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# Unmanned Air Vehicle Operational Framework for Public Safety Communications

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***Abstract*—The aviation and air mobility sector are experiencing a profound evolution, fuelled by swift technological progress and escalating requirements for effective, secure, and dependable airborne communication frameworks. The integration of Unmanned Aerial Systems (UAS), such as drones, into commercial and logistical activities is revolutionizing traditional concepts of air mobility. Integrating the Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) protocol into UAS communication networks enhances safety and reliability by preventing collisions. CSMA/CA allows UAS to sense the communication medium's availability before transmitting data, minimizing the risk of collisions and ensuring efficient data transmission, crucial for scenarios where safety is paramount. Sixth-Generation (6G) technology coupled with CSMA/CA protocol integration strengthens reliability and effectiveness in ensuring safe and efficient UAS operations. Simulation analysis using MATLAB helps understand signal quality and latency variations with distance from the Unmanned Aerial Vehicle (UAV) to the receiver, essential for safety communications analysis. Analyzing handover procedures is crucial for public safety, especially in scenarios where UAS encounter situations requiring a change from one base transceiver station (BTS) to another. Vertical handovers, particularly relevant in the context of evolving Unmanned Traffic Management (UTM) and Air Traffic Management (ATM) architectures, may become more prevalent due to the significant altitude variations inherent in UAS operations.**

***Index Terms*—Unmanned Aerial Vehicle; public safety; 6G;link budget; handover;**

## I. Introduction

The field of aviation and air mobility is undergoing a remarkable transformation, driven by rapid advancements in technology and a growing demand for efficient, safe, and reliable airborne communication systems. The integration of UAS including drones, into commercial and logistical operations, has created new paradigms in air mobility [1] [2] [3]. Figure 2 shows an example of a next-generation architecture

A robust infrastructure is imperative to support modern air mobility systems, requiring reliable and high-capacity communication channels to facilitate various applications including flight and traffic management. Stability and mobility, especially during take-off and landing, are crucial for unmanned systems, making multirotor UAS particularly suitable for such missions. Wireless communication systems incorporating UASs present cost-effective connectivity solutions, particularly in areas lacking infrastructure coverage. Low-altitude UASs offer advantages over terrestrial systems, including rapid deployment, flexible re-configuration, and potentially improved communication channels.These channels must support a diverse array of applications, including but not limited to flight management systems, traffic management, and the seamless integration of various communication technologies, as shown in figure 1. This diagram illustrates an operational framework for utilizing UAS in managing public safety scenarios, (such as wildfires or urban fires). The framework involves different types of UAVs and their communication protocols. The framework ensures robust and reliable communication during emergencies by utilizing advanced protocols (CA Protocol and VDL Mode 4). It allows for real-time monitoring, data sharing, and efficient coordination between aerial units (UAVs) and ground units (fire trucks, PGS), thereby enhancing the overall safety and effectiveness of public safety operations.

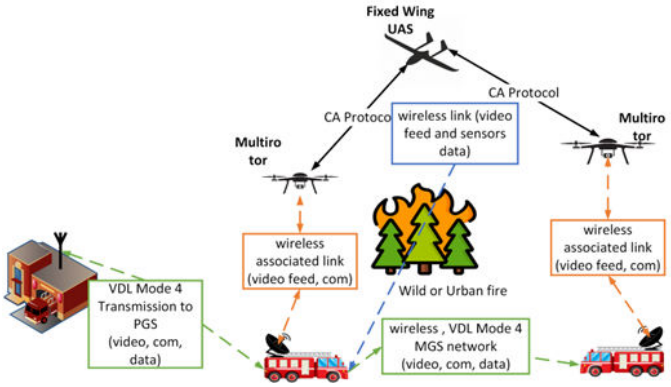


Fig. 1: Seamless Integration of Various Communication Technologies

Figure 2 showcases of future communications sixth generation (6G) enabled framework for advanced air mobility, integrating edge computing, AI/ML, mmWave, THz communication, and big data. The system comprises several layers: SDN and NFV networks enhance network flexibility and scalability; mobile edge computing supports real-time applications like intelligent patient monitoring [4] [5].

Drones and UAVs utilize high-speed communication for data transfer to ground stations, while the intelligent access

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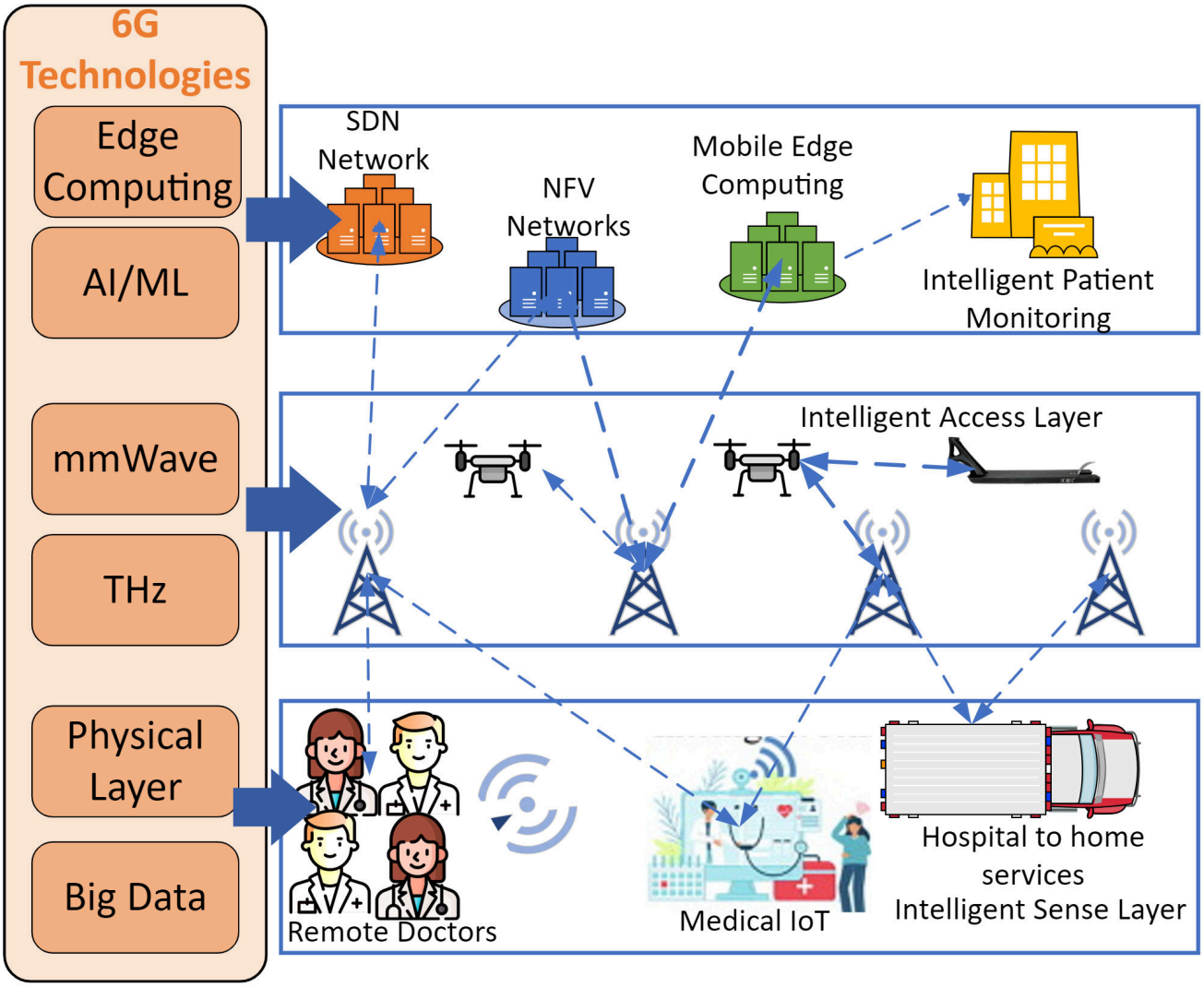


Fig. 2: Future Air Mobility Architecture

and sense layers ensure seamless integration of IoT devices for applications such as continuous patient monitoring and hospital-to-home services. Remote doctors rely on this infrastructure for accurate, timely telemedicine, ensuring efficient healthcare delivery and urban air mobility.

The current state of the art in airborne communication systems [6] involves sophisticated technologies designed for uplink/downlink models, signal-to-noise ratio (SNR) optimization, link budget analysis, and robust antenna design [7]. These systems are geared to address the fundamental principles of airborne and ground communication systems, ensuring secure and efficient data transmission [8] [9]. Additionally, there is a growing focus on enabling long-range autonomous drone delivery, highlighting the need for mobility management for reliable data links and system integration of software and hardware for traffic management within controlled airspace. Research projects like UAS Authentication Service under the Future Flight Challenge [10], emphasize the integration of unmanned aircraft in shared airspace, exploring the performance requirements of UAS communications and developing seamless handover mobility.

Recent advancements in wireless technology have laid a crucial foundation for future developments in the field [11] [12]. The emergence of next-generation networks and progress in ultra-reliable and low-latency communications present promising solutions for ensuring reliable communication, particularly in emergency and time-critical scenarios. These innovations hold significant potential to address communication challenges in critical and emergency situations, enabling not only reliable interconnections among individuals but also the integration of numerous smart devices, thereby creating smart automated environments. The necessity for critical, time-sensitive, and emergency communications in infrastructure-less networks is particularly evident in emergency and safety applications, such as post-disaster rescue operations, sensitive process control, feedback systems, essential machine-to-machine (M2M) com-

munications, and emergency safety systems [13] [14].

In the context of post-disaster rescue activities, drones are increasingly considered for their dual role in cellular link establishment and data delivery. Drones facilitate a two-tier communication hierarchy, where information is relayed from user equipment (UE) to drones, and subsequently from drones to the core network, thereby minimizing communication delays in such networks. Although the field of drone-based communication networks is still in its infancy, some preliminary efforts have been made to develop viable infrastructures. For instance, research highlighted in [15] explores the use of drones as relays to address cell overloading and outage issues, although this study was limited to an analytical model and lacked details on drone base station coverage and deployment methods. Further studies, such as those by [16], analyzed the optimal altitude for drone base stations to minimize transmission power while effectively covering target areas and addressing interference issues. Research investigated the optimal positioning of drones to serve designated zones, while providing an analytical model to determine the optimal altitude for maximizing coverage area, defining the service edge by the maximum allowable path loss. Additionally, the optimal cell boundaries and deployment locations for multiple non-interfering UAVs, aiming to reduce transmission power requirements was also discussed [17] [18] [19].

Beyond network optimization, location data offers significant potential for monetization in various applications including public safety services, smart city initiatives, emergency response systems, and tracking lost individuals [20] [21]. [22] provides a comprehensive survey of enabling technologies for network localization and tracking using 3D location information, highlighting the potential for novel location-based services. Research in drone-based communication networks is in its initial stages, with limited existing work. However, promising efforts have been made to establish workable drone-based communication infrastructure [16] [23] [24]. Link budget analysis is crucial for understanding the performance of UAS communication systems. It involves calculating the gains and losses in a communication system to ensure that the signal quality is maintained over long distances. Studies have shown that factors such as altitude, distance, and environmental conditions significantly impact the Free Space Path Loss (FSPL), received power ($Prx$), carrier-to-noise ratio ($C/N$) and latency . It provides insights into how UAV communication systems perform under various scenarios [25] [26]. Handover processes are critical in maintaining continuous communication as UAS's move between different coverage areas of base transceiver stations (BTS). There are two primary types of handovers: horizontal and vertical. Horizontal handovers occur when a UAV switches from one BTS to another at the same altitude [27], while vertical handovers involve transitioning from ground-based BTS to satellite-based ones as the UAS's altitude changes.

## II. System Architecture and Communication Links

The main components of a communication system are GCSs , UAVs, sensors, and satellites along with the different communication links. These are shown in 3 and discussed in this section.

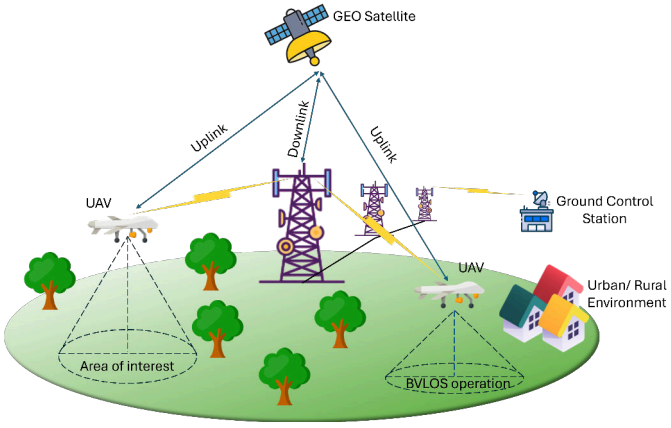


Fig. 3: High-Level Communication Architecture

The ground control station is the command center where operators control the UAV's flight path, payload, and other functionalities. It consists of software for mobile ground control stations. This system allows operators to focus more on the mission than on piloting and it is even compliant with standards which means it can work on a variety of off-the-shelf technologies. An unmanned common ground control system utilizes a single, cyber-hardened workstation to operate a wide range of unmanned systems.

For the ground sensor nodes, these are typically a network of distributed sensors that collect and transmit data back to the ground control station. They can include weather stations, radar installations, or other surveillance equipment. They include radar systems that provide real-time data on weather conditions and potential airborne threats.

Communication between the satellite, ground sensor nodes, and the ground control station occurs through data links. These links are supported by communication protocols like the Common Data Link (CDL) which is often used in military applications. The data link to the satellite usually employs protocols that can include SATCOM standards such as Inmarsat or Iridium for wide-range communication. This depends on the operational requirements and the level of security needed. In context of advanced encryption standards for data at rest and in transit, secure and resilient communication protocols for remote operations, and Transport Layer Security (TLS) for data integrity and privacy are used.

### A. Link Budget Analysis

The link budget analysis is a method used to calculate the total amount of losses and gains experienced by a signal as it travels from a transmitter to a receiver. It encompasses all the factors that would attenuate or boost the signal along its path, including the transmitter power, antenna gains, free-space path

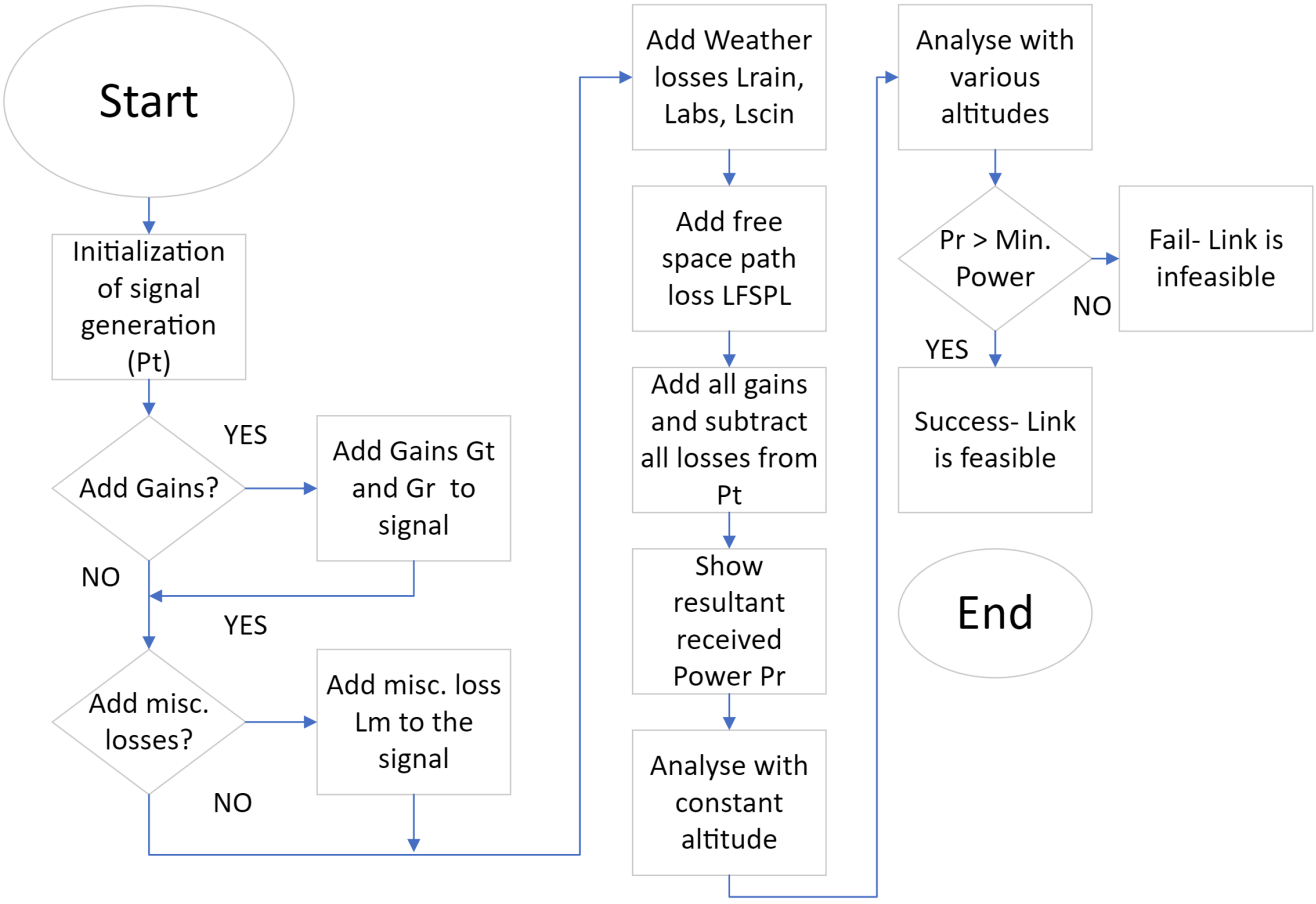


Fig. 4: Link Budget Analysis Flowchart

loss, and system losses such as cable and connector losses. The steps involve adding all the gains and subtracting all losses in the link, this is shown in figure 4.

The link budget analysis involves a mathematical model which includes formulas for calculating the path loss. This is typically based on the Friis original transmission formula:

$$\frac{P_r}{P_t} = \frac{A_r A_t}{d^2 \lambda^2} \tag{1}$$

where $P_t$ is the power transmitted, $P_r$ is the power received, $A_r$ is the aperture of the receiving antenna, $A_t$ is the aperture of the transmitting antenna and $d$ and $\lambda$ are the distance and the wavelength.

The FSPL formula is derived from the Friis transmission formula, which describes the relationship between the power of radio waves received by a receiving antenna and the power of radio waves transmitted by a transmitting antenna in a radio system :

$$\frac{P_r}{P_t} = D_t D_r \left(\frac{\lambda}{4\pi D}\right)^2 \tag{2}$$

where $D_t$ and $D_r$ are the directivities of the antenna w.r.t. an isotropic radiator.

The conversion into decibels is possible using the following equation:

Finally the FSPL formula for usual calculation in dB can be expressed as follows:

$$FSPL = 20log_{10}(d) + 20log_{10}(f) + 20log_{10}\left(\frac{4\pi}{c}\right) \tag{3}$$

The fundamental equation for LBA in a free-space environment is given by:

$$P_r = P_t + G_t + G_r - FSPL - L_m \tag{4}$$

where $G_t$ and $G_r$ are the gains and $L_m$ are the sum of all losses (atmospheric absorption, foliage loss, etc.)

The results of a link budget analysis will show whether the expected signal at the receiver is above the minimum required for the communication standard being used, which indicates a viable link. This analysis is critical for ensuring reliable communication, as it helps to determine the necessary transmitter power, antenna requirements, and potential need for signal repeaters.

Link budget analysis, when combined with simulations and empirical measurements, offers a comprehensive approach

to communication system design. Simulations can model complex environments, accounting for variables like terrain, buildings, foliage, and weather, which affect signal propagation. Tools like ray tracing and finite element methods can simulate how signals propagate and attenuate, offering insights that complement the basic LBA. Empirical measurements involve field tests where actual signal strength and quality are measured over the communication path. These measurements validate and calibrate simulation models and refine the LBA, ensuring that theoretical predictions match real-world performance. By integrating LBA with simulations and empirical data, engineers can predict system performance under various conditions, optimize system parameters, and ensure robust and reliable communication links that adhere to design specifications and operational requirements. This holistic approach reduces the risk of system failure and enhances the quality of service in real-world deployments.

## III. Simulation Set-up and Analysis

In this section, we delve into the simulation of a drone's communication link, exploring both scenarios where the UAV maintains a constant altitude and where it varies. The aim of the simulation is to understand how the altitude of a UAV affects the key parameters of its communication system, particularly the FSPL, $Prx$, $C/N$, and signal latency. The FSPL is a critical component, calculated based on the Euclidean distance between the UAV and the receiver, the operating frequency, and the speed of light. It provides insight into how much signal strength is lost purely due to the signal's travel through free space.

### *A. Constant UAV Altitude*

For the constant UAV altitude scenario, the MATLAB code defines a set of system parameters like frequency, antenna gains, and UAV height. It then calculates the FSPL, $Prx$, and $C/N$ for a UAV at a constant altitude of 300 m above the ground level, over varying horizontal distances. The outcomes of this simulation would show how signal quality and latency are affected by the distance from the UAV to the receiver at this fixed altitude.

Figure 5 shows the FSPL as a function of distance for a UAV at a constant altitude. The FSPL increases with distance, indicating that the signal strength decreases as the distance between the UAV and the GCS increases. The relationship is logarithmic, meaning the loss increases at a diminishing rate with increasing distance.

The received power is plotted against distance for three different scenarios: free space, with gas attenuation, and with both gas and rain attenuation. In free space, the received power remains higher compared to the other two scenarios, indicating that environmental factors significantly influence the signal. The plot shows a clear decrease in received power as distance increases, with the most severe attenuation observed in the scenario with both gas and rain attenuation. This is shown in figure 6

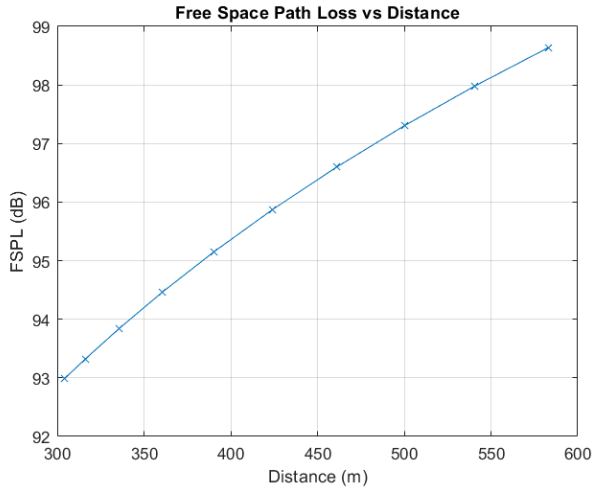


Fig. 5: Free Space Path Loss for variable vertical component

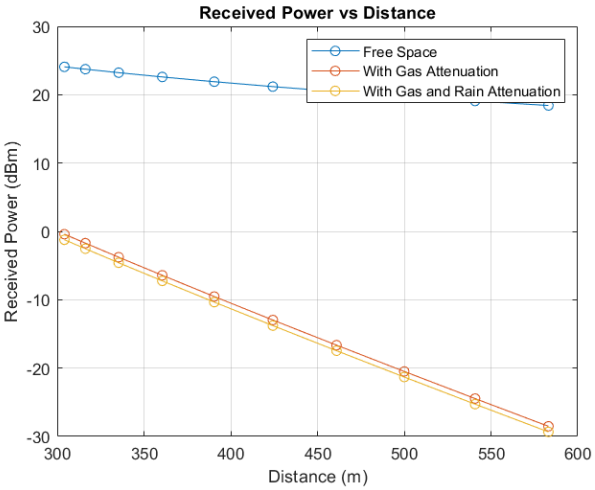


Fig. 6: Received Power against Distance for constant vertical component

Figure 7 depicts the $C/N$ as a function of distance. Similar to the received power, the $C/N$ ratio decreases with increasing distance, and the decrease is more pronounced under gas and rain attenuation. The $C/N$ ratio is used for determining the quality of the communication link, with higher values indicating better signal quality. The plot shows that environmental factors can substantially degrade the $C/N$ ratio, highlighting the importance of considering these factors in link budget analysis. Latency is plotted against distance, showing that latency increases linearly with distance. This is expected because the time taken for the signal to travel from the UAV to the GCS increases with distance. Figure 8 demonstrates that even in a free space scenario, latency can be a significant factor for long-distance communication links, affecting real-time applications and requiring careful consideration in system design.

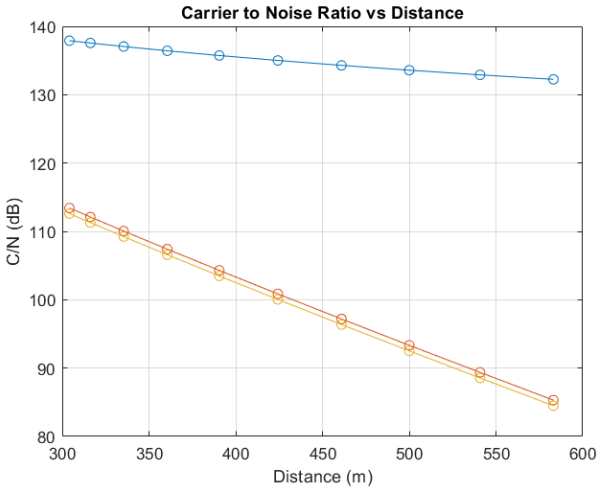


Fig. 7: Carrier to Noise evolution for constant vertical component

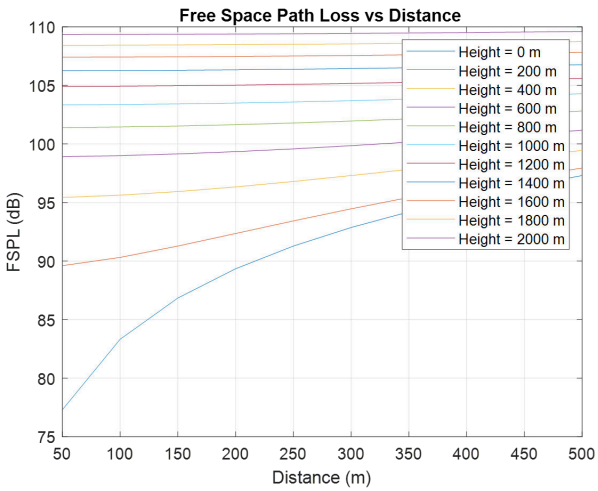


Fig. 9: FSPL at various altitudes

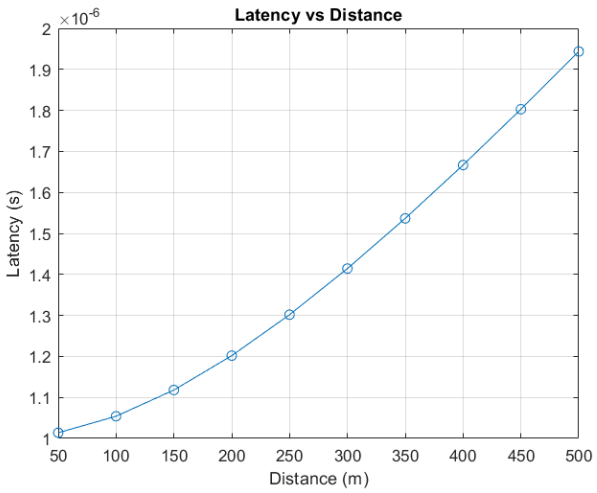


Fig. 8: Latency for constant vertical component

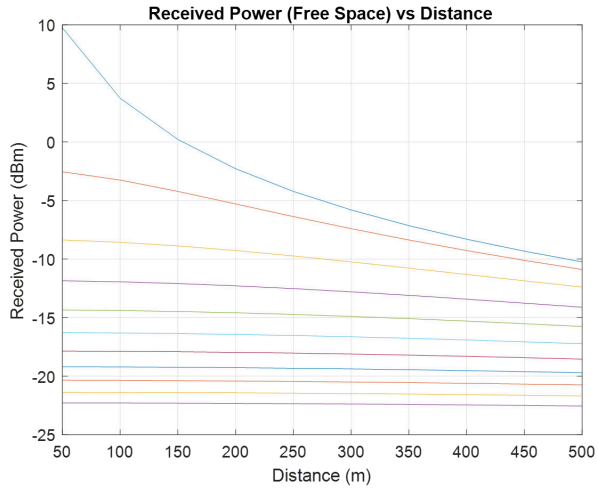


Fig. 10: Received power at different altitudes

### *B. Variable UAV Altitude*

In this case, the UAV altitude is variable, it ranges from 0 m to 2000 m with a different LBA at each 2000m. The horizontal distance is also variable. The code runs through multiple UAV distances, calculating the same parameters for each altitude at the given distances. The results from this part would reveal the optimal operating altitudes for different distances to maintain signal integrity and minimize latency.

Figure 9 shows the FSPL as a function of distance for different UAV altitudes. Each line represents a different altitude, ranging from 0 to 2000 meters. The FSPL increases with distance for all altitudes, but the rate of increase varies. Higher altitudes generally show higher FSPL values for the same horizontal distance, reflecting the combined effect of vertical and horizontal distances on signal loss. The received power is plotted against distance for various UAV altitudes in a free space environment in figure 10. As distance increases, the received power decreases for all altitudes. However, the rate of decrease is steeper for higher altitudes, indicating that the UAV's height exacerbates signal attenuation. This plot emphasizes the importance of altitude in communication link performance, with lower altitudes generally providing better received power levels. Figure 11 shows the $C/N$ ratio as a function of distance for different UAV altitudes in a free space scenario. The $C/N$ decreases with distance for all altitudes, with higher altitudes showing a more significant decrease. The plot illustrates that maintaining a higher C/N ratio, and thus better signal quality, is more challenging at higher altitudes and longer distances.

Latency is plotted against distance for various UAV altitudes. Figure 12 shows that latency increases linearly with distance, consistent across all altitudes. However, the difference in latency between different altitudes is minimal compared to the difference caused by horizontal distance. This indicates that while altitude affects signal strength and quality, its impact

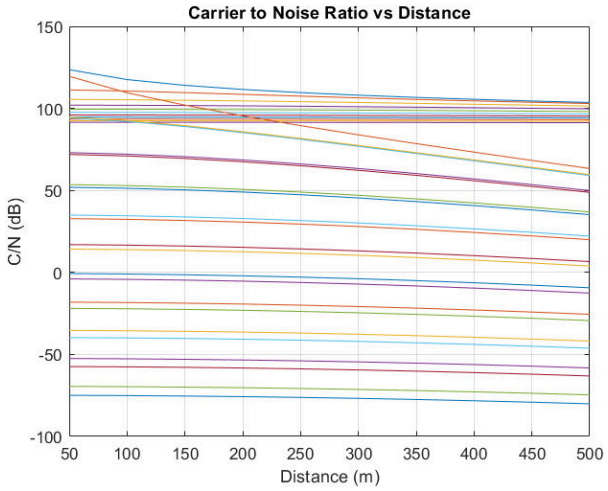


Fig. 11: Carrier-to-Noise Ratio at different altitudes

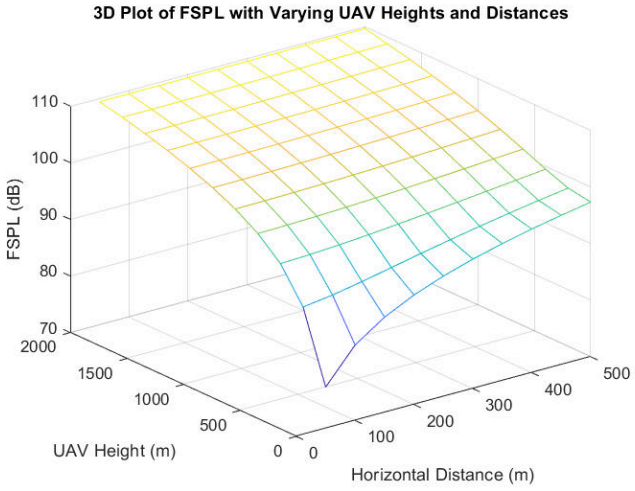


Fig. 13: FSPL dependency on distance

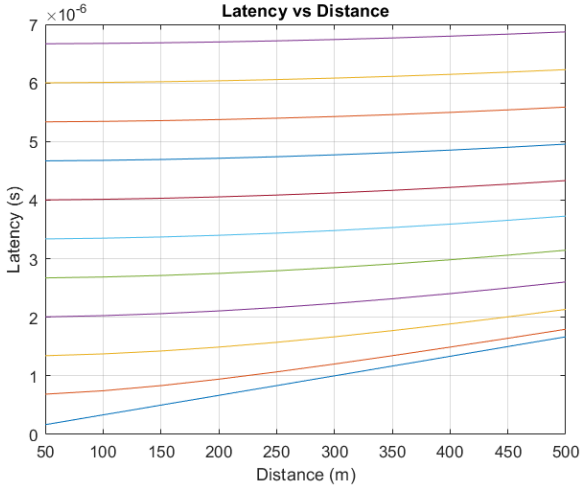


Fig. 12: Latency at at different altitudes

on latency is relatively less significant.

This 3D plot visualizes the FSPL as a function of both UAV height and horizontal distance. The surface plot shows that FSPL increases with both height and distance. The curvature of the surface indicates that the FSPL is more sensitive to changes in distance than in height. However, at higher altitudes, the FSPL increases more rapidly with distance, suggesting a compounding effect of altitude on signal loss. This plot provides a comprehensive view of how both vertical and horizontal components influence the FSPL, offering valuable insights for optimizing UAV communication links by balancing altitude and distance to minimize path loss.

### *C. Handover Analysis*

Handover analysis is key when operation in regions where the UAV encounters situations where changing from a base transceiver station (BTS) to another is required. In practical cases there are only two types of handovers: horizontal and/or vertical. Vertical handover is usually encountered when the aircraft climbs and needs to change from a ground BTS to a satellite one. In the future, the UTM/ATM architecture might enable vertical handovers, considering the nature of UAV operations, which can involve significant differences in altitude where they operate.

For instance, when switching operational layers, one could benefit from vertical handover in case different data exchanges are prioritized or the ground BTS does not have enough coverage. The handover study will exclusively focus on horizontal handover from one BTS to another. There will be Also, for the duration of this study, the altitude of the UAV is considered constant and does not factor in handover decision.

Initial assumptions:

- The altitude of the UAV is considered constant and does not factor in calculations.
- The distance between the UAV and the BTSs does not influence handover decision.
- The UAV is not initially connected to any BTS.
- The vehicle coordinates are inputed by human intervention.

Case 1: The inputed vehicle coordinates place the UAV outside of any BTS range as shown in figure 14, therefore, no calculation is required and the adequate message is displayed.

Case 2: Figure 15 shows the UAV within the coverage area of BS3 only. The base stations are depicted as previously described, but now the UAV is located at coordinates (100, -100). In this scenario, the program would display the message ”Handover required, UAV connected to BS3 with entropy: 0.” The entropy is zero because the UAV connects automatically to BS3 without needing to consider any other base stations. This case demonstrates a straightforward connection where the UAV is clearly within the range of a single base station, making the handover process simple and direct.

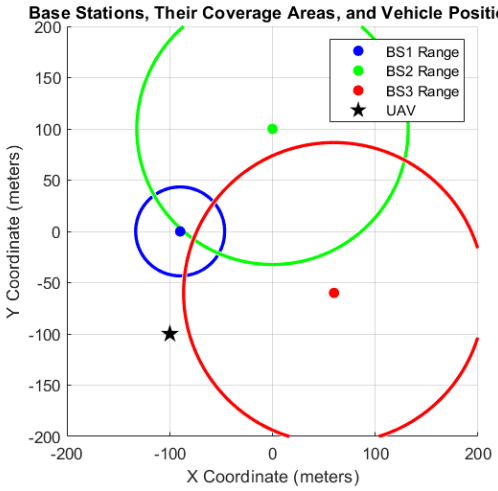


Fig. 14: Case 1 Results

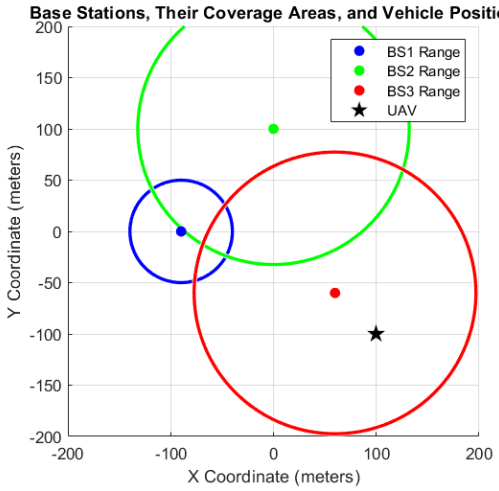


Fig. 15: Case 2 Results

Case 3: The inputed vehicle coordinates place the UAV inside two and only two BTS ranges, therefore, entropy is calculated using the formula:

$$Entropy = -\sum(p(x) \times log_2(p(x))) \tag{5}$$

The handover happens only when [15]:

$$P_{new} = P_{old} + entropy \tag{6}$$

Here, the UAV sits at coordinates (-90, 0). he program would calculate the entropy based on the received signal strength (RSS) from both BS1 and BS2. The UAV would connect to the base station with the greater power, and the message would include which base station it connects to along with the entropy value calculated. This scenario illustrates the complexity of decision-making when the UAV is within the range of multiple base stations, requiring an optimal selection based on signal strength and entropy.

Case 4: The figure 17 shows the UAV within the coverage areas of all three base stations, the UAV having coordinates (-80, 0). In this case, the program would calculate the entropy based on the RSS from BS1, BS2, and BS3. The UAV would connect to the base station with the greatest power, considering the calculated entropy. The message would specify which base station the UAV connects to and the corresponding entropy value. This scenario emphasizes the need for advanced algorithms to manage connections when the UAV is within multiple overlapping coverage areas, ensuring optimal connectivity and efficient handover processes. The UAV automatically connects to the BTS that has the greater power. The entropy gets displayed along with the BTS to which the UAV is connected.

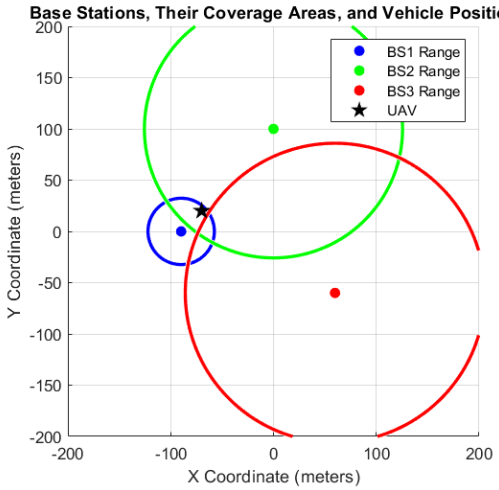


Fig. 16: Case 3 Results

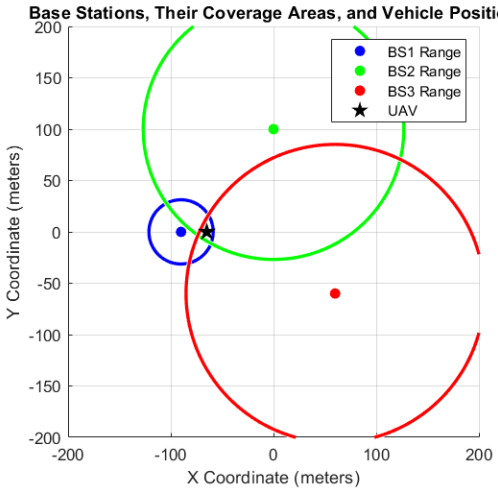


Fig. 17: Case 4 Results

## IV. Conclusion

This paper has extensively explored the dynamics of UAV-based communication systems for public safety, underpinning the integration of advanced link budget analysis (LBA) and simulation techniques to enhance system efficiency and reliability. The research commenced with a comprehensive introduction, providing a solid background on the system requirements and the current state of the art in UAV communication technologies. This foundational section not only delineated the critical need for robust UAV communication systems in public safety operations but also highlighted the technological advancements and challenges currently facing this field. Moreover, a comprehensive handover analysis was conducted to evaluate the efficiency and reliability of communication links during UAV movement. The simulations, integrated with the link budget analysis, were pivotal in understanding the performance of UAV-based communication systems under various conditions, including environmental factors and operational constraints. The integration of advanced LBA and simulation techniques, coupled with a thorough handover analysis and effective visualization methods, has provided a comprehensive understanding of system performance for enhancing public safety operations.

## Acknowledgment

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# Unmanned air vehicle operational framework for public safety communications

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