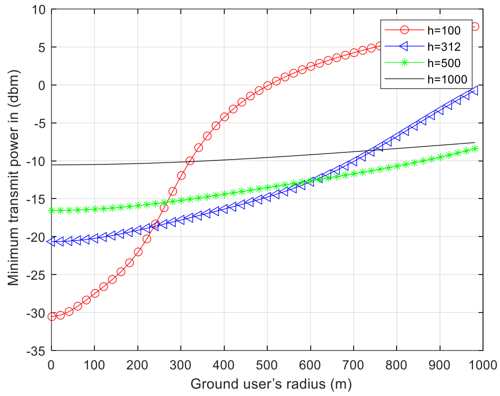

Fig 12. Minimum transmit power versus ground user's radius.

In Figures (11,12) we consider the UAV-based communications over 2 GHz in an urban environment, where the user is considered 500,1000m away from the projection of the UAV(*R*=500,1000m). the signal-noise to noise ratio (SNR) threshold (γ_{th})is equal to 10 dB, and the noise power(*N*)= - 120 dBm. We can see from Figure (11) that as the radius of the target area increases, so do the optimal altitude and the minimum transmit power needed to cover the area. For example, when the target area radius is R_c =500m, the optimal altitude facing the minimum transmit power at an urban environment is equal to 312 m, and it rises to 623m as the coverage radius increases to 1000m So as the altitude of the UAV increases the probability of LOS connections between the transmitter and receiver increases, until it reaches the optimum altitude, After that, the minimum required transmit power starts to increase to compensate for this attenuation because the distance between the UAV and the user increases, resulting in higher path loss and weaker signal strength.

Figure (12) examines the relationship between the altitude of the UAV and the minimum transmit power required for communication between a UAV and a ground user. It is observed that as the UAV's altitude increases, the rate of increase in the minimum transmitted power decreases. We notice that at an altitude of 1000 meters, the transmit power remains relatively constant, while at an altitude of 100 meters, the transmit power varies significantly from -30 dB to 8 dB as the user distance increases. This is attributed to the lower probability of line-of-sight (LOS) communication at lower altitudes, where buildings and other obstacles can block signals. Additionally, we find that for users closer than 250 meters, an altitude of 100 meters is most effective. For users between 250 meters and 600 meters, an altitude of 312 meters is optimal. And for users between 600 meters and 1000 meters, an altitude of 500 meters is most suitable. These findings are consistent with the results obtained from the analysis in the previous figure. Finally, we conclude that the UAV should rise in the sky for better LOS likelihood, which results in better performance, as the user travels away from the UAV.

3. CONCLUSIONS

In this paper, we have explored the utilization of unmanned aerial vehicles, or UAVs, as a means to augment existing wireless networks and extend connectivity solutions. We began by categorizing UAVs based on their operating parameters, such as flight altitude and wing design. Our analysis considered UAVs serving important wireless roles like temporary mobile cellular towers, flying relays between locations, and devices that could deliver internet access from the sky. Also, we viewed different types of UAV propagation losses, from large-scale fading channel models to small-scale fading. Then we have generally surveyed and analyzed the UAV characteristics and categories, focusing on A2G and A2A channel measurements. The measurement results presented in this paper provide valuable insights into the performance of UAVs as base stations for wireless communication networks. Simulation results showed that the UAV's altitude deployment depends on the environment type, where a higher pathloss exponent leads to a lower coverage probability. Results also showed that higher altitudes provided better coverage for long distance or crowded settings by helping signals travel further. However, coverage declined sharply once aircraft altitude exceeded a certain optimal height. Furthermore, we conclude that the optimal elevation angle and minimum UAV transmit power will vary depending on several factors, including the height and density of the buildings, the coverage radius, the UAV altitude, and the desired network throughput. In summary, UAVs show promise as flying wireless infrastructure due to their unconstrained mobility. But in order to reach their full potential, they must take into account issues with spectrum, interference reduction, validating dynamic 3D channel models, energy-efficient large-scale operation, and mobility control. Future work should aim to experimentally verify models and solve challenges around large-scale UAV network energy and operation. With proper research, UAVs should meaningfully augment wireless networks and enhance connectivity.

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