UNICO I+D Project

6G-INTEGRATION 02

6G-INTEGRATION-02-E9

Strategies for federation of terrestrial and spatial edge segments version 1

Financiado por la Unión Europea NextGenerationEU
GOBIERNO DE ESPAÑA MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL
SECRETARÍA DE ESTADO DE TELECOMUNICACIONES E INFRAESTRUCTURAS DIGITALES
Plan de Recuperación, Transformación y Resiliencia
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Document properties

Document number	6G-INTEGRATION-02-E19
Document title	Strategies for federation of terrestrial and spatial edge segments version 1
Document responsible	Carmen Guerrero
Document editor	Carmen Guerrero
Editorial team	Carmen Guerrero, Daniel Segovia (UC3M)
Target dissemination level	Public
Status of the document	Final version
Version	1.0
Delivery date	31/07/2024
Actual delivery date	31/07/2024

Production properties

Reviewers	María Molina Matas

Disclaimer

This document has been produced in the context of the 6G-INTEGRATION Project. The research leading to these results has received funding from the Spanish Ministry of Economic Affairs and Digital Transformation and the European Union-NextGenerationEU through the UNICO 5G I+D programme.

Abstract

This deliverable E9 is the preliminary version of the studies on the edge solutions for integration of terrestrial and non terrestrial networks, TN and NTN respectively. This document introduces the state of the art in the alternatives and standardisation for the deployment of edge computing in this kind of integrated ecosystems, with special emphasis in the challenges in future 6G networks. The final version of this document will be the deliverable E10.

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List of Acronyms

GEO	Geostationary Earth Orbit
HAPS	High Altitude Platform System
LEO	Low Earth Orbit
LTE	Long Term Evolution
MEC	Mobile Edge Computing
MEO	Medium Earth Orbit
NTN	Non Terrestrial Networks
RIS	Reconfigurable Intelligent Surfaces
TN	Terrestrial Networks
UAV	Unmaned Aerial Vehicle

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1. Introduction

The rapid growth of computation-intensive applications like augmented reality, autonomous driving, remote healthcare, and smart cities has exposed the limitations of traditional terrestrial networks, particularly in terms of inadequate coverage, limited capacity, and high latency in remote areas. This document explores how integrated terrestrial and non-terrestrial networks (IT-NTNs) can address these challenges and enable efficient computation offloading. There is a initial study of the mobile edge computing (MEC) and its evolution toward multiple-access edge computing, highlighting the critical role computation offloading plays for resource constrained devices. We then discuss the architecture of IT-NTNs, focusing on how terrestrial base stations, unmanned aerial vehicles (UAVs), high-altitude platforms (HAPs) and LEO satellites work together to deliver ubiquitous connectivity.
A final version of this document will include various computation offloading strategies, including edge, cloud, and hybrid offloading, identifying their strengths and weaknesses. Key enabling technologies are also explored as essential components of existing algorithms for resource allocation, task offloading decisions, and mobility management.

2. Background on MEC and NTN

The convergence of mobile edge computing (MEC) and IT-NTNs is reshaping computation and communication, particularly for devices with limited resources and in challenging environments. First we need to understand the main challenges on MEC integration within IT-NTN networks. MEC is revolutionizing modern networking by bringing data storage and computation closer to user equipment. This significantly reduces latency for applications that demand quick response times, such as AR, VR, autonomous driving, and the industrial IoT (IIoT).

By strategically positioning data centers near users, MEC avoids the delays inherent in long-distance data transmission to centralized cloud servers [1][2]. The evolution of MEC towards multiple-access edge computing has further expanded its capabilities. Supporting various access technologies, including Wi-Fi, 5G, and satellite networks, has enhanced MEC's versatility and adaptability [3]. This allows MEC to cater to diverse application needs across different network environments. Multiple-access edge computing also offers greater flexibility in resource allocation and enables dynamic adjustments based on real-time network conditions, thereby enhancing network performance, reliability, and supporting a wider range of applications, from high-resolution streaming to complex data analytics. MEC offers significant advantages for resource-constrained devices (RCDs) through computation offloading. This involves transferring the processing tasks from RCDs, like IoT sensors and wearable electronics, to more powerful edge servers. Computation offloading reduces latency and enhances energy efficiency at the device level. Efficient computation offloading process requires careful consideration of multiple factors like task complexity, latency requirements, energy constraints, available computing resources, and associated costs.

IT-NTNs for computation offloading offer a powerful approach to overcome the limitations

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of purely terrestrial MEC deployments. This integration allows for the seamless convergence of terrestrial networks with NTN, capitalizing on the strengths of both to provide ubiquitous connectivity, enhanced capacity, and reduced latency for computation-intensive applications, especially in remote or challenging environments [4][5].

A typical IT-NTN architecture incorporates a multi-tiered structure comprising terrestrial base stations, UAVs, HAPS, and LEO satellites. Terrestrial base stations act as the foundation, offering high-speed, low latency communication in densely populated areas, while non-terrestrial platforms extend coverage to remote or underserved regions. Specifically, LEO satellites provide global connectivity and enable communication in areas where terrestrial infrastructure is limited or non-existent. HAPS are generally positioned in the stratosphere and offer wide-area coverage by acting as relay stations, thereby enhancing connectivity and offloading traffic from congested terrestrial networks. Similarly, UAVs provide on-demand coverage, proving particularly valuable in temporary or dynamic scenarios like disaster relief operations or large-scale events. This integrated architecture facilitates streamlined data transmission and computation offloading by dynamically selecting the most appropriate link for each communication session.

IT-NTNs offer a versatile and resilient infrastructure that can adapt to changing network conditions, user mobility, and application requirements. Utilizing the distributed nature of these platforms, IT-NTNs can enable efficient offloading of computationally intensive tasks and data processing, improving the overall performance and reliability of the network.

3. Edge computing strategies in NTN networks

Optimizing performance for resource-constrained devices is a crucial aspect of modern networking. Computation offloading offers a powerful solution by shifting computationally demanding tasks from these devices to more capable servers or networks. This section explores different computation offloading strategies within IT-NTNs, highlighting their benefits, limitations, and suitability for various application scenarios.

- <u>Edge Offloading</u>

Edge offloading involves shifting computational tasks from end devices to nearby edge servers strategically placed within the network. These servers might be located at roadside units (RSUs) or at other intermediate nodes close to users. The primary benefit of edge offloading is minimizing latency by reducing the distance data travels for processing, which is especially advantageous for applications demanding real-time processing. Edge offloading also reduces congestion and bandwidth usage on the core network by processing and aggregating data locally. This frees up resources for other critical services. Local data transmission enhances privacy and security by reducing the exposure of sensitive information to broader network vulnerabilities. Despite these advantages, edge offloading has several limitations. Edge servers typically have less computational power and storage capacity than cloud servers, potentially restricting task complexity. The distributed nature of edge infrastructure also presents management and maintenance challenges. Nevertheless, edge offloading remains promising for applications requiring low latency and localized data processing, particularly in scenarios with limited or unreliable cloud connectivity.

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- Cloud-based Offloading

Cloud offloading transfers computational tasks from mobile devices to remote cloud servers via terrestrial or NTNs backhaul [6]. This strategy leverages the substantial processing power and storage capacity of cloud servers, delivering significant performance boosts for mobile applications while conserving the limited resources of mobile devices. Cloud offloading is well-suited for applications requiring complex computations, access to large datasets, or long-term data storage, such as machine learning model training, scientific computing, and big data analytics. Cloud offloading also faces challenges in the form of increased latency arising due to the physical distance between devices and remote servers. Network connectivity issues can affect reliability and thus require careful planning. Security and privacy concerns related to data transmission and storage in the cloud must also be addressed.

- Hybrid Offloading

Hybrid offloading combines the strengths of edge and cloud computing by dynamically allocating computational tasks based on their specific needs [7][8]. This approach offers flexibility by offloading tasks either to edge nodes for low latency or to more powerful cloud servers for ample resources, albeit with higher latency. Decisions are guided by factors such as latency sensitivity, computational intensity, and data privacy concerns. This enables efficient resource use, reduces latency for time-critical tasks, and enhances overall system performance. Hybrid offloading is particularly beneficial for applications with diverse requirements, such as video analytics. Initial processing can occur at the edge for real-time object detection, while more complex analysis and long-term storage can be handled in the cloud. Implementing hybrid offloading requires effective task scheduling algorithms to distribute tasks efficiently between edge and cloud environments. Load balancing is also required to prevent node overload. As with cloud offloading, addressing security and privacy concerns arising from distributing tasks across multiple computing layers is also essential.

- Deployment Models

Edge computing deployment models within IT-NTNs are more diverse and dynamic than traditional terrestrial systems due to the integration of non-terrestrial platforms. While concepts like network edge, regional edge, on-premise edge, and on-device edge still apply, their implementation and characteristics are highly influenced by the attributes of each NTN component. This flexibility allows edge computing deployments to be tailored to specific application needs and environmental constraints. In network edge deployments, edge servers can be located not only at terrestrial base stations but also on UAVs, HAPs, or LEO satellites. This expanded reach of edge computing enables services in remote areas and supports applications like real-time data processing for autonomous vehicles or remote patient monitoring. Regional edge deployments can leverage local data centers interconnected with satellite gateways or terrestrial backhaul links, bringing computation closer to users in regions with limited terrestrial infrastructure. On-premise edge deployments in IT-NTNs might involve setting up edge servers at remote monitoring stations or industrial facilities, using satellite or UAV connectivity for backhaul and data transmission. Similarly, on-device edge computing in this context can utilize the processing capabilities of devices onboard UAVs or other mobile platforms, enabling localized data processing and analysis for applications like precision agriculture or environmental monitoring. These diverse deployment models offer a wide range of offloading options within IT and NTN ar-

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chitectures. The most suitable model depends on the application's specific requirements, the available network infrastructure, and security considerations. For example, delay-sensitive applications may benefit from network edge or on-device computing, while computationally intensive tasks might be better suited for regional edge or cloud offloading. Building upon these deployment models and offloading strategies, the next section explores the enabling technologies and algorithms that facilitate efficient computation offloading in integrated TN and NTN networks.

4. Challenges and future directions

IT-NTNs for computation offloading show immense promise, but several challenges must be addressed to fully realize their benefits. This field also presents exciting research opportunities that can drive innovation and development. This section outlines key challenges and explores promising future research directions. The heterogeneity, dynamism, and complexity of IT-NTNs pose unique challenges for efficient and reliable computation offloading. Tackling these ***key challenges*** is essential to unlocking the full potential of these networks and enabling their widespread adoption across various domains.

IT-NTNs encompass diverse resources, including terrestrial base stations, UAVs, HAPs, and satellites, each with varying capabilities, coverage areas, and energy constraints. ***Efficiently managing these heterogeneous and dynamic resources*** is essential to maximize network performance and meet the QoS requirements of offloaded tasks. This requires intelligent algorithms for dynamic resource allocation, scheduling, and orchestration. For instance, in a scenario where UAVs assist in offloading tasks from ground vehicles to a HAP, an efficient scheme must consider the UAVs' limited battery life, the HAP's processing capacity, and the dynamic channel conditions between all components [5].

User mobility in IT-NTNs, particularly in scenarios involving aerial vehicles, can lead to frequent ***handovers*** between different NTN nodes. This dynamism challenges maintaining seamless connectivity and the smooth transfer of offloaded tasks and data during handover. Effective handover management involves designing efficient protocols and mechanisms to minimize service interruption and data loss. Predictive handover techniques can anticipate events based on user mobility patterns and network topology, allowing for proactive resource reservation at the target node [9]. In scenarios with fast-moving aerial vehicles, the impact of Doppler shift on communication links needs careful consideration and compensation using advanced signal processing techniques.

Offloading computation tasks to external servers raises concerns ***about data security and user privacy***. The extended coverage and distributed nature of IT-NTNs make them susceptible to various security threats, including eavesdropping, data breaches, and malicious attacks. Ensuring secure and private computation offloading requires robust security measures such as data encryption, authentication, and access control. As Hartmann et al. [10] emphasize, sophisticated privacy and data reduction methods are particularly crucial for edge computing in healthcare to protect sensitive patient data. Advanced cryptographic techniques, like homomorphic encryption, can enable computation on encrypted data without decryption, further enhancing data privacy during offloading [11].

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Integrating diverse NTN technologies with terrestrial networks requires ***standardized protocols and interfaces to ensure seamless interoperability***. The lack of standardized frameworks can hinder the development and deployment of IT-NTNs, limiting their scalability and efficiency. Therefore, industry and research communities must collaborate to develop and promote standardized protocols for communication, resource management, and security in IT-NTNs. These standards should address the unique characteristics of different NTN technologies while ensuring compatibility and seamless integration with existing terrestrial networks.

Integrating IT-NTNs and computation offloading opens up exciting opportunities for future research and development. Exploring these avenues can lead to significant advancements, enabling novel applications and pushing the boundaries of communication and computation capabilities. The dynamic nature of IT-NTNs necessitates ***advanced algorithms*** that can adapt to varying channel, user mobility, and task requirements in real-time. Leveraging machine learning techniques, such as reinforcement learning and deep learning, can significantly enhance the efficiency of resource allocation and task offloading decisions [4].

Efficient mobility management in IT-NTNs requires exploring novel architectures and protocols that seamlessly handle frequent handovers between different NTN nodes. Integrating software defined networking (SDN) and network function virtualization (NFV) can provide flexible and dynamic control over network resources, facilitating efficient handover management [12]. Developing ***predictive handover mechanisms based on user mobility patterns*** and network topology can minimize handover latency and maintain service continuity.

5. Conclusion

The preliminary version of this document explore computation offloading alternatives within IT-NTNs, revealing their potential to revolutionize data processing. We examined the rationale behind this integration, highlighting how non-terrestrial elements like UAVs, HAPs, and LEO satellites can overcome the limitations of traditional terrestrial networks. While challenges such as resource management, mobility, security, and standardization remain, ongoing research actively addresses these issues. As our future becomes increasingly data-intensive and resource-constrained devices proliferate, computation offloading in IT-NTNs offer a compelling solution for real-time data processing and analysis.

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References

[1] M. Hartmann, U. S. Hashmi, A. Imran, Edge computing in smart health care sys tems: Review, challenges, and research directions, Trans. Emerg. Telecommun. Technol. 33 (3) (2022) e3710, e3710ett.3710.

[2] A. H. Sodhro, Z. Luo, A. K. Sangaiah, S. W. Baik, Mobile edge computing based QoS optimization in medical healthcare applications, Int. J. Inf. Manag. 45 (2019) 308–318.

[3] A. Filali, A. Abouaomar, S. Cherkaoui, A. Kobbane, M. Guizani, Multi-access edge computing: A survey, IEEE Access 8 (2020) 197017–197046.

[4] N. Waqar, S. A. Hassan, A. Mahmood, K. Dev, D.-T. Do, M. Gidlund, Computation offloading and resource allocation in MEC-enabled integrated aerial-terrestrial ve hicular networks: A reinforcement learning approach, IEEE Trans. Intell. Transp. Syst. 23 (11) (2022) 21478–21491.

[5] G. Sun, L. He, Z. Sun, Q. Wu, S. Liang, J. Li, D. Niyato, V. C. M. Leung, Joint task offloading and resource allocation in aerial-terrestrial UAV networks with edge and fog computing for post-disaster rescue, IEEE Trans. Mob. Comput. 23 (9) (2024) 8582–8600.

[6] S. E. Mahmoodi, R. N. Uma, K. P. Subbalakshmi, Optimal joint scheduling and cloud offloading for mobile applications, IEEE Trans. Cloud Comput. 7 (2) (2019) 301–313

[7] Q. Tang, Z. Fei, B. Li, Z. Han, Computation offloading in LEO satellite networks with hybrid cloud and edge computing, IEEE Internet Things J. 8 (11) (2021) 9164–9176.

[8] X. Zhang, J. Liu, Z. Xiong, Y. Huang, R. Zhang, S. Mao, Z. Han, Cost-effective hy brid computation offloading in satellite-terrestrial integrated networks, IEEE Internet Things J. (2024)

[9] A. A. R. Alsaeedy, E. K. P. Chong, A survey of mobility management in non- ter restrial 5G networks: Power constraints and signaling cost, IEEE Access 12 (2024) 107529–107551

[10] M. Hartmann, U. S. Hashmi, A. Imran, Edge computing in smart health care sys tems: Review, challenges, and research directions, Trans. Emerg. Telecommun. Technol. 33 (3) (2022) e3710, e3710, ett.3710.

[11] A. lakhan, M. A. Mohammed, B. Garcia-Zapirain, J. Nedoma, R. Martinek, P. Tiwari, N. Kumar, Fully homomorphic enabled secure task offloading and scheduling sys tem for transport applications, IEEE Trans. Veh. Technol. 71 (11) (2022) 12140–12153. doi:10.1109/TVT.2022.3190490

[12] R. Kirichek, A. Vladyko, A. Paramonov, A. Koucheryavy, Software-defined architect ture for flying ubiquitous sensor networking, in: Proc. Int. Conf. Adv. Commun. Technol., 2017, pp. 158–162.

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