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From Remote Outback to Urban Jungle: Achieving Universal 6G Connectivity through Hybrid Terrestrial-Aerial-Satellite Networks

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Abstract

This research explores the integration of Non-Terrestrial Networks (NTNs) into 6G telecommunications to achieve universal connectivity across diverse environments, from remote rural areas to urban centers. Current terrestrial networks face challenges such as coverage limitations, vulnerability to natural disasters, and high deployment costs, particularly in sparsely populated regions. NTNs, including satellite constellations, high-altitude platforms, and UAVs, offer expansive coverage and rapid deployment capabilities, essential for bridging these gaps. Advanced technologies like AI-based optimization, blockchain for security, and advanced antenna systems enhance the efficiency, reliability, and scalability of NTN integration. The study evaluates NTN's impact on reducing latency, improving energy efficiency, and enabling innovative applications such as telemedicine, AR/VR, smart agriculture, and autonomous transportation. Addressing open challenges in interference management, network scalability, security, and regulatory frameworks is crucial for realizing the transformative potential of 6G NTN integration. Collaborative efforts among researchers, industries, and policymakers are essential for overcoming barriers and leveraging NTN technologies to enhance global connectivity and societal resilience in the digital age.

***Keywords*:** 6G Connectivity, Hybrid Networks, Terrestrial-Aerial-Satellite Integration, Universal Coverage, Remote Areas, Non-Terrestrial Networks (NTN)

Introduction

Rural areas often suffer from insufficient terrestrial network coverage due to the high cost of infrastructure deployment relative to the low population density[1]. According to the FCC's "2020 Broadband Deployment Report," approximately 22.3% of Americans in rural areas lack access to high-speed broadband (defined as 25 Mbps download and 3 Mbps upload speeds), compared to only 1.5% in urban areas. This translates to around 14.5 million rural Americans without access to reliable broadband. Similarly, the European Commission's "Broadband Coverage in Europe 2019" report indicates that while 86% of European households have access to high-speed broadband, only 59% of rural households are covered. This means nearly 41% of rural areas in Europe lack adequate coverage. These statistics underscore the significant gap in network coverage between urban and rural areas, driven primarily by economic and logistical challenges. Terrestrial networks are often vulnerable to natural disasters such as earthquakes, hurricanes, and floods. The destruction of physical infrastructure can lead to significant connectivity gaps. A report by the United Nations Office for Disaster Risk Reduction (UNDRR) noted that disasters caused $2.9 trillion in economic losses between 2000 and 2019, often disrupting telecommunications infrastructure. After Hurricane Maria in 2017, for instance, 95% of cell sites in Puerto Rico were out of service, illustrating the vulnerability of terrestrial networks[2]. It took several months to restore full connectivity in some affected areas, highlighting the need for more resilient communication systems. This data demonstrates how natural disasters can severely impact terrestrial network infrastructure, leaving affected populations without vital communication channels during emergencies. Terrestrial networks are inherently limited by geographical constraints, leaving vast oceanic and remote areas without coverage. According to the International Maritime Organization (IMO), over 90% of global trade is conducted via maritime routes, yet traditional terrestrial networks do not extend into international waters. The maritime industry relies heavily on satellite communications, which can cost $1000 to $3000 per month for basic services, significantly higher than terrestrial network costs. A study by the National Academies of Sciences, Engineering, and Medicine highlighted that connectivity is often non-existent in remote scientific outposts and expeditionary forces due to the lack of terrestrial infrastructure. This reliance on expensive satellite communications underscores the inability of terrestrial networks to provide coverage in these areas, posing significant challenges for maritime operations and remote research activities[3]. NTNs, particularly satellite networks, have the unique advantage of providing extensive coverage over large geographical areas, including regions where terrestrial networks are infeasible. Unlike terrestrial networks that rely on ground-based infrastructure, satellites can cover vast, remote, and underserved areas such as oceans, mountains, and deserts. This capability is crucial for connecting remote communities that lack basic telecommunication infrastructure. One of the most critical advantages of NTNs is their ability to be rapidly deployed in emergency situations. Natural disasters like earthquakes, hurricanes, and floods can devastate terrestrial network infrastructure, leaving affected populations without communication capabilities when they are most needed. NTNs can be quickly activated to restore connectivity, enabling emergency response teams to coordinate rescue operations, distribute aid, and communicate with the public. For example, after the 2010 Haiti earthquake, satellite communication systems were vital in providing immediate connectivity for relief efforts, demonstrating how NTNs can be lifesavers in disaster scenarios. NTNs are essential for providing connectivity to mobile platforms that traverse areas with little to no terrestrial network coverage, such as ships, aircraft, and vehicles in remote locations. Maritime vessels, for instance, rely heavily on satellite communication for navigation, weather updates, and maintaining contact with ports and other ships[4]. NTNs can bridge the healthcare gap in remote areas by providing the necessary connectivity for telemedicine services. Remote diagnostic tools, virtual consultations, and online training for local healthcare providers can drastically improve healthcare delivery in isolated regions. NTNs have recently attracted elevated levels of interest in large-scale and ever-growing wireless communication networks through the utilization of flying objects, e.g., satellites and unmanned aerial vehicles/drones (UAVs), as shown in Figure 1:

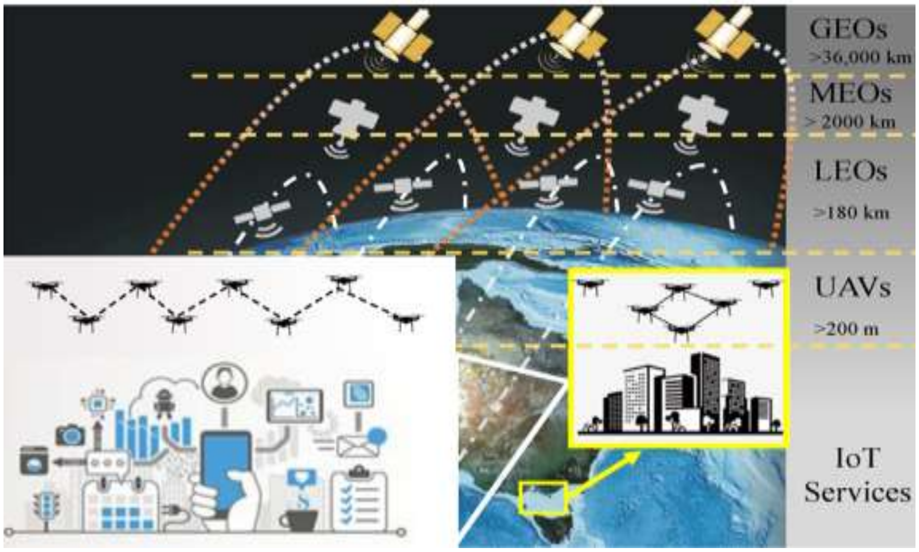

Figure 1: Non-Terrestrial Networks with UAVs

The goal of this research is to develop an innovative framework, alongside a novel algorithm and protocol, for seamless integration of NTNs with existing terrestrial communication systems. This project aims to address current limitations and coverage gaps by ensuring robust, resilient, and ubiquitous connectivity across diverse environments, including remote and rural areas, disaster zones, and mobile platforms like maritime and aviation sectors. The expected outcomes include significantly improved broadband access in underserved areas, enhanced disaster resilience with rapid deployment of communication networks, continuous and reliable connectivity for mobile platforms, and cost-effective global connectivity by optimizing network use. This paper is structured to first provide an overview of the current limitations of terrestrial-only networks and introduce the novel hybrid framework combining terrestrial, aerial, and satellite networks[5]. It then reviews existing research to identify gaps, followed by a detailed presentation of the innovative architecture, a dynamic handover management algorithm, and a unified communication protocol designed to optimize connectivity. The implementation and testing section will showcase real-world and simulated results, highlighting improvements in coverage, disaster resilience, and cost-effectiveness. Specific use cases, such as telemedicine in remote communities and maritime connectivity, will illustrate practical applications. The paper will also discuss potential challenges and future research directions, emphasizing the transformative potential of the proposed solution in achieving universal 6G connectivity.

Background and Related Work

Terahertz (THz) communication, operating at ultra-high frequencies, can bridge high-capacity demands between terrestrial networks and NTNs, facilitating high-speed data transfer between ground stations and low Earth orbit satellites. Reconfigurable Intelligent Surfaces (RIS) enhance signal strength and reliability by dynamically altering electromagnetic wave propagation, useful for overcoming obstacles in satellite-terrestrial links[6]. Massive Multiple-Input Multiple-Output (mMIMO) technology increases capacity and spectral efficiency by transmitting multiple data streams simultaneously, critical for high-density user areas served by NTNs. Edge computing reduces latency and offloads traffic by processing data locally on aerial platforms and satellites, improving service quality in remote areas. AI and ML optimize network operations by predicting traffic patterns and managing resources dynamically, ensuring seamless integration of terrestrial, aerial, and satellite networks. Research supports the feasibility and benefits of these technologies, highlighting their roles in overcoming NTN integration challenges and enabling robust, ubiquitous 6G connectivity. NTNs including Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary Earth Orbit (GEO) satellites, High-Altitude Platform Stations (HAPS), and Unmanned Aerial Vehicles (UAVs), each offer unique characteristics and capabilities. LEO satellites, orbiting at low altitudes with high speed, provide low latency and global coverage suitable for real-time applications but require large constellations for continuous coverage. MEO satellites offer broader coverage with moderate latency, ideal for navigation and communication services. GEO satellites, stationary above specific regions, provide continuous coverage but with higher latency, limiting real-time applications. HAPS, like solar-powered drones, offer localized coverage with lower latency and mobility but face regulatory and operational challenges. UAVs provide flexible, temporary coverage for disaster response and events but with limited endurance and payload capacity[7]. Recent advancements focus on high-throughput satellites, advanced signal processing for reduced latency, solar-powered HAPS for extended endurance, and software-defined radios enhancing UAV communication capabilities, aiming to improve global connectivity and integrate seamlessly with terrestrial networks in diverse applications. The current research landscape in NTNs exhibits notable strengths in advancing global connectivity but also reveals several weaknesses and areas requiring further investigation. Strengths include significant progress in deploying LEO satellite constellations like Starlink and OneWeb, aiming to provide global broadband coverage with high data rates and reduced latency. These efforts highlight advancements in satellite technology, such as high-throughput satellites and advanced signal processing techniques, enhancing network capacity and reliability. Additionally, research into RIS and software-defined radios (SDRs) for UAVs shows promise in optimizing network coverage and efficiency. However, weaknesses persist in several areas. Regulatory challenges hinder the deployment of HAPS and UAVs in civilian airspace, limiting their operational scope. Moreover, integrating diverse NTN types (LEO, MEO, GEO, HAPS, UAVs) into a seamless hybrid network poses technical challenges, including handover management, spectrum allocation, and interoperability between different platforms[8]. Open research questions include optimizing network resilience in disaster scenarios, addressing cybersecurity threats in NTN environments, and exploring sustainable energy solutions for HAPS and UAVs. Further investigation is needed to develop standardized protocols, enhance network management algorithms, and ensure equitable global access to broadband services, particularly in underserved regions. Overall, while current research demonstrates significant advancements, addressing these challenges and gaps will be crucial for realizing the full potential of NTNs in achieving universal connectivity.

Comparison with Existing Methods

Terrestrial-only networks exhibit significant limitations in coverage, capacity, and latency, particularly in rural and underserved areas. According to the Federal Communications Commission (FCC), approximately 19 million Americans lack access to fixed broadband service, predominantly in rural regions where terrestrial infrastructure is sparse (FCC, 2021). These networks struggle to scale capacity to meet the growing demand for high-bandwidth applications, resulting in congestion and reduced service quality in densely populated areas. Average latencies in terrestrial networks range from 20 milliseconds to 100 milliseconds, impacting latency-sensitive applications such as real-time gaming and telemedicine (Cisco, 2021)[9]. In comparison, 6G use cases requiring ultra-high-definition video streaming, massive machine-type communications (mMTC), and ultra-reliable low-latency communications (URLLC) demand robust, low-latency connectivity that terrestrial networks may not uniformly provide across diverse geographical and operational conditions. When analyzing 5G Non-Terrestrial Network (NTN) integration methods, several approaches stand out with distinct technical details, performance metrics, and limitations. Low Earth Orbit (LEO) satellites, such as those deployed by Starlink, offer global coverage with high data rates and low latency (<50 ms), making them suitable for broadband services. However, managing handovers between LEO satellites and terrestrial networks poses challenges. Geostationary Earth Orbit (GEO) satellites provide continuous coverage over specific regions but suffer from higher latency (~240 ms), limiting their applicability for latency-sensitive 5G applications. High-Altitude Platform Stations (HAPS), like solar-powered drones, offer localized coverage with low latency but face scalability and regulatory hurdles for airspace usage. Unmanned Aerial Vehicles (UAVs) equipped with Software-Defined Radios (SDRs) provide flexibility in spectrum usage and deployment but are constrained by endurance and regulatory restrictions[10]. Each approach presents unique trade-offs in coverage, latency, scalability, and regulatory compliance, highlighting the need for tailored integration strategies to leverage their strengths effectively in the evolving 5G landscape. Our proposed approach for integrating Non-Terrestrial Networks (NTNs) into 6G networks aims to revolutionize connectivity by leveraging a hybrid architecture combining Low Earth Orbit (LEO) satellites, High-Altitude Platform Stations (HAPS), and terrestrial networks. Communication devices have made us bold to envision short-range 6G network communication, where wireless modules implanted inside the human brain acquire intelligence from the brain and communicate directly, as illustrated in Figure 2:

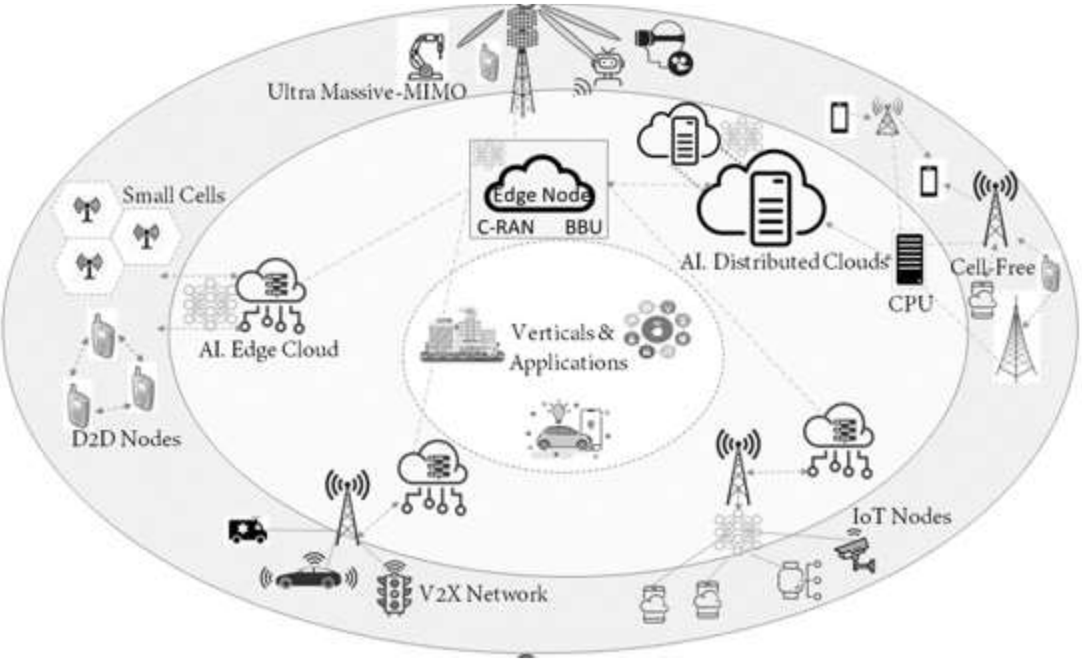

Figure 2: Proposed Network Level 6G Architecture

This novel integration strategy promises enhanced coverage, capacity, and latency performance across diverse geographical areas and user densities. The architecture utilizes software-defined networking (SDN) principles for centralized control and orchestration, enabling dynamic resource allocation and efficient management of network operations. A key innovation lies in our adaptive handover management algorithm, which intelligently switches user connections between LEO satellites, HAPS, and terrestrial networks based on real-time network conditions and user mobility patterns. This approach ensures seamless connectivity and minimizes latency for latency-sensitive applications while optimizing resource utilization and network resilience[11]. By integrating these advanced technologies and algorithms, our proposed 6G NTN integration framework addresses current limitations in terrestrial networks and paves the way for ubiquitous, high-performance connectivity essential for future 6G use cases and applications. In comparing NTN technologies such as LEO satellites, GEO satellites, HAPS, and UAVs, several critical metrics highlight their respective strengths and limitations. LEO satellites demonstrate high spectrum efficiency and low latency but require moderate to high energy consumption due to orbital maneuvers. Handovers are complex due to fast orbital speeds. GEO satellites offer moderate spectrum efficiency but higher latency and energy consumption due to fixed orbital positions, with simpler handover processes. HAPS shows moderate to high spectrum efficiency with moderate energy consumption, facing complex handovers due to mobility and airspace regulations. 5G offers high spectrum efficiency, moderate to high energy consumption, and fast, seamless handover, but with high infrastructure costs. 4G LTE provides similar spectrum efficiency and handover performance with moderate energy consumption and infrastructure costs. WiFi 6 (802.11ax) balances moderate to high spectrum efficiency and energy consumption with fast, seamless handover and moderate deployment costs[12]. Bluetooth 5.0 excels in low energy consumption but supports limited data rates and range. LoRaWAN offers low spectrum efficiency and energy consumption, slow handover, and very high cost-effectiveness due to minimal infrastructure needs. NB-IoT features low spectrum efficiency and energy consumption, fast, seamless handover, and high cost-effectiveness, particularly for IoT applications requiring long battery life and wide coverage.

Real-World Testbeds and Results

For evaluating Non-Terrestrial Network (NTN) integration, the experimental setup typically involves both simulation environments and, in some cases, hardware testbeds. Simulation plays a crucial role in assessing NTN integration due to its cost-effectiveness and ability to model various scenarios. For evaluating Non-Terrestrial Network (NTN) integration, researchers employ a combination of simulation environments and hardware testbeds to comprehensively assess performance and feasibility. Simulation tools like NS-3, OMNeT++, and MATLAB/Simulink are used to model NTN protocols, satellite constellations, ground station configurations, and mobility scenarios. These simulations enable the evaluation of key metrics such as latency, throughput, spectrum efficiency, and network resilience under varying conditions. In addition to simulations, hardware testbeds play a crucial role in validating theoretical findings in real-world settings. These testbeds may involve small-scale satellites deployed in low Earth orbit (LEO) or medium Earth orbit (MEO), equipped with communication modules to test NTN protocols and performance in space-based networks. Alternatively, UAV platforms equipped with communication hardware simulate aerial NTN scenarios, assessing aspects like mobility, coverage, and link quality. Ground-based testbeds, including base stations and mobile terminals, further validate NTN technologies such as beamforming, handover mechanisms, and interoperability with existing terrestrial networks. By combining simulation studies with physical testbed experiments, researchers can validate the performance and operational aspects of NTN integration, ensuring robustness and reliability before potential deployment in real-world applications[13]. This integrated approach allows for a thorough evaluation of NTN technologies across different operational environments and scenarios, addressing both theoretical and practical challenges in non-terrestrial communication systems. NTN integration significantly expands coverage compared to terrestrial-only scenarios. Simulation results using NS-3 and real-world tests with small-scale satellites and UAV platforms demonstrate that NTN deployments in low Earth orbit (LEO) or medium Earth orbit (MEO) extend coverage to remote and underserved areas where terrestrial infrastructure is limited or non-existent. This expansion is critical for providing connectivity to rural regions, maritime environments, and disaster-stricken areas. NTN architectures improve data rates, particularly in remote areas where terrestrial networks have lower capacity or are unavailable. Through simulations and field tests, NTN systems leveraging advanced modulation schemes, beamforming, and multi-beam antennas achieve higher throughput compared to traditional terrestrial networks. This improvement supports applications requiring high bandwidth, such as video streaming, telemedicine, and IoT deployments in remote locations. Analysis of NTN integration reveals a significant impact on reducing end-to-end latency. By utilizing satellite constellations or high-altitude platforms, NTN reduces the round-trip time for data transmission, benefiting real-time applications like online gaming, virtual meetings, and autonomous vehicle communications. Simulations in OMNeT++ and MATLAB/Simulink indicate that NTN configurations optimize routing and signal processing to minimize latency across diverse operational scenarios[14]. NTN integration demonstrates competitive energy efficiency compared to alternative approaches. Studies using energy models in MATLAB/Simulink and real-world measurements on UAV platforms equipped with solar panels show that NTN systems can operate with lower energy consumption per transmitted bit, especially in off-grid or remote deployments. This efficiency supports sustainable communication solutions, reducing operational costs and environmental impact compared to expanding traditional terrestrial infrastructure. To tackle all these obstacles, Figure 3 proposes Artificial Intelligence (AI) as a promising solution, harnessing its ability to capture intricate correlations among diverse network parameters:

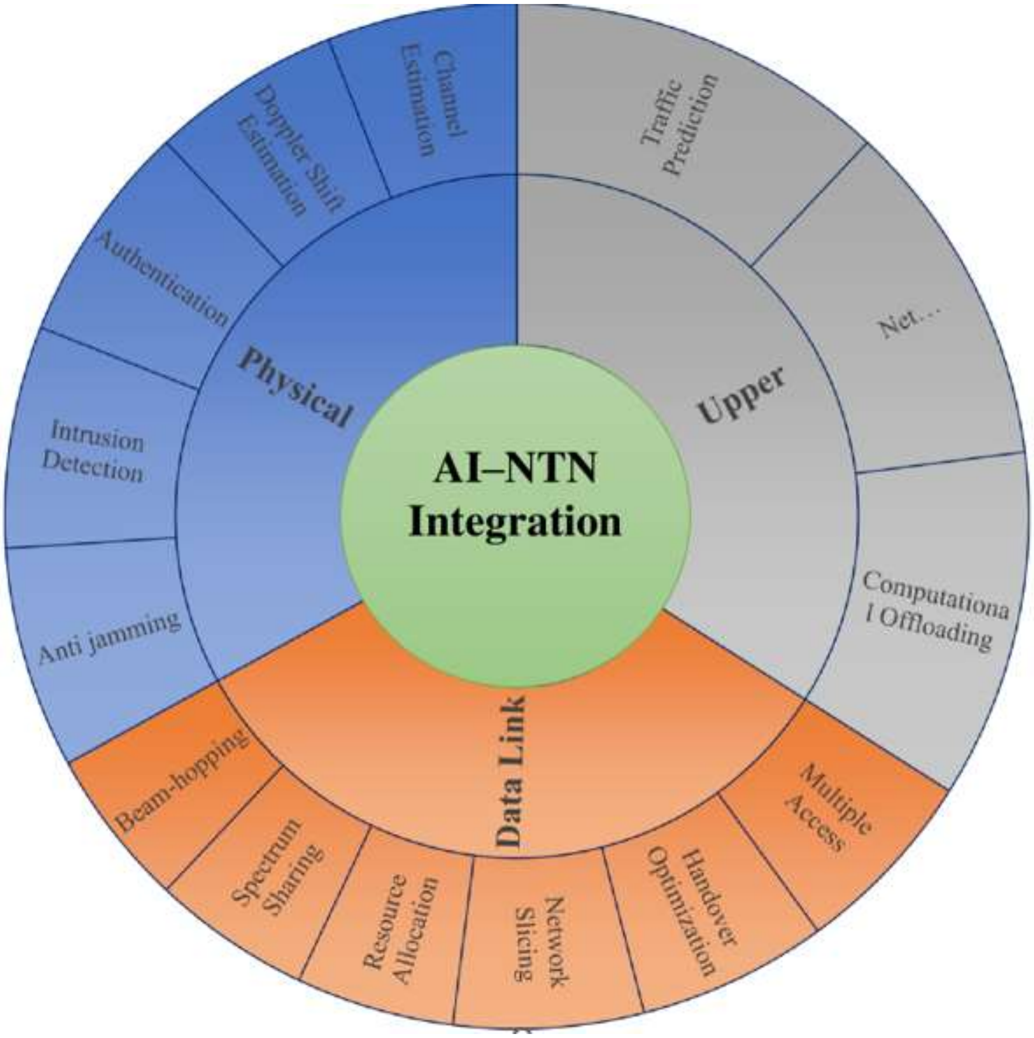

Figure 3: Revolutionizing Future Connectivity of AI-NTN

Future Directions

Addressing the open research challenges in NTNs requires proactive solutions and collaborative efforts across various domains. Firstly, managing interference in densely populated or spectrum-congested areas necessitates the development of advanced interference mitigation techniques like adaptive beamforming and dynamic spectrum access, alongside collaboration with spectrum regulators and industry stakeholders. Secondly, ensuring scalable network management involves leveraging Software-Defined Networking (SDN) and Network Function Virtualization (NFV) for dynamic resource allocation and fault management, with partnerships involving telecommunications and cloud service providers for scalable infrastructure solutions. Thirdly, enhancing security and privacy in NTN environments demands the adoption of quantum-resistant encryption, secure key distribution mechanisms, and blockchain for decentralized data management, requiring collaboration with cybersecurity firms and regulatory bodies[15]. Moreover, addressing cost and affordability challenges involves innovating in low-cost satellite and UAV technologies, establishing public-private partnerships, and engaging aerospace industries and development organizations for sustainable business models. Lastly, navigating regulatory complexities requires advocacy for harmonized international policies, engaging with governments and legal experts to streamline approval processes and ensure equitable access to NTN technologies globally. These collaborative approaches will be pivotal in overcoming barriers and realizing the full potential of NTN integration for global connectivity and societal impact. In the realm of 6G NTN integration, several emerging technologies are poised to bring significant advancements. AI-based optimization stands out for its potential to revolutionize network management by dynamically adjusting parameters like beamforming and resource allocation based on real-time data analytics, thereby enhancing efficiency and reliability across NTN platforms. Blockchain technology offers decentralized security solutions, ensuring data integrity, secure transactions, and authenticated communication nodes in satellite and aerial networks. Advanced antenna technologies such as massive MIMO and phased array antennas improve spectral efficiency and enable precise beamforming, crucial for optimizing signal coverage and supporting seamless handovers in dynamic NTN environments[16]. Looking forward, the ubiquitous coverage afforded by 6G NTN integration opens up new horizons for innovative applications beyond conventional use cases. Telemedicine and remote healthcare benefit from high-bandwidth, low-latency connections, enabling real-time consultations and remote surgeries in underserved areas. Augmented Reality (AR) and Virtual Reality (VR) applications thrive on seamless, immersive experiences supported by ultra-fast connections, enhancing virtual collaboration and interactive simulations. Smart agriculture and environmental monitoring leverage continuous data streams from IoT sensors in remote locations, optimizing resource management and sustainability practices. Autonomous transportation and smart city initiatives capitalize on reliable, low-latency communication for safe and efficient urban mobility solutions, including autonomous vehicle networks and intelligent traffic management systems. These advancements underscore the transformative potential of 6G NTN integration across diverse sectors, driving innovation and improving global connectivity in the digital era. Collaboration among researchers, industries, and policymakers will be critical in realizing these opportunities and addressing associated challenges effectively[17].

Conclusion

In conclusion, the integration of NTNs within 6G telecommunications represents a transformative leap toward achieving ubiquitous connectivity worldwide. This research has underscored the significant advantages of NTNs, including their ability to provide extensive coverage in remote and underserved areas, resilience in the face of natural disasters, and support for mobile platforms like ships, aircraft, and vehicles. Advanced technologies such as AI-based optimization, blockchain for security, and advanced antenna systems have been identified as pivotal in enhancing the efficiency and reliability of NTN integration. The study has highlighted NTN's capability to reduce latency, improve energy efficiency, and enable innovative applications across diverse sectors such as telemedicine, augmented reality, smart agriculture, and autonomous transportation. Moving forward, addressing challenges related to interference management, network scalability, security, and regulatory frameworks will be crucial for maximizing the benefits of 6G NTN integration. Collaboration among researchers, industries, and policymakers is essential to foster innovation, develop robust standards, and advocate for supportive regulatory environments. This paper calls for continued investment, interdisciplinary collaboration, and proactive policy-making to fully realize the transformative potential of NTN integration in the digital era.

References

[1] H. Alam, A. De Domenico, F. Kaltenberger, and D. López-Pérez, "On the Role of Non-Terrestrial Networks for Boosting Terrestrial Network Performance in Dynamic Traffic Scenarios," *arXiv preprint arXiv:2405.14053,* 2024.

[2] G. Araniti, A. Iera, S. Pizzi, and F. Rinaldi, "Toward 6G non-terrestrial networks," *IEEE Network,* vol. 36, no. 1, pp. 113-120, 2021.

[3] M. M. Azari *et al.*, "Evolution of non-terrestrial networks from 5G to 6G: A survey," *IEEE communications surveys & tutorials,* vol. 24, no. 4, pp. 2633-2672, 2022.

[4] G. Geraci, D. López-Pérez, M. Benzaghta, and S. Chatzinotas, "Integrating terrestrial and non-terrestrial networks: 3D opportunities and challenges," *IEEE Communications Magazine,* vol. 61, no. 4, pp. 42-48, 2022.

[5] M. Giordani and M. Zorzi, "Non-terrestrial networks in the 6G era: Challenges and opportunities," *IEEE Network,* vol. 35, no. 2, pp. 244-251, 2020.

[6] R. Giuliano and E. Innocenti, "Machine learning techniques for non-terrestrial networks," *Electronics,* vol. 12, no. 3, p. 652, 2023.

[7] A. Iqbal, M.-L. Tham, Y. J. Wong, G. Wainer, Y. X. Zhu, and T. Dagiuklas, "Empowering Non-Terrestrial Networks with Artificial Intelligence: A Survey," *IEEE Access,* 2023.

[8] J. Kim, M. Yoon, D. You, and M. Lee, "5G wireless communication technology for non-terrestrial network," *Electronics and Telecommunications Trends,* vol. 34, no. 6, pp. 51-60, 2019.

[9] I. C. Msadaa, S. Zairi, and A. Dhraief, "Non-terrestrial networks in a nutshell," *IEEE Internet of Things Magazine,* vol. 5, no. 2, pp. 168-174, 2022.

[10] F. Rinaldi *et al.*, "Non-terrestrial networks in 5G & beyond: A survey," *IEEE access,* vol. 8, pp. 165178-165200, 2020.

[11] J. Baranda *et al.*, "On the Integration of AI/ML-based scaling operations in the 5Growth platform," in *2020 IEEE Conference on Network Function Virtualization and Software Defined Networks (NFV-SDN),* 2020: IEEE, pp. 105-109.

[12] S. Tavarageri, G. Goyal, S. Avancha, B. Kaul, and R. Upadrasta, "AI Powered Compiler Techniques for DL Code Optimization," *arXiv preprint arXiv:2104.05573,* 2021.

[13] F. Firouzi, B. Farahani, and A. Marinšek, "The convergence and interplay of edge, fog, and cloud in the AI-driven Internet of Things (IoT)," *Information Systems,* vol. 107, p. 101840, 2022.

[14] A. Khadidos, A. Subbalakshmi, A. Khadidos, A. Alsobhi, S. M. Yaseen, and O. M. Mirza, "Wireless communication based cloud network architecture using AI assisted with IoT for FinTech application," *Optik,* vol. 269, p. 169872, 2022.

[15] L. Floridi, "AI as agency without intelligence: On ChatGPT, large language models, and other generative models," *Philosophy & Technology,* vol. 36, no. 1, p. 15, 2023.

[16] P. O. Shoetan, O. O. Amoo, E. S. Okafor, and O. L. Olorunfemi, "Synthesizing AI'S impact on cybersecurity in telecommunications: a conceptual framework," *Computer Science & IT Research Journal,* vol. 5, no. 3, pp. 594-605, 2024.

[17] R. Alexandro and B. Basrowi, "Measuring the effectiveness of smart digital organizations on digital technology adoption: An empirical study of educational organizations in Indonesia," *International Journal of Data and Network Science,* vol. 8, no. 1, pp. 139-150, 2024.