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# Communication Network Architecture with 6G Capabilities for Urban Air Mobility

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***Abstract*—As the demand for urban air mobility (UAM) increases, a robust communication, navigation, and surveillance (CNS) network architecture is needed to support the integration of sustainable UAM vehicles and technologies. Specifically, a new digital communication infrastructure is imperative to support increased levels of digitisation and autonomy within the aviation industry. This infrastructure must remain compatible with existing technologies, while enabling the integration of future 6G systems. This paper thereby discusses the communication challenges and opportunities associated with UAM integration. Potential communication technologies and standards needed to support UAM operations are presented and consolidated into a unified communication architecture with ground-, air-, and satellite-based infrastructure. The functional requirements of this architecture are also discussed, to enable seamless communication between UAM vehicles, air traffic control, and other ground- or air-based systems. Notably, 6G is highlighted as a key enabler of dense and sustainable UAM operations with high data traffic demands. A simple link budget analysis for a 6G air-to-ground data link in a green urban environment is thereby performed, emphasising the infrastructural development necessary to support 6G roll-out. These findings pave the way for a more sustainable and accessible UAM transportation system, backed by a secure and reliable communication infrastructure.**

***Index Terms*—6G, advanced air mobility, architecture, communication, urban air mobility**

## I. Introduction

### A. Urban Air Mobility

Urban air mobility (UAM) is the subset of advanced air mobility (AAM) concerned with transporting passengers and cargo in urban and suburban environments. It utilises highly automated electric vertical take-off and landing (eVTOL) aircraft flying in low-altitude airspace, operating within air traffic management (ATM) and unmanned aircraft system (UAS) traffic management (UTM) ecosystems [1].

Despite the perceived benefits of UAM, several challenges still hinder the full-scale deployment of a sustainable UAM ecosystem. Notably, communication, navigation and surveillance (CNS) technologies and infrastructure must evolve to cater for the requirements of this emerging industry, including increased aircraft heterogeneity and greater levels of digitisation, electrification and autonomy [2]. Simultaneously, UAM should have minimal impact on existing airspace operations. Consequently, a robust CNS network architecture for UAM must remain compatible with existing and well-established frameworks, without restricting the introduction of new and innovative technologies [3].

### B. Communication Infrastructure for UAM

In controlled airspace, UAM operations are expected to operate within the requirements of the current human-centric ATM environment, according to existing procedures and/or concessions [4]. This includes voice communication between pilots and air traffic controllers (ATCOs) over aviation very high frequency (VHF) bands, backed by digital datalinks such as the Aircraft Communication Addressing and Reporting System (ACARS) and Controller Pilot Data Link Communications (CPDLC) [5]. Nonetheless, UAM operations should have minimal impact on air traffic control (ATC) workload, and controller responsibilities should be limited to monitoring, rather than actively managing, UAM flights.

At low altitudes below 400 feet, UAM aircraft will operate in uncontrolled airspace shared with UASs, and must therefore comply with UTM system requirements for communication, authorisation and deconfliction purposes. In contrast to the ATM framework, no voice communications are expected within the UTM ecosystem. Conversely, all interactions between UTM entities, UASs and ground control stations (GCSs) will occur through automated and digital links, as shown in Fig. 1. Additionally, inter-communication between the ATM and UTM systems is critical to support enhanced deconfliction within non-segregated airspace volumes, shared situational awareness, and collaborative decision making. Nonetheless, reliably integrating diverse communication technologies in a single, upgradeable and robust architecture remains a considerable challenge. Specifically, urban environments present unique connectivity challenges, owing to high levels of interference and dense communication networks.

### C. Contributions

Erturk et al. [6] comprehensively discuss the CNS requirements and technologies needed to support UAM operations, and Wang et al. [7] confirm that UAM poses significant challenges to the communication infrastructure. Moreover, Bae et al. [8] systematically analyse potential communication technologies for UAM, and conclude that 5G, and eventual 6G networks, are key enablers of this emerging industry. Similarly, Zeng et al. [9] analyse aircraft-to-ground (A2G) communication networks for UAM, and Park et al. [10] propose a novel cell deployment methodology for advanced 5G UAM communications. Furthermore, Kim et al. [11] present the challenges and opportunities of 6G for UAM applications.

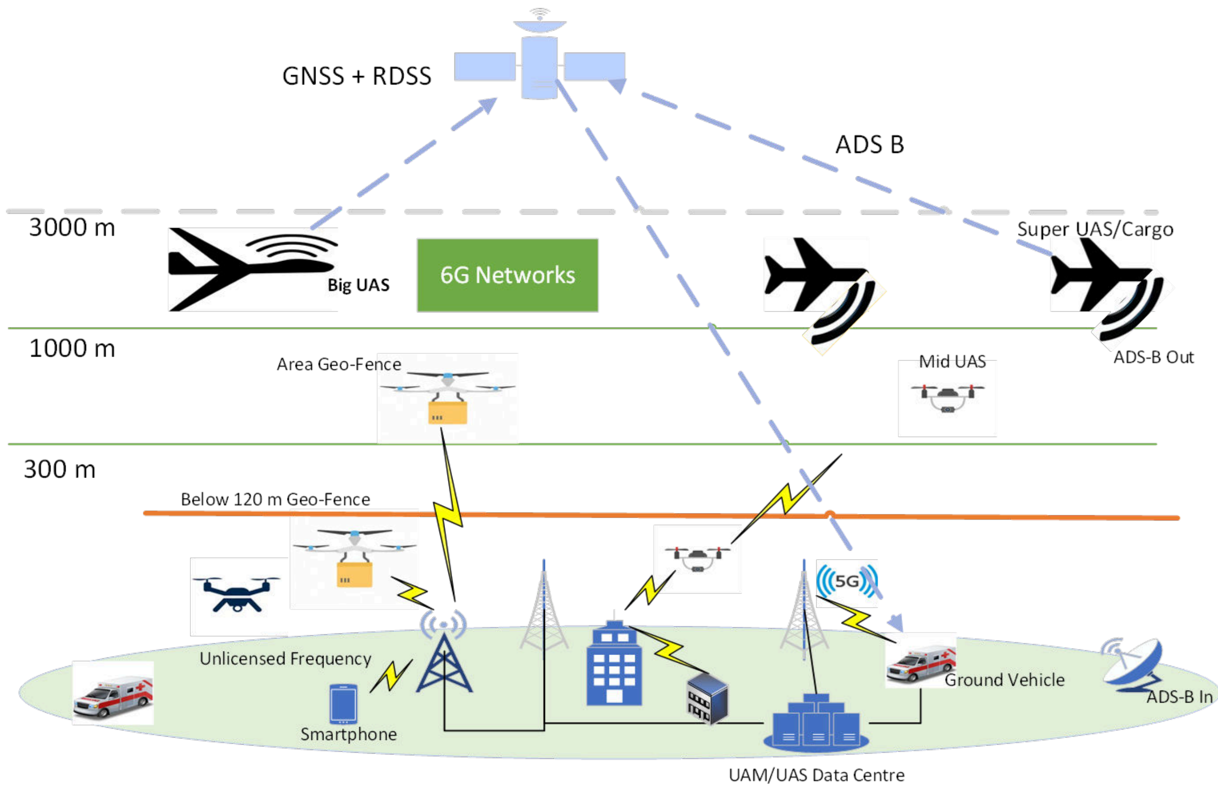


Fig. 1. Communication network architecture for UAM.

This paper builds on existing work to propose a robust communication network architecture with 6G capabilities for sustainable UAM operations. It further investigates the use of 6G for UAM through a simple link budget analysis. The main contributions of this work are as follows:

- Existing communication technologies and standards are systematically reviewed in the context of UAM;
- A unified architecture with 6G support is proposed for UAM communications;
- A preliminary link budget analysis for 6G A2G communications in green urban environments is performed, to highlight the benefits, limitations, and challenges of 6G for emerging UAM applications.

### D. Paper Structure

Section I introduced UAM as a sustainable means of urban transportation, and highlighted the need for a robust communication network architecture to support this emerging industry. Section II subsequently reviews existing communication technologies and standards, to highlight their suitability for UAM applications. These technologies are consolidated into a unified communication architecture in Section III, complemented by qualitative functional requirements. Additionally, Section IV presents a link budget analysis in green urban environments, to emphasise the challenges of using 6G for handling the high data demands of UAM. Finally, Section V concludes by summarising the findings of this work and suggesting promising avenues for further research.

## II. Communication Technologies and Standards

### A. VHF and UHF Direct Links

VHF and ultra-high frequency (UHF) direct links can provide direct communication between the UAS and operator without relying on external infrastructure. These links operate on frequencies in the range of 30 MHz to 3 GHz and provide longer-range communication capabilities than systems such as wireless fidelity (WiFi). Additionally, VHF and UHF direct links are less prone to interference and attenuation by obstacles such as buildings or trees. Such direct links thereby enable real-time control and monitoring of a UAS, while supporting the transmission of high-quality CNS data [5].

When using VHF and UHF data links, the standard for Control and Non-Payload Communications (CNPC) created by the Radio Technical Commission for Aeronautics (RTCA) can be applied to medium and large UAS platforms [12]. This standard applies to A2G line-of-sight (LOS) communication links, and pertains to the L-band (900-1000 MHz) and a portion of the C-band allocated to aviation (5.03-5.091 GHz). Moreover, the RTCA is currently working on creating an equivalent standard for beyond LOS (BLOS) operations. To support direct VHF links, the International Civil Aviation Organisation (ICAO) has also reserved four VHF channels (136.900, 136.925, 136.950, and 136.975 MHz) for data communications [13]. Digital modulation is typically employed within these channels, using differential 8-phase-shift keying with a symbol rate of 10,500 symbols per second.

### B. Satellite Data Links

Satellite data links play a crucial role in supporting global coverage for UAM operations, especially in areas where terrestrial network coverage is unavailable or non-existent. They can also help relay data between widely separated UASs and ground gateways, or act as a backup in case of a failure in the ground-based communication infrastructure.

Satellite links can provide UAM vehicles with reliable and high-bandwidth communication links. Specifically, each satellite has a dedicated bandwidth, such that the quality of service in a peer-to-peer (P2P) connection does not drop under high load. Satellites also avoid handover failures, and offer an availability rate of up to 99.99%. Three classes of satellite system orbits exist, namely low earth orbits (LEO), medium earth orbits (MEO), and geostationary orbits (GEO), as summarised in Table I. The communication latency increases as the orbit altitude increases, with GEO satellites potentially experiencing a latency of up to $0.5\,\mathrm{s}$. This can severely restrict the autonomous functionality of UAS systems. Consequently, LEO constellations are becoming increasingly more popular for 5G applications, with a latency as low as 1 ms [14].

Despite their potential benefits, satellite connections tend to be an expensive solution. A one minute voice connection, for instance, can cost over £1 over a satellite data link and under 0.1p when using terrestrial cellular networks. Additionally, satellite equipment suitable for aircraft is much more expensive than radio or cellular communication equipment. Satellite links may further struggle due to high latency and urban canyon effects in urban areas, since LOS is necessary to establish communications. Moreover, satellite communication can introduce higher packet loss rates compared to terrestrial technologies, due to atmospheric conditions, long propagation distances, and potential signal interference. Consequently, UAM vehicles cannot solely rely on satellite data links.

### C. Terrestrial Networks

Terrestrial networks will form the backbone of distributed UAM operations. Notably, 4G and 5G are designed to provide faster data transfer rates, improved reliability, and increased connectivity, as summarised in Table II. These adhere to the 3rd Generation Partnership Project (3GPP) standards, representing a collaborative standardisation effort to promote system and equipment interoperability [3], [15].

TABLE I
COMPARISON OF COMMUNICATION SATELLITE ORBITS.

| Satellite Type | LEO | MEO | GEO |
|---|---|---|---|
| Satellite height (km) | 500-1500 | 5000-12000 | 35800 |
| Orbital period | 95-115 mins | 3-7 hours | 24 hours |
| Number of satellites | 40-800 | 8-20 | 3 |
| Coverage | global | global | no polar |
| Satellite life (years) | 3-7 | 10-15 | 15+ |
| Gateway cost | very expensive | expensive | cheap |
| Doppler | high | medium | low |
| Round-trip delay | 10-230 ms | 70-200 ms | 500 ms |
| Propagation path loss | least | high | highest |

Cellular networks generally exhibit relatively low packet loss rates and are designed to provide robust and reliable communication for mobile devices. Nonetheless, packet loss in terrestrial networks can be influenced by factors such as signal strength, network congestion, and interference. Advanced error correction and re-transmission mechanisms in cellular protocols are therefore required to minimise packet loss in congested UAM operating environments.

The European Conference of Postal and Telecommunication Administrations (CEPT) identified existing mobile network bands as a potential means to provide connectivity to UASs and UAM vehicles, using the existing Long-Term Evolution (LTE) standard for 4G communications. This approach would leverage existing infrastructure and enable UAS operators to benefit from the widespread coverage and high data rates of LTE networks. Similarly, the RTCA UAS Advisory Committee identified LTE and its successors as promising technologies for UAS identification, command, and control [16]. In this context, the Technical Advisory Committee of the Federal Communications Commission (FCC) evaluated the spectrum requirements for UASs and concluded that LTE networks can initially fulfill the communications requirements for low-altitude UASs [17]. Nonetheless, conventional 4G systems will be unable to cater for the high data and communication demands of dense UAS and UAM operations.

5G boasts further performance improvements over 4G systems, through the use of higher frequency bands, massive multiple-input, multiple-output (MIMO) antennas, and network slicing techniques. This enables 5G to provide data transfer rates of up to $20\,\mathrm{Gbps}$ and a latency as low as $1\,\mathrm{ms}$. Moreover, 5G offers secure wireless connectivity, mobility, and high data rates, making it a promising technology for UAS identification, command, and control as the density and data traffic of UAM operations increase [18].

### D. Emerging 6G Technologies

6G represents the next generation of cellular networks, and is expected to provide faster data transfer rates, ultra-low latency, and unprecedented levels of connectivity when compared to its 4G and 5G predecessors, as summarised in Table II [11]. The higher frequency bands used by 6G will enable much faster data throughput, with theoretical maximum speeds up to 100 times faster than existing 5G systems. Additionally, 6G will support greater bandwidth capacity, to enable massive connectivity and ultra-dense networks. This makes it particularly suitable for future UAM operations, where large volumes of UASs and aerial vehicles will need to transfer high volumes of safety-critical data. Furthermore, the concept of network slicing employed in 5G systems will be refined and optimised for 6G networks, enabling more efficient resource allocation. Moreover, 6G is expected to be the first technology that guarantees end-to-end user-perceived performance at the application layer, thereby fostering increased customer satisfaction and bolstering support for UAM. A robust communication architecture for UAM should thereby facilitate the introduction of future 6G systems.

TABLE II
COMPARISON OF CELLULAR DATA NETWORKS.

| | 3G | | 4G | | 5G | 6G |
|---|---|---|---|---|---|---|
| Standard | HSPA | HSPA+ | LTE | LTE-A | Undefined | Undefined |
| Freq Bands | 900 MHz<br>2100 MHz | | 800 MHz<br>1800 MHz<br>2600 MHz | | 700 MHz<br>3500 MHz<br>26 GHz | Undefined<br>(up to THz<br>frequencies) |
| Multiplexing | FDD/TDD | FDD/TDD | FDD/TDD | FDD/TDD | FDD/TDD | FDD/TDD |
| Bandwidth | 5 MHz (single carrier) | 10 MHz (dual carrier) | 1.4 MHz to 20 MHz | 1.4 MHz to 100 MHz | Up to 100 MHz | Undefined |
| MIMO | No | 2x2 | No | 4x4 (UL) and 8x8 (DL) | mMIMO | mMIMO |
| Theoretical data rates | $<$ 5.76 Mbps (UL)<br>$<$ 14.4 Mbps (DL) | $<$ 28 Mbps (UL)<br>$<$ 42 Mbps (DL) | $<$ 75 Mbps (UL)<br>$<$ 300 Mbps (DL) | $<$ 1.5 Gbps (UL)<br>$<$ 3 Gbps (DL) | $<$ 20 Gbps | $<$ 1 Tbps |
| Expected data rates | $<$ 2 Mbps (UL)<br>$<$ 7.2 Mbps (DL) | $<$ 5.7 Mbps (UL)<br>$<$ 21.6 Mbps (DL) | $<$ 50 Mbps (UL)<br>$<$ 100 Mbps (DL) | $<$ 500 Mbps (UL)<br>$<$ 1 Gbps (DL) | $>$ 100 Mbps | Undefined |
| Latency | $<$ 150 ms | $<$ 100 ms | 50 ms | | 1 ms | 0.1 ms |

Despite the potential benefits of 6G, considerable work is still required to investigate its underlying infrastructure, technologies and standards. Additionally, 6G networks will have a larger attack surface than existing 4G and 5G systems, necessitating new and improved cybersecurity protocols and techniques [19]. This is particularly important for safety-critical UAM systems, where cyber-attacks can serve as an entry point for cyber-warfare and remote terrorist attacks.

## III. Communication Network Architecture

### A. Consolidated Architecture

Direct, terrestrial and satellite links must be consolidated into a unified network architecture for UAM applications. Primarily, terrestrial networks will serve typical UAM communication requirements, offering cheap, ultra-low latency, high bandwidth, and good reliability for real-time communication and control of autonomous UAM vehicles. Specifically, existing 4G and 5G infrastructure can be leveraged for initial deployment of UAM, before transitioning to emerging 6G systems as the density and complexity of the UAM ecosystem increase. Notably, distributed terrestrial base stations in urban environments can reliably cater for distributed communication demands in metropolitan areas, where satellite communication links are likely to fail due to urban canyon effects. Additionally, terrestrial networks may be linked to ground vehicles and end-user devices for enhanced decision making within a connected mobility ecosystem. This paves the way for smart cities and new intelligent multimodal transportation systems.

In suburban or rural areas with sparse base station coverage, exclusive reliance on terrestrial networks becomes impractical. Consequently, the inclusion of satellite communication links remains pivotal to ensure the safety and reliability of UAM operations. Similarly, satellites play a critical role in facilitating communication with high-altitude UAM vehicles that encounter limited cellular coverage. Additionally, satellite systems may serve as a backup for any handover or coverage failures in other communication networks, despite incurring additional costs. Conversely, direct VHF and UHF links may be used for specific missions in which other communication networks are unavailable.

High-performance UAM vehicles will therefore necessitate dual support for satellite and terrestrial communication when operating across expansive and varied geographical areas. Conversely, smaller UASs may exclusively rely on terrestrial networks or direct VHF/UHF links for short-range missions within predefined geo-fenced regions boasting robust network coverage. Furthermore, both UASs and advanced eVTOLs may require direct data link support when engaged in missions within communication-challenged environments.

### B. Functional Requirements

The impact of latency, cost, and packet loss on UAM is significant. Primarily, low latency is crucial for the safety of UAM operations, ensuring real-time data transfer for quick decision making and control. This is particularly important in dense urban environments, where vehicles must navigate complex airspace structures. Nonetheless, high costs associated with communication infrastructure, equipment, and regulatory compliance can affect the feasibility and scalability of UAM services. Additionally, packet loss can occur due to the communication technology used and the environment in which the vehicles operate. It therefore poses safety and reliability risks by introducing errors in the communication between ground systems and aerial vehicles. Balancing these factors is essential for the successful integration and sustainable growth of UAM.

The 3GPP define key performance indicators (KPIs) for UASs in cellular networks [20], [21] that may be extended to higher-performance eVTOL aircraft. Specifically, these metrics emphasise the need for low latency, high throughput, high reliability, wide coverage and robust security guarantees for safety-critical aerial applications. Additionally, failure in handover during the transition from one cell to another can also lead to catastrophic results in UAM scenarios [22]. The 3GPP thereby propose several handover metrics for UAS operations, including handover rate, handover failure (HOF) rate, radio link failure (RLF) rate, time in handoff, time in Qout, and ping pong rate. Such metrics, however, should be adapted for the expected scale and density of UAM operations.

## IV. 6G UAM Link Budget

### A. Numerical Experiments

To investigate the use of 6G for UAM, an A2G link in a green urban environment is considered. Specifically, a 6G operating frequency of $300\,\mathrm{GHz}$ is assumed, with LOS between the base station and UAM vehicle. A bandwidth of $5\,\mathrm{GHz}$ and a vehicle altitude of $50\,\mathrm{m}$ are also assumed. During data uplink from the GCS, a massive MIMO phased array antenna is assumed at an altitude of $25\,\mathrm{m}$, with a gain of $25\,\mathrm{dBi}$. Similarly, a smaller on-board phased array antenna with a gain of $15\,\mathrm{dBi}$ is considered. Body losses of $3\,\mathrm{dB}$ are assumed on the UAM vehicle, together with an additional $1\,\mathrm{dB}$ margin to cater for interference by other on-board equipment. Moreover, pointing and cable losses of $1\,\mathrm{dB}$ are assumed, and an effective loss of $32\,\mathrm{dB}$ due to sub-carriers is considered.

No existing propagation model effectively caters for 6G frequencies under UAM operating conditions. Consequently, the 3GPP TR38.901 model is considered, owing to its widespread use for sub-6 GHz frequencies. In particular, an urban macro (UMa) cell environment is assumed. Nonetheless, this calculation should be revised as new path loss models are proposed for 6G frequencies at higher operational altitudes. According to this model, the breakpoint distance $d'_{BP}$ can be determined using (1), such that the respective LOS pathloss is calculated using (2) for $10m \leq d_{2D} \leq d'_{BP}$,

$$d'_{BP} = \frac{4(h'_{BS})(h'_{UT})(f_c)}{c} \tag{1}$$

$$PL_{UMa-LOS} = 28 + 22\log_{10}(d_{3D}) + 20\log_{10}(f_c) \tag{2}$$

where $PL_{UMa-LOS}$ is the LOS UMa pathloss in dB; $d_{3D}$ is the 3D distance between the receiving and transmitting elements in m; $f_c$ is the carrier centre frequency in GHz; $d_{2D}$ is the horizontal distance between the receiving and transmitting elements in m; $h'_{BS}$ and $h'_{UT}$ are the effective base station and vehicle antenna heights in m, computed as the difference between the actual antenna heights and the effective environmental height (equal to 1 m in a UMa model); and $c$ is the speed of light in $ms^{-1}$. Additional losses are also incurred due to shadow fading, with 3GPP standards specifying a shadow fading standard deviation margin of $4\,\mathrm{dB}$ for LOS operations. These values, however, may be revised to consider the unique characteristics of a UAM environment with fast moving vehicles. An interference margin of $2\,\mathrm{dB}$ is further assumed to account for adjacent interference sources and multi-path effects. Penetration losses, however, are neglected for outdoor-to-outdoor communications.

Trees and foliage may also incur losses in green urban environments with the advent of green skyscrapers and rooftop gardens. Consequently, a sparse foliage environment is assumed, incurring losses of $7.5\,\mathrm{dB}$. Moreover, the P.676 model is used to estimate atmospheric losses, assuming typical atmospheric conditions of $998.917\,\mathrm{kPa}$, $14\,°\mathrm{C}$ and a water vapour density of $7.5\,\mathrm{g/m^3}$. Similarly, rainfall is considered through the ITU rainfall attenuation model, ranging from light ($1\,\mathrm{mm/h}$) to heavy ($10\,\mathrm{mm/h}$) rainfall.

Finally, Doppler effects due to a moving vehicle are considered by subtracting the respective frequency change in dB from the calculated link budget, according to (3),

$$P'_{rx} = P_{rx} - 10\log(f_{ds}) = P_{rx} - 10\log\left(\frac{|v_{rel}|f_c}{c}\right) \tag{3}$$

where where $P'_{rx}$ is the estimated received power in dBm when considering the Doppler shift, $P_{rx}$ is the estimated received power in dBm without considering the Doppler shift, $f_{ds}$ is the frequency deviation due to the Doppler shift in Hz, $v_{rel}$ is the relative velocity of the UAM vehicle with respect to the base station in $\mathrm{ms}^{-1}$, $f_c$ is the centre frequency of the carrier signal in Hz, and $c$ is the speed of light in $\mathrm{ms}^{-1}$.

For typical UAM vehicle velocities and a transmitter power of $40\,\mathrm{dBm}$, this results in the received signal powers illustrated in Fig. 2. Additionally, at a typical velocity of $25\,\mathrm{ms}^{-1}$, the impact of different rainfall rates is shown in Fig. 3. Similarly, the variation in received singal power as the vehicle moves further away from the transmitting antenna is shown in Fig. 4. Throughout all experiments, a latency of under 0.1 ms was also recorded. These plots were extracted in Matlab and highlight the impact of vehicle position, vehicle velocity and weather conditions on the 6G communications channel.

### B. Discussion and Limitations

The observed results underscore the need for scalable infrastructural development to accommodate the power and sensitivity demands of 6G within urban settings. Moreover, high-velocity UAM vehicles and adverse weather can have a notable impact on data link reliability, necessitating equipment tailored to worst-case scenarios. Additionally, the extreme frequency considerations of 6G, potentially approaching the THz range, demand precise signal propagation modelling and extensive base station deployment to mitigate propagation loss and penetration issues, particularly in urban canyons.

Dynamic mobility challenges further arise due to the varying altitudes and speeds of UAM vehicles, demanding effective handovers and continuous connectivity during rapid movements. Additionally, interference mitigation techniques and dynamic spectrum sharing strategies are required to manage interference and coexistence concerns. Security and privacy concerns are also paramount, necessitating advanced encryption, authentication, and privacy-preserving technologies.

This numerical experiment solely serves as a preliminary demonstration of the challenges associated with 6G for UAM. Further analysis is required to consider more accurate environment models under LOS and BLOS conditions within updated regulatory frameworks. Specifically, the 3GPP TR38.901, P.676 and ITU models must be revised to address the operating frequencies of 6G and mobility challenges imposed by UAM. Moreover, more accurate models of high-altitude and urban communication environments are imperative to support the evaluation of emerging UAM communication technologies. These must be complemented by provisions for carrier aggregation, MIMO array capabilities, and better margin estimates for different UAM vehicle models.

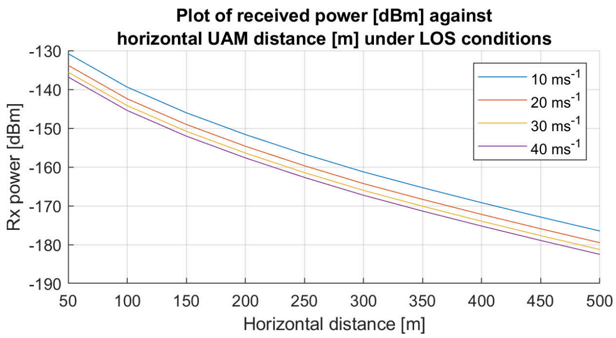


Fig. 2. Received signal power against horizontal distance between the vehicle and GCS, for different vehicle velocities.

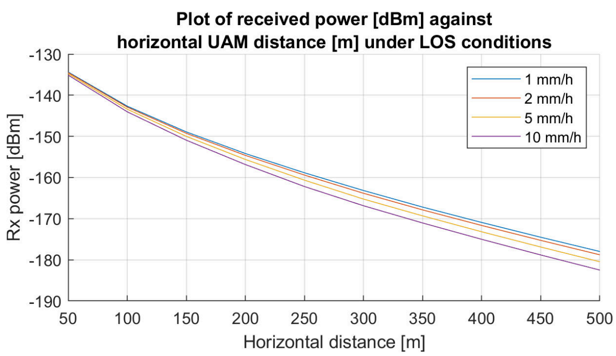


Fig. 3. Received signal power against horizontal distance between the vehicle and GCS, for different rainfall rates.

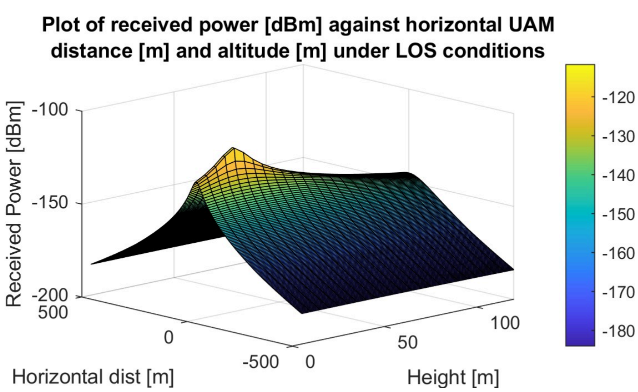


Fig. 4. Variation in received signal power for different vehicle positions.

## V. Conclusions

This study examined communication technologies to enable sustainable UAM operations. It proposed an integrated architecture for UAM with functional requirements for typical UAM operations. The challenges of 6G for dense UAM operations in green metropolitan environments were subsequently analysed through a link budget analysis. This suggested promising directions for future research on UAM communications systems, paving the way for a more efficient, secure and sustainable UAM transportation system. Future research will expand on the proposed model, employing advanced channel modelling techniques for 6G in UAM applications.


## VI. Acknowledgement

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