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Sustainable 6G-NTN for Seamless Air Mobility: Exploring Channel Propagation Characteristics

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***Abstract*—The air transportation vision for sustainable sixth-generation (6G) wireless communications networks revolves around ensuring ubiquitous coverage and spectral efficiency with enhanced network intelligence in the diverse communication scenarios. This vision extends beyond terrestrial networks to include non-terrestrial networks (NTN) by incorporating GX Inmarsat satellites and aircraft networks. In the context of 6G GX satellite scenarios, aircraft seamless transportation plays a crucial role as a densely populated intermediate network layer between ground networks and space-based ones. The paper proposes a new sustainable mechanism with mathematical model to improve channel propagation, which has been validated by crucial analysis of propagation channel modeling within the framework of 6G technology. It highlights the significance of such modeling with the guarantee of dependable communications, maximizing availability, and establishing system parameters like antenna layout and relay deployment.It explores industry trends and ongoing field trial initiatives, offering valuable insights into the progress and outcomes that will shape the future of 6G NTN.**

I. INTRODUCTION

The integration of Non-Terrestrial Networks (NTN) and 6G communication is anticipated to ensure the widespread and uninterrupted coverage of the wireless network [1] [2], involving both outdoor and indoor areas [3]. In Release-17, the 3rd Generation Partnership Project (3GPP) outlined support for NTN [4] applicable to both fixed wireless and handheld devices that are compatible with New Radio (NR) technology and internet of thinks (IoT) [5], including NarrowBand-Internet of Things (NB-IoT) and enhanced Machine-Type Communication (eMTC). The objective of NTN is to provide not only truly global satellite service availability but also resilience to natural disasters such as tsunamis and earthquakes [6]. The NTN scope encompasses satellites positioned at various altitudes, ranging from Geostationary Earth Orbit (GEO) to Low Earth Orbit (LEO), as well as High-Altitude Platform Systems (HAPS) [7]. To improve energy efficiency, the resource utilization of base stations (BSs) and their co-located servers is expected to assign with a highly effective and sustainable strategy, such as integer linear programming (ILP) [8], alternating direction method of multipliers (ADMM) [9],and software-defined networking (SDN) controller [10]. In general, sustainable 6G intends to secure the data link for air transportation [11] by addressing the shortcomings of current mobile networks, and respond to growing Quality of Service (QoS) and energy efficiency with ultra-high peak data rates, ultra-low latency, wide coverage and high connection density [12].

Over the past few decades, satellite communication has become a potential candidate for broadband services with the constellation of non-geostationary satellite orbit (NGSO) in future 6G networks [13]. The integration of satellite and 6G communication technologies has benefitted advanced air mobility (AAM) from a robust data link and efficient traffic management [14]. In air transportation, sustainable 6G is detailed in seamless in-flight connectivity and AAM integration [15]. A key component of these systems is a robust command and control (C2) data link, which oversees essential flight and safety systems, transmits telemetry data, and facilitates communication between the air vehicle and the ground station [16]. This synergy has facilitated the seamless exchange of crucial information between aircraft and 6G ground stations [17], [18], contributing to improved safety and operational effectiveness in aviation [19], [20]. This evolution reflects a paradigm shift, as modern aircraft increasingly rely on high-speed data connectivity for a myriad of applications, including real-time navigation updates, weather monitoring, and passenger connectivity [21]. The deployment of advanced satellite communication technologies [22], such as those exemplified by the GX satellite communication system, has proven crucial to meeting the flexible requirement of contemporary aircrafts. These systems not only improve data link reliability, but also pave the way for enhanced connectivity, supporting the growing demands of aviation stakeholders and passengers alike. As we dive deeper into the challenges posed by the demand for a high data rate in aerial communication, the role of NTN remains central to ensure robust and efficient connectivity for airborne platforms.

The main contribution of this paper is to present a new sustainable 6G mechanism for air-to-ground (A2G) data link using the system model of GX satellite-based 6G communication for air transportation. The evaluation of channel propagation [23] provides valuable insight into their performance and capabilities. The limitations of the proposed model are transparently addressed, with references to existing literature providing insights into potential solutions and avenues for improvement. This critical assessment enhances the overall robustness and applicability of the presented model, guiding future research towards refining and expanding the capabilities of satellite-based 6G systems for aircraft communication.

The remaining is organized as following. Section. II describes the integration of Non-Terrestrial Networks (e.g LEO, GEO) with 6G technology, and aircraft communications. Sec-

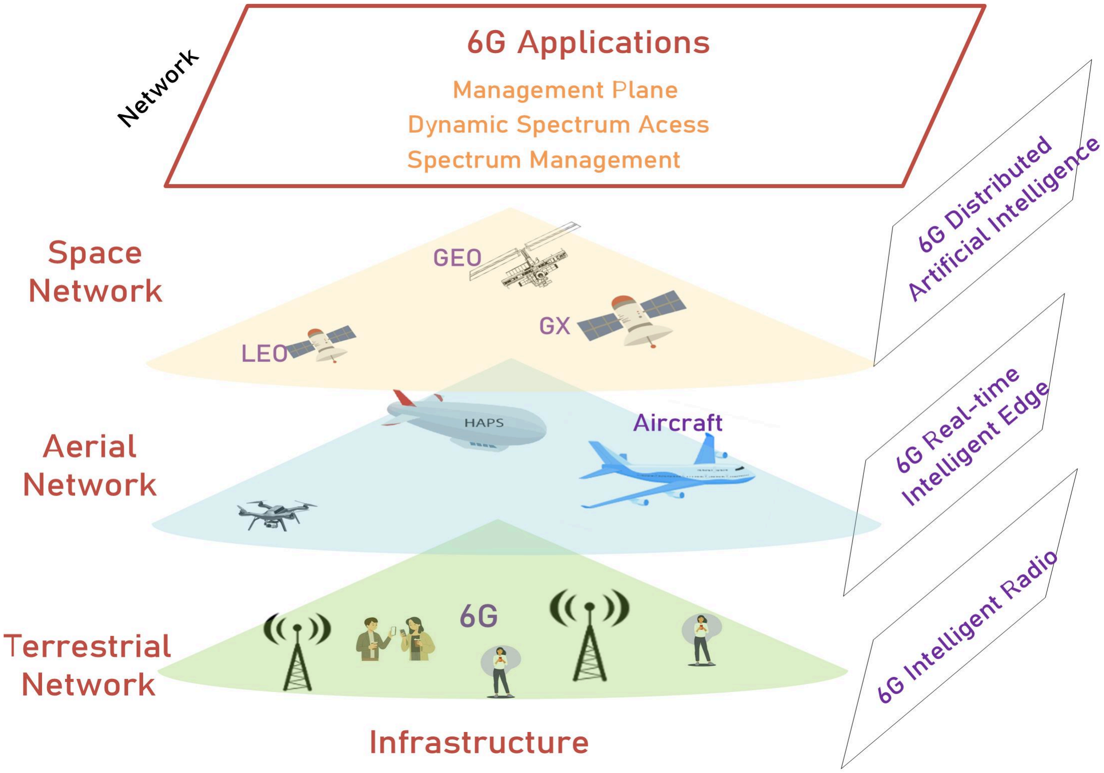

Fig. 1. Seamless air transportation integrated satellite-terrestrial network

tion. III indicated the system design analysis for a high link budget and quantitative analyses are consolidated into the aircraft communication in Section. IV. Finally, Section. V concludes by summarizing the findings and suggesting promising avenues for further research.

II. FUTURE 6G SATELLITE NETWORK

Satellite communication systems offer a solution to reduce the limitations of terrestrial networks by providing extensive coverage, especially in complex terrains, and the ability to multicast and broadcast. Despite their advantages, these systems still have to address several challenges, including complex deployment, expensive infrastructure, and deep fading at higher frequency bands. [24].

A. Satellite Terrestrial Network

In the context of 6G, satellite wireless backhaul is being explored for rural and remote areas due to the high costs associated with terrestrial networks [7]. Various types of satellites exhibit distinct features. Geostationary (GEO) satellites, positioned at a fixed orbit of 36000 km, substantially expand the covering area with the price of propagation delay and signal attenuation due to their high altitude. Medium Earth orbit (MEO) satellites, with orbits between 2000 and 36000 km, released propagation delay and signal attenuation with the decreased coverage. Their variable altitude ensures generally adequate orbit resources, as shown in Fig. I. Low Earth orbit (LEO) satellites operate at altitudes between 500 and 2000 km, minimizing propagation delay and signal attenuation with the enhanced structural complexity due to the requirement for covering a significant area. Nonetheless, The orbit resources of LEO are comparatively sufficient and not fixed with height [13].

LEO is characterized as a circular orbit in the range of approximately 160 to 1000 km with an orbital period of about 90 minutes. For telecommunications purposes, the constellation of satellites in LEO is essential to ensure continuous service within limited visible time from the ground to each satellite [1]. GEO is positioned at an altitude of 35786 km, where satellites travel at the same angular rate as Earth and complete an orbit in sync with Earth's rotation (23 hours, 56 minutes, and 4 seconds), known as a sidereal day. This orbit is dominant in telecommunications due to the unique feature of satellites staying fixed over a specific area on Earth. This characteristic ensures a constant link between the satellite and a specific location, facilitating continuous and stable communication [1]. In the pursuit of advancing communication technologies like 6G technology, very low Earth orbit (VLEO) has been proposed to lower the communication latency [13]. VLEO, with an altitude below 300 km, offers benefits such as improved link budget, lower latency, and the decreased power for transmission. The new orbit also benefits from enhanced frequency reuse capability, a lower radiation environment, and a wider available band, resulting in lower rainfall interference and improved launcher uplift capability [25].

B. Key Drivers for 6G NTN Integration

Owing to the broad coverage of NTNs and their resilience against physical disruptions and natural disasters, they are expected to play an essential role in supporting the 6G terrestrial networks [26]:

- Leveraging on the efficient over-the-air computation / communication, NTNs can extend 6G connectivity to the limited regions where the 6G terrestrial networks are unavailable.
- NTNs accelerate the development of reliable 6G transportation networks, which guarantees uninterrupted connectivity for IoT sensors at airport, railway station, and so on.
- NTNs can increase the scalability of high-capacity broadcasting to edge devices, therefore avoiding the network overload during massive streaming and offloading.

The substantial propagation delay inherent in satellite systems poses a formidable challenge for their application in ultra-reliable low-latency communication (uRLLC) scenarios. Despite this limitation, the role of aircraft and other aerial vehicles in 6G use cases cannot be overstated. These vehicles serve as highly flexible platforms capable of dynamically adjusting their 3D locations, leveraging the advanced communication technologies embedded in 6G to efficiently meet the communication needs of target users.

Aircraft and aerial vehicles [27] possess inherent advantages, such as their ability to traverse various terrains and navigate complex environments, making them valuable assets in scenarios where terrestrial communication infrastructure may be limited or impractical [28]. The dynamic nature of these platforms allows for strategic positioning, optimizing communication links, and reducing latency for critical applications. Furthermore, these aerial platforms can be integrated into the 6G landscape to support emerging applications such as autonomous systems, remote sensing, and disaster response. Their adaptability and transportation make them well suited for scenarios requiring rapid deployment and real-time communication, significantly contributing to the robustness and resilience of 6G networks. The ongoing development of 3GPP NTN features further underscores the commitment to unlocking the full potential of these platforms, offering promising avenues to meet and exceed consumer expectations in the evolving landscape of 6G networks.

C. Global Aircraft-Satellite System

According to the released bands from European Space Agency (ESA) [29], satellites play a pivotal role in ensuring seamless global communication for aircraft, particularly in remote regions such as oceans and polar areas where conventional ground-based communication systems are ineffective. Advancements in non-terrestrial networks (NTN) and Low Earth Orbit (LEO) satellite constellations, like Starlink and OneWeb, deliver high-speed, low-latency connectivity, enabling real-time data exchange between aircraft, air traffic management, and ground-based systems. The transition to the 6G era will further integrate space and terrestrial networks, fostering ultra-reliable, low-latency communications tailored for the aviation industry, as shown in Fig. 2 . These satellite-powered 6G networks will bolster the resilience of aviation communication systems, supporting autonomous flight operations, advanced real-time analytics, and cutting-edge cockpit technologies.

Fig. 2. Global System Architecture for 6G Aircraft-Satellite

III. System Design for High-fidelity link budget

This section intends to design and demonstrate data link communications between aircraft and satellite communications. This is achieved by increasing the reliability of the link budget during a situation with different parameters such as orbit, frequencies, weather, atmospheric conditions, location, and inclination of the aircraft.

To define the strength of data link between satellite and the ground station, it's common to use the following link budget equation in order to understand the feasibility of the communication system [7].

$$P_{\text{received}}(dB) = P_{\text{transmitted}}(dB) + Gains(dB) - Losses(dB) \tag{1}$$

A. Losses

1) Path losses:

a) Free space path loss: The evaluation of the variation in the free space path loss (FSPL) in this case of study for free space path loss is defined as:

$$\begin{aligned} \text{FSPL(dB)} &= 10\log_{10}\left(\frac{4\pi df}{c}\right)^2 \\ &= 20\log_{10}(d) + 20\log_{10}(f) + 20\log_{10}\left(\frac{4\pi}{c}\right) \end{aligned} \tag{2}$$

where d denotes the distance between the transmitter and receiver, f represents the frequency of the transmitted wave, and c denotes the speed of light. Given that the satellite position is defined as (x_0, y_0, z_0) while the aircraft position is denoted as (x_1, y_1, z_1), the distance d is defined as

$$d = \sqrt{(x_1 - x_0)^2 + (y_1 - y_0)^2 + (z_1 - z_0)^2}. \quad (3)$$

According to (2), the magnitude of FSPL is dependent on the distance between the satellite and the aircraft. The upper bound of the FSPL is derived as around $7.0436(dB)$ with the highest frequency for the Ku-band and the lowest frequency for X-band.

b) Atmospheric losses: Atmospheric losses are determined by the link performance, which depends on lots of impact factors such as rain, clouds, or even gaseous absorption. To demonstrate these losses or attenuation with high accuracy, the ITU-R P618 module is implemented to simulate their effects on the link budget.

c) Ionospheric losses: In this study case, considering that the frequencies are between 8 and 18 GHz, the ionospheric losses can be totally negligible.

2) Other Losses:

a) The Internal Losses from transceiver: These losses highly rely on the system specification. In the next section, we will conduct a quantitative analysis with the information from the selected antennas.

b) Noise losses: Noise losses are generally defined in NTNs as

$$L_{\text{N}} = 10 \log(k_b B T), \quad (4)$$

where k_b denotes the Boltzmann constant, T denotes the absolute temperature in Kelvin, B means the bandwidth of the system. In accordance with (4), noise losses are tied to both the noise temperature and the bandwidth of the system, primarily due to the random motion of electrons within the system.

c) Aircraft attenuation: The aircraft also suffers from unique attenuation from the reflection of the sea surface to the airframe as well as other environmental factors [30]. For simplification, we neglected these factors in this paper.

B. Gains

1) Transmitter Gain : A dish antenna will be implemented to formulate the gain of the satellite antenna as

$$G_t = 20 \log \left(\frac{\pi D_t F \sqrt{\eta}}{c} \right), \quad (5)$$

where D_t denotes the diameter of the antenna, f denotes the frequency of wave, η denotes the antenna efficiency accounting for feed losses, and surface imperfections, c means the speed of light.

2) Receiver Gain : Considering the dish antenna on aircraft, the receiver gain will be directly derived with the benchmark dataset.

C. Carrier to noise ratio

The carrier to noise ratio (C/N) indicates how noise will affect the receiver power as:

$$C/N\,(\text{dB}) = EIRP + G_{\text{R}} - L_{\text{P}} - L_{\text{R}} - L_{\text{N}} \quad (6)$$

$$EIRP = G_{\text{T}} + L_{\text{T}} + P_{\text{T}} \quad (7)$$

where EIRP is the Effective Isotropic Radiated Power as (7), where G_{T} and G_{R} denote the array gain for transmitter and receiver separately, L_{T} and L_{R} denote the losses from transmitter and receiver, respectively. In addition, L_{P} means path losses, L_{N} denotes noise losses, P_{T} means transmitted power.

D. The Metrics of Signal Strength

The signal strength is evaluated by the energy per bit to noise ratio as (9), where R denotes data rate of the downlink. As a result, the link margin (LM) is defined as the bit error rate (BER) between uplink and downlink like

$$LM = (E_b/N_0)_{RQ} - E_b/N_0 \quad (8)$$

$$E_b/N_0 = C/N - 10 \log(R) \quad (9)$$

where $(E_b/N_0)_{RQ}$ is the minimum ratio needed to achieve a target BER or quality of service (QoS). This value depends on factors such as modulation type, coding scheme, or performance specifications in standards. If the Link Margin is positive, it means the actual ratio E_b/N_0 exceeds the required threshold, ensuring the desired bit error rate can be met.

IV. SUSTAINABLE MECHANISM AND ANALYSIS

The flowchart design highlights the complexities of maintaining seamless connectivity over large geographical distances, especially when dealing with the variability in path losses between regions like Aswan and Svalbard. The incorporation of 6G technology ensures enhanced bandwidth, reduced latency, and improved resilience against communication disruptions. The flowchart in Fig. 3 illustrates the process of configuring an aircraft flight data link mechanism by leveraging 6G communication technologies and the Inmarsat GX GEO satellite. This mechanism demonstrates the end-to-end connectivity and the challenges of maintaining reliable communication across different locations, specifically between Aswan (Egypt) and Svalbard (Norway).

The system starts by initializing the aircraft's communication module, ensuring compatibility with 6G technology and the Inmarsat GX GEO satellite infrastructure. Parameters such as aircraft location, altitude, velocity, and flight data are acquired from onboard systems. The aircraft antenna used is the GAT-5530 from Viasat Ka Band with bandwidth of 500MHz and a Gain of 50dB [30]. The flight data transmission path is calculated, including uplink from the aircraft to the satellite and downlink from the satellite to the ground station. The mechanism evaluates the geographical distance and position changes between Aswan and Svalbard, identifying intermediate waypoints if necessary.

The analysis is performed based on the propagation path, latency, and data rates achievable for the data link between aircraft and satellite.

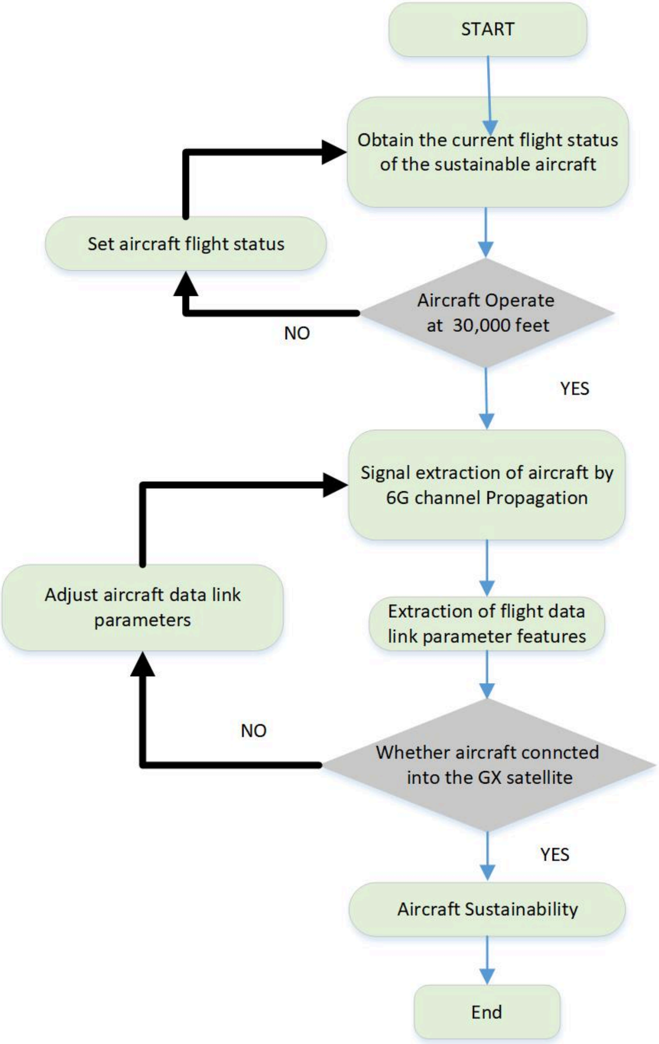

Fig. 3. Sustainable aircraft data link mechanism

A. *GX Satellite Communications*

Satellite communication (SATCOM) was first utilized in aerospace during the late 1970s to address challenges associated with low spectral efficiency and restricted coverage in the conventional aviation communication. Its primary aim was to enhance communication reliability, particularly for long-distance flights, where conventional systems struggled to provide adequate coverage. One of its flagship initiatives is the Global Xpress (GX) project, comprising a fleet of five satellites designated GX1 through GX5. For aircraft flying from Aswan to Svalbard, we'll be assessing the capabilities of three specific satellites within the GX fleet including GX1, GX4, and GX5 [30]. This evaluation will help determine the most effective satellite for ensuring uninterrupted communication during our journey.

B. *Propagation Path loss Calculations*

The path losses beyond FSPL can be determined using MATLAB module p618, where we just considered the limited parameter, including the position and attitude of the aircraft relative to satellite and antenna efficiency. In this scenario, the flight path [31] is described with the position and the elevation angle of the aircraft as Fig. 4. The sine law has been developed to find α as (10), where D denotes the distance between the aircraft and the satellite. Under Cartesian coordinate, D is calculated with (x_s, y_s, z_s) and (x_a, y_a, z_a) as (11).

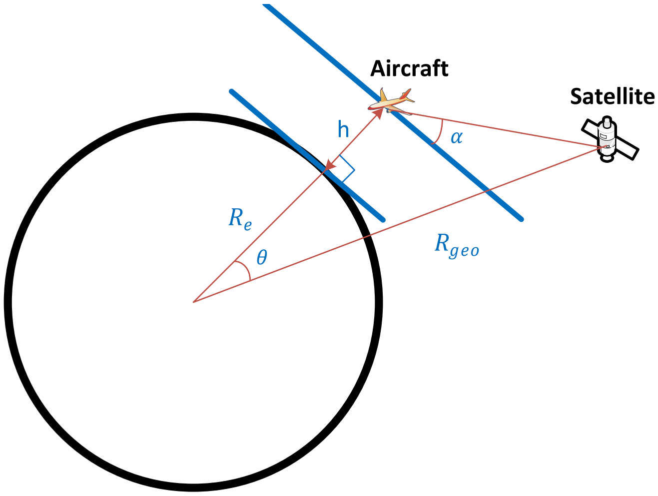

Fig. 4. The Architecture of Aircraft SATCOM

$$R_{geo}^2 = D^2 + 2(R_e + h)D\sin\alpha - (R_e + h)^2 \tag{10}$$

$$D = \sqrt{(x_a - x_s)^2 + (y_a - y_s)^2 + (z_a - z_s)^2} \tag{11}$$

The experiments have been conducted against latitude on the three satellites, namely GX1, GX4, and GX5, as depicted in Fig. 5. The results indicate that the error observed at the end of each curve is attributed to an elevation angle lower than 5°, making it unprocessed by the P618 module. Notably, at approximately 70° latitude, there is a significant disparity of around 10dB between GX5 and GX1. This difference is noteworthy, especially considering that the perturbation range spans from 2 dB to 24dB.

C. *Latency*

To calculate the latency for GX1, GX4, and GX5 satellites at an aircraft altitude of 2 km, $\delta t = \frac{d}{c}$ is implemented, where δ denotes the latency of SATCOM, d is the distance between the satellite and the aircraft, c is the speed of light. Based on observations, it has been observed that GX5 consistently exhibits the lowest latency in aircraft latitudes ranging from 20 to 80 degrees, as illustrated in Fig. 6. This implies that within this latitude range, GX5 provides the fastest communication or the strongest signal transmission between the satellite and the aircraft compared to GX1 and GX4.

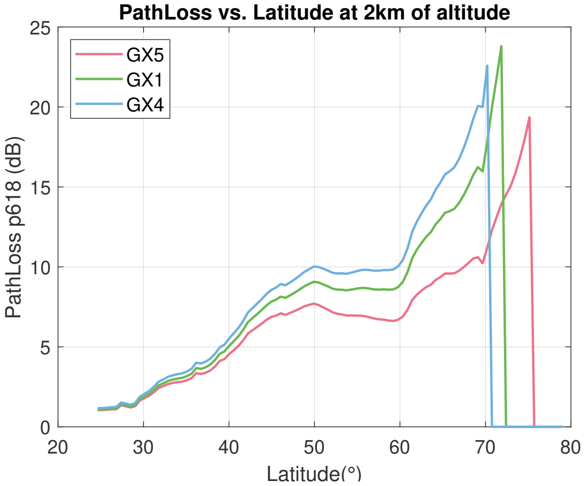

Fig. 5. Path Losses against the Latitude of Aircraft

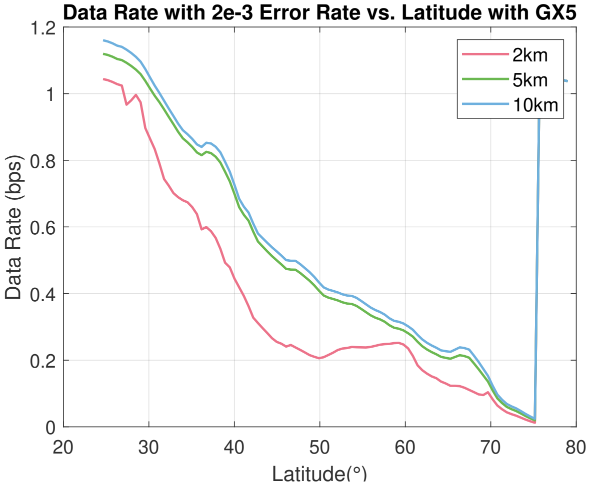

Fig. 7. Data rate in function of latitude and aircraft altitude

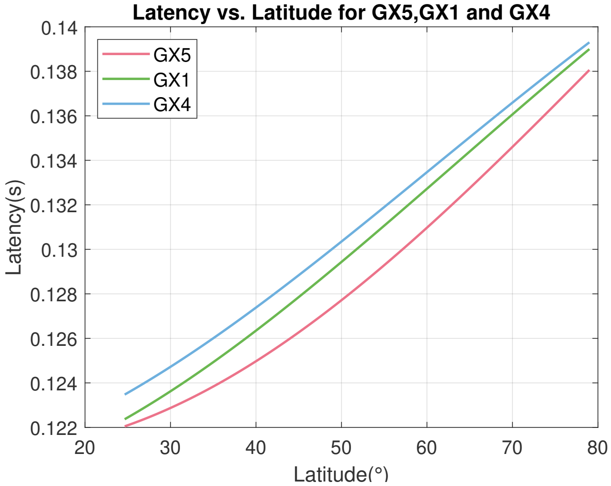

Fig. 6. Latency in function of Aircraft Latitude

D. Carrier to Noise ratio

The C/N ratio (CNR) is determined by subtracting the noise power from the received power. In the calculations, a temperature of 290K and a bandwidth of 500MHz were considered for the noise power calculation. Assessment of aircraft elevation has revealed significant variations, particularly in the latitudinal range of 42–52°, where notable changes of approximately 2-3 dB were observed in the CNR. Furthermore, Fig. 7 indicates the singal strength is seriously affected by the specific position and attitude of aircraft. These variations in the C/N ratio emphasize the impact of aircraft elevation on the received signal quality, with distinct changes observed at specific latitudes. The non-linear decrease observed in the C/N ratio signifies that propagation losses are not linear. As the altitude of the aircraft increases, the C/N curve appears to become more linear. This observation suggests that atmospheric perturbations, particularly those encountered at low altitudes such as 2 km, have a substantial impact on the communication link between the aircraft and the satellite. The non-linearity in the C/N ratio at low altitudes implies that atmospheric conditions, such as variations in temperature, pressure, and humidity, introduce non-uniform effects on the signal propagation, leading to a non-linear decline in the C/N ratio. As the aircraft ascends to higher altitudes, where atmospheric perturbations may be less pronounced, the C/N ratio tends to exhibit a more linear behavior. This understanding is crucial for optimizing communication systems, especially when operating at lower altitudes, where atmospheric conditions play a significant role in signal quality.

E. Data rates

The data rates obtained in this segment were determined using an acceptable bit error rate of 2×10^{-5}. This corresponded to a required $(\frac{E_b}{N_0})_{required}$ of 5 dB with Binary Phase Shift Keying (BPSK) encoding. As depicted in Fig. 7, when latitude is constrained within 70°, the data rate will share the negative correlation with latitude, and positive correlation with altitude.

To ensure a reliable and consistent communication link, incorporating a link margin of 3–4 dB is essential. This margin helps compensate for various uncertainties in the system, including atmospheric losses, signal fading, and potential interference, thereby enhancing the robustness of the connection. Without this additional margin, the reliability of the communication link could be compromised, particularly in scenarios involving adverse weather conditions or rapidly changing communication environments. The transition to the 6G era will enable greater integration of space-based and terrestrial networks, providing ultra-reliable, low-latency communications tailored specifically for the aviation industry. Satellite-enabled 6G networks will enhance the resilience of aviation communication systems by incorporating advanced technologies such as error correction algorithms, adaptive beamforming, and dynamic frequency allocation to mitigate potential losses.

V. CONCLUSION

In this paper, the feature of channel propagation is investigated in seamless air transportation, highlighting the role of sustainable 6G wireless networks. With regard to sustainable 6G NTN communication, dynamic challenges are presented by linking aircraft mobility with satellites. The data attenuation is quite serious with an altitude around 2 km. The link capacity is reduced due to the impact of the longitude of the satellite on the distance and the angle of elevation. The calculation of data rates faces hurdles due to uncertainties in gains and power. Moreover, path propagation perturbations are not strictly linear and can potentially be attributed to variations in atmospheric composition across different latitudes. According to these insights, further research is expected to conducted on sustainable 6G communication for channel modeling in 6G NTN to accelerate the integration between seamless air transportation and NTN 6G.

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REFERENCES

[1] A. Warrier, L. Aljaburi, H. Whitworth, S. Al-Rubaye, and A. Tsourdos, "Future 6G communications powering vertical handover in non-terrestrial networks," *IEEE Access*, vol. 12, pp. 33 016–33 034, 2024.

[2] S. Al-Rubaye, A. Al-Dulaimi, and J. Cosmas, "Pilot power optimization for autonomous femtocell networks," in *2011 Wireless Advanced*, 2011, pp. 170–175.

[3] X. Lin, S. Rommer, S. Euler, E. A. Yavuz, and R. S. Karlsson, "5G from space: An overview of 3GPP non-terrestrial networks," *IEEE Communications Standards Magazine*, vol. 5, no. 4, pp. 147–153, 2021.

[4] X. Liu, H. Zhang, M. Sheng, W. Li, S. Al-Rubaye, and K. Long, "Ultra dense satellite-enabled 6G networks: Resource optimization and interference management," *China Communications*, 2023.

[5] S. Al-Rubaye, J. Rodriguez, L. Z. Fragonara, P. Theron, and A. Tsourdos, "Unleash narrowband technologies for industrial internet of things services," *IEEE Network*, vol. 33, no. 4, pp. 16–22, 2019.

[6] B. G. Evans, P. T. Thompson, G. E. Corazza, A. Vanelli-Coralli, and E. A. Candreva, "1945-2010: 65 years of satellite history from early visions to latest missions," pp. 1840–1857, 2011.

[7] F. A. Dicandia, N. J. G. Fonseca, M. Bacco, S. Mugnaini, and S. Genovesi, "Space-air-ground integrated 6G wireless communication networks: A review of antenna technologies and application scenarios," *Sensors*, vol. 22, no. 9, 2022. [Online]. Available: https://www.mdpi.com/1424-8220/22/9/3136

[8] S. Al-Rubaye and B. J. Choi, "Energy load management for residential consumers in smart grid networks," in *2016 IEEE International Conference on Consumer Electronics (ICCE)*, 2016, pp. 579–582.

[9] Y. He *et al.*, "Two-timescale resource allocation for automated networks in IIoT," *IEEE Transactions on Wireless Communications*, vol. 21, no. 10, pp. 7881–7896, October 2022.

[10] S. Al-Rubaye and J. Aulin, "Grid modernization enabled by SDN controllers: Leveraging interoperability for accessing unlicensed band," *IEEE Wireless Communications*, vol. 24, no. 5, pp. 60–67, 2017.

[11] B. Fraser, S. Al-Rubaye, S. Aslam, and A. Tsourdos, "Enhancing the security of unmanned aerial systems using digital-twin technology and intrusion detection," in *2021 IEEE/AIAA 40th Digital Avionics Systems Conference (DASC)*, 2021, pp. 1–10.

[12] A. Machumilane, P. Cassara, and A. Gotta, "Toward a fully-observable markov decision process with generative models for integrated 6G-Non-Terrestrial Networks," *IEEE Open Journal of the Communications Society*, vol. 4, pp. 1913–1930, 2023.

[13] A. Bhattacharya and M. Petrova, "Study on handover techniques for satellite-to-ground links in high and low interference regimes," in *2023 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit)*, 2023, pp. 359–364.

[14] S. Al-Rubaye, A. Tsourdos, and K. Namuduri, "Advanced Air Mobility Operation and Infrastructure for Sustainable Connected eVTOL Vehicle," *Drones*, 2023.

[15] M. Mousa, S. Al-Rubaye, and G. Inalhan, "Unmanned aerial vehicle positioning using 5G new radio technology in urban environment," in *2023 IEEE/AIAA 42nd Digital Avionics Systems Conference (DASC)*, 2023, pp. 1–9.

[16] S. Al-Rubaye, A. Al-Dulaimi, and Q. Ni, "Power interchange analysis for reliable vehicle-to-grid connectivity," *IEEE Communications Magazine*, vol. 57, no. 8, pp. 105–111, August 2019.

[17] S. Al-Rubaye and A. Tsourdos, "Airport Connectivity Optimization for 5G Ultra-Dense Networks," *IEEE Transactions on Cognitive Communications and Networking*, vol. 6, no. 3, pp. 980–989, 2020.

[18] K. Mohanta and S. Al-Rubaye, "Towards 6G satellite–terrestrial networks: Analysis of air mobility operations," *Electronics*, vol. 13, no. 14, 2024. [Online]. Available: https://www.mdpi.com/2079-9292/13/14/2855

[19] H. Whitworth, S. Al-Rubaye, A. Tsourdos, J. Jiggins, N. Silverthorn, and K. Thomas, "Aircraft to Operations Communication Analysis and Architecture for the Future Aviation Environment," in *2021 IEEE/AIAA 40th Digital Avionics Systems Conference (DASC)*, 2021, pp. 1–8.

[20] J. Maguire-Day, S. Al-Rubaye, A. Warrier, M. A. Sen, H. Whitworth, and M. Samie, "Emerging decision-making for transportation safety: Collaborative agent performance analysis," *Vehicles*, vol. 7, no. 1, p. 4, 2025. [Online]. Available: https://doi.org/10.3390/vehicles7010004

[21] S. Al-Rubaye, C. Conrad, and A. Tsourdos, "Communication network architecture with 6G capabilities for urban air mobility," in *2024 IEEE International Conference on Consumer Electronics (ICCE)*, 2024.

[22] P. Angeletti, U. Guida, M. Lisi, and G. Lucchi, "HEO satellite systems for broadband aeronautical communications." American Institute of Aeronautics and Astronautics Inc., 2003.

[23] X. Wang *et al.*, "A multi-task learning model for super resolution of wireless channel characteristics," in *GLOBECOM 2022 - 2022 IEEE Global Communications Conference*, 2022, pp. 952–957.

[24] S. B. R. Tirmizi, Y. Chen, S. Lakshminarayana, W. Feng, and A. A. Khuwaja, "Hybrid satellite–terrestrial networks toward 6g: Key technologies and open issues," *Sensors*, vol. 22, no. 21, 2022. [Online]. Available: https://www.mdpi.com/1424-8220/22/21/8544

[25] L. Berthoud, R. Hills, A. Bacon, M. Havouzaris-Waller, K. Hayward, J.-D. Gayrard, F. Arnal, and L. Combelles, "Are very low earth orbit (vleo) satellites a solution for tomorrow's telecommunication needs?" *CEAS Space Journal*, vol. 14, no. 4, pp. 609–623, 2022.

[26] M. M. Azari, S. Solanki, S. Chatzinotas, O. Kodheli, H. Sallouha, A. Colpaert, J. F. Mendoza Montoya, S. Pollin, A. Haqiqatnejad, A. Mostaani, E. Lagunas, and B. Ottersten, "Evolution of non-terrestrial networks from 5G to 6G: A survey," *IEEE Communications Surveys & Tutorials*, vol. 24, no. 4, pp. 2633–2672, 2022.

[27] V. Towhidlou, S. Al-Rubaye, and A. Tsourdos, "LTE Handover Design for Cellular-Connected Aircraft," in *2022 IEEE/AIAA 41st Digital Avionics Systems Conference (DASC)*, 2022, pp. 1–5.

[28] M. Ozpolat, S. Al-Rubaye, A. Williamson, and A. Tsourdos, "Integration of Unmanned Aerial Vehicles and LTE: A Scenario-Dependent Analysis," in *2022 ICCVE*, 2022, pp. 1–6.

[29] S. Chen, S. Sun, and S. Kang, "System integration of terrestrial mobile communication and satellite communication —the trends, challenges and key technologies in B5G and 6G," *China Communications*, vol. 17, no. 12, pp. 156–171, 2020.

[30] H. Whitworth, S. Al-Rubaye, and A. Tsourdos, "Utilizing satellite communication to enable robust future flight data links," in *2023 IEEE/AIAA 42nd Digital Avionics Systems Conference (DASC)*, 2023, pp. 1–8.

[31] S. K. Gopalakrishnan, S. Al-Rubaye, and G. Inalhan, "Adaptive uav swarm mission planning by temporal difference learning," in *2021 IEEE/AIAA 40th Digital Avionics Systems Conference (DASC)*, 2021, pp. 1–10.

[32] M. El Debeiki, S. Al-Rubaye, A. Perrusquía, C. Conrad, and J. A. Flores-Campos, "An advanced path planning and uav relay system: Enhancing connectivity in rural environments," *Future Internet*, vol. 16, no. 3, 2024. [Online]. Available: https://www.mdpi.com/1999-5903/16/3/89

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https://doi.org/10.1109/icns65417.2025.10976967