Journal on Sustainable Wireless Systems (ISSN: 2582-3167)
https://irojournals.com/irosws/

Comprehensive Review of Satellite-Terrestrial Integration in Next-Generation Wireless Networks

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Abstract

Satellite and terrestrial integration is one of the important methods of extending wireless coverage beyond the limitations of existing terrestrial infrastructure, especially for remote and infrastructure-limited areas. In this review paper, satellite and terrestrial integrated networks (STINs) are presented with regard to 5G-Advanced and future 6G communications. First, the basics of satellite and terrestrial communications, which include geostationary orbit (GEO), medium Earth orbit (MEO), and low Earth orbit (LEO) satellites, are explained, and then, integrated space-air-ground architecture is described. Enabling technologies for STINs are introduced, such as software defined networking (SDN), network function virtualization (NFV), artificial intelligence/machine learning (AI/ML), deep reinforcement learning, massive multiple-input-multiple-output (MIMO), intelligent reflecting surface (IRS), edge computing, network slicing, and inter-satellite link.A comparative analysis of satellites and terrestrials is discussed based on parameters such as coverage, latency, throughput, and quality of service. Moreover, previous research has been reviewed to identify areas where research is still lacking to develop satellite–terrestrial integrated systems.

Keywords: Satellite-Terrestrial Integrated Networks (STINs), Non-Terrestrial Networks, LEO Satellites, Spectrum Sharing, Artificial Intelligence, Resource Allocation.

DOI: https://doi.org/10.36548/jsws.2026.4.004
Received: 21.09.2026, received in revised form: 19.10.2026, accepted: 04.11.2026, published: 20.11.2026
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1. Introduction

With the advent of wireless communications, there has been a great need for networks that offer high data transmission speeds, low latency, reliability, and wide coverage. While 5G and 5G-Advanced can cater to a variety of communication needs, terrestrial-only networks cannot guarantee coverage in places where there is no infrastructure. This has led to the emergence of satellite and terrestrial integration as a solution for next-generation wireless communications [3]. While satellite systems augment terrestrial systems through wide area connectivity, terrestrial systems are able to provide high bandwidth in areas of dense population. Integration of satellites together with airborne systems, such as high-altitude platform systems (HAPS) is another way that can help to enhance coverage and flexibility of the network [14]. But seamless integration leads to problems such as spectrum sharing, interference control, resource allocation, mobility, and handover [2].

Advanced technologies, including artificial intelligence (AI), machine learning (ML), deep reinforcement learning (DRL), and intelligent reflecting surfaces (IRS), can help ensure effective network management and resource utilization. AI-based systems have been considered for the optimization of multibeam satellite communication [12]. Similarly, IRS provides the chance to enhance wireless transmission and interference control [16]. STINs may be useful in applications like rural broadband connectivity, IoT, maritime and aeronautical communications, disaster management, vehicular connectivity, and integrated access and backhaul. Satellite computing and content delivery provide the scope to go beyond traditional ground-based network services [7]. But the successful implementation of these technologies will depend on the enhancement of performance, QoS, energy efficiency, reliability, and security.

This review aims to study the architecture, enabling technologies, and technical issues related to the integration of satellite and terrestrial systems in 5G-Advanced and 6G networks. The objectives of this review include: network basics and integrated architecture; enabling technologies; spectrum sharing, interference handling, and resource management; mobility management, routing, and handover; performance and applications; and security issues and research areas.

2. Fundamentals of Satellite and Terrestrial Communication Networks

Satellite and terrestrial communications networks can be regarded as complementary segments in next generation wireless networks. The satellite network delivers connectivity using space based communication, whereas the terrestrial network offers its services using base stations, access points, and network nodes. A satellite network includes satellites, gateway stations, user stations, and network control elements. Satellites receive, process, or relay signals and transmit them back to destination stations or gateways. Geographical diversity in the coverage range of these satellites makes them ideal for providing connectivity in remote areas where there is no physical terrestrial infrastructure or where setting up such an infrastructure is not economically viable [3].

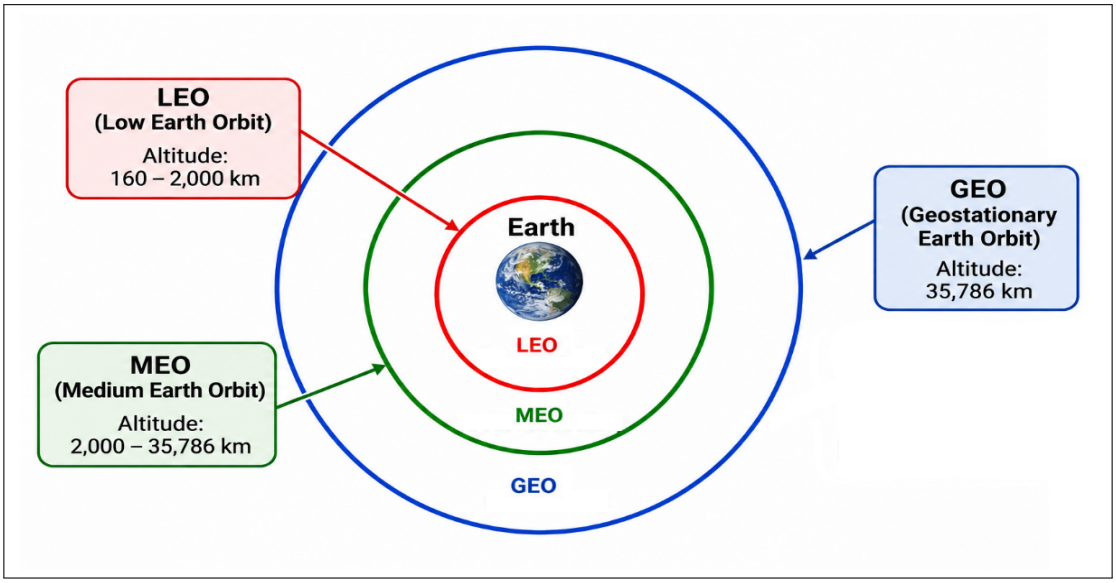

Figure 1. Orbits of different satellites

Satellite systems are classified into three principal orbital categories based on their distance Earth: Geosynchronous Earth Orbit (GEO), Medium Earth Orbit (MEO), and Low Earth Orbit (LEO). GEO satellites operate in orbits ~35,786 km Earth's equator and have large coverage areas with a long propagation time delay. MEO satellites are located between GEO and LEO and represent a trade-off between the two. LEO satellites normally orbit about 160 to 2,000 km above Earth's surface, resulting in a short propagation time delay [3], [14], [18].

Terrestrial wireless communication networks employ dispersed network infrastructures that deliver connectivity using LTE and 5G New Radio. High-speed communication and reduced

propagation delays are made possible by sophisticated radio access technology, efficient spectrum utilization, and MIMO transmission. However, terrestrial coverage is limited by the presence of infrastructure, making connectivity difficult to achieve in sparsely populated areas and other challenging environments [14].

Satellite and terrestrial networks have complementary features: terrestrial systems offer high-capacity connectivity at local levels, while satellite systems have the capability to cover a large geographical area. Nevertheless, some issues associated with the operation of satellite systems Include propagation delay, the Doppler effect, narrow spectrum, interference, and changing topology. The constraints related to terrestrial networks include infrastructure cost and coverage limitations [1], [3].

Successful integration relies on harmonized spectrum usage, interference management, and resource allocation. Spectrum sharing between terrestrial and non-terrestrial communication networks was discussed by Lee et al. [2], whereas interference management in integrated LEO satellite and terrestrial communications was studied by Heydarishahreza et al. [4]. In addition, joint user association and beamforming among satellite, HAPS, and ground communication networks indicate the significance of resource coordination among different communication networks [6].

3. Satellite–Terrestrial Integrated Network Architecture

The STINs architecture combines satellite communication systems with terrestrial cellular communications to deliver continuous connectivity that extends beyond normal reach. In the STINs architecture, user equipment has the option of using satellite communication links, terrestrial base stations, or both, for delivering the required communication services based on network availability and the required services. The addition of non-terrestrial networks (NTNs) increases the coverage of traditional cellular networks by integrating the use of satellite and aerial communication networks. The networks can be used as an access network, backhaul link, or additional connectivity network [3]. Satellite-based integrated access and backhaul can further extend terrestrial network services to areas where conventional infrastructure is limited [10].

Integrated architecture can be classified into three major categories: space, aerial, and terrestrial. The space segment includes satellites at GEO (geostationary Earth orbit), MEO

(medium Earth orbit), and LEO (low Earth orbit) to ensure wide area communications and satellite connectivity. Linking between satellites can enable communication and information exchange between satellites. The aerial segment includes high altitude platform stations (HAPS) and unmanned aerial vehicles (UAVs). The terrestrial segment is comprised of cellular base stations, gateway stations, edge servers, core network functions, and user equipment. Proper coordination among segments allows flexible resource access and utilization. For instance, satellites can help to ensure connectivity in remote areas, terrestrial elements can ensure high-speed services in populated areas, and HAPS can act as an intermediate communication platform [6].

The integration of space, aerial, and terrestrial components forms a space–air–ground integrated network. This architecture makes the deployment of resources more flexible through coordination among different layers in the network. Liu et al. [6] carried out research on joint user association and beamforming in integrated satellite-HAPS-ground networks, showing the significance of coordinating transmission and user selection. Similarly, Sharif et al. [15] studied resource management issues for space-aerial-ground-sea integrated systems. The above systems are suitable for applications that need geographic coverage, including sea communication and remote areas.

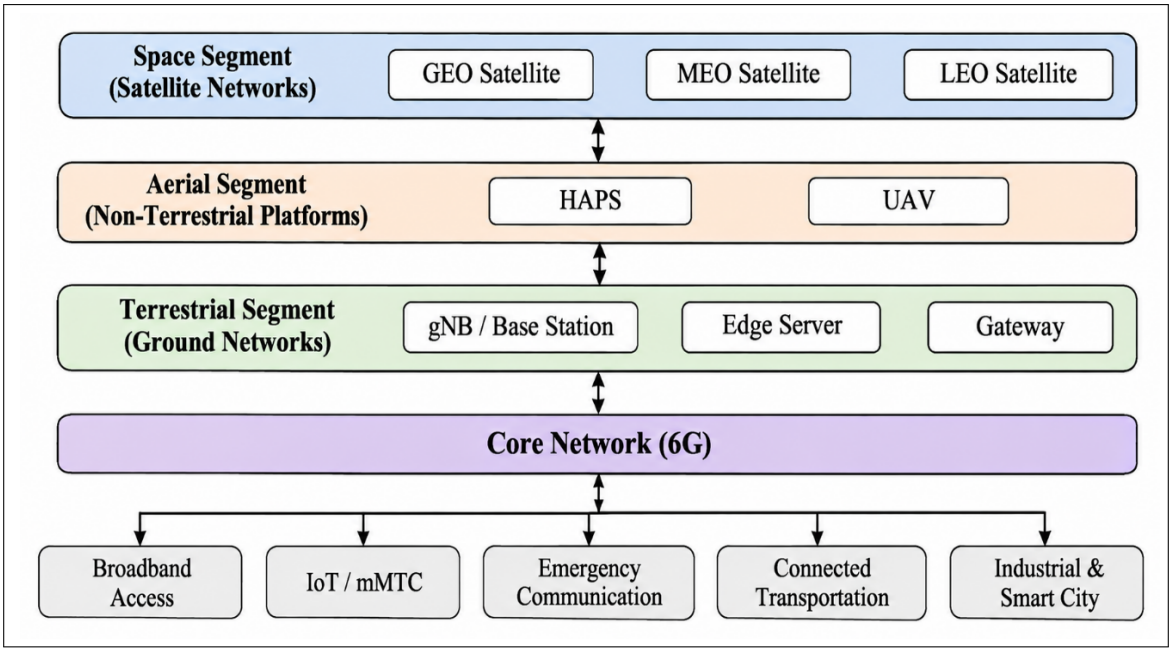

Figure 2. Conceptual architecture of STINs

Figure 2 shows the combination of satellite, aerial, using the same network coordination

and infrastructure. Integrating satellite communications into 5G and post-5G networks requires coordination among radio access networks, core networks, and satellite communications. Satellite communication systems can either establish direct connections with users or serve as backhaul connections to terrestrial base stations. This strategy improves network coverage without diminishing the terrestrial system's role in offering high capacity and localized services. As we develop toward the 6G era, future network designs are expected to offer intelligent and flexible network management systems that utilize AI-based resource allocation, edge computing, network virtualization, and beamforming technologies. Kerboeuf et al. [5] analyzed the end-to-end 6G architecture design, while Mahboob and Liu [19] provided a review of AI-enabled NTN satellite networks.

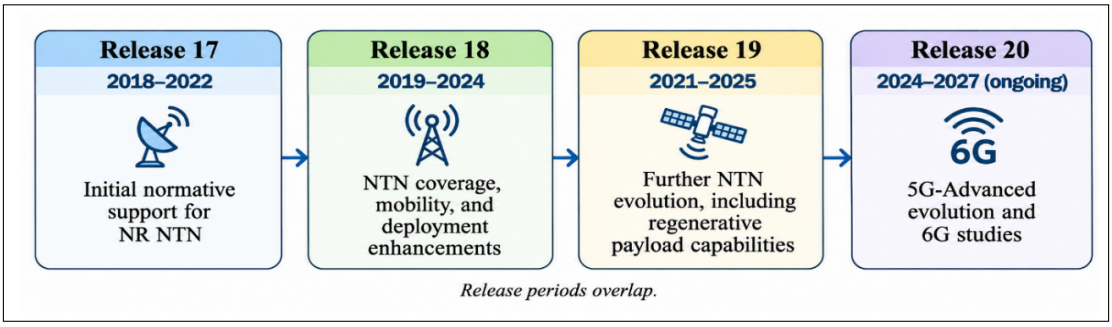

Figure 3. Evolution of 3GPP NTN standardization and release timeline

NTN functionalities have been incrementally added by 3GPP (Third Generation Partnership Project) through their respective releases to facilitate the integration of satellite communication with the terrestrial mobile communications network. The following figure shows the evolution process of the NTN functionality along with the key NTN standardization steps [8]. The first standard for 5G NR NTN was introduced in Release 17, whereas other improvements to NTN functionalities have been added in other releases. It should be noted that development is ongoingwith overlapping release times.

4. Enabling Technologies for Satellite–Terrestrial Integration

The integration of space and terrestrial networks depends on enabling technologies that facilitate network management, resource allocation, transmission, and connection. The most important technologies for this integration are listed in Figure 4.

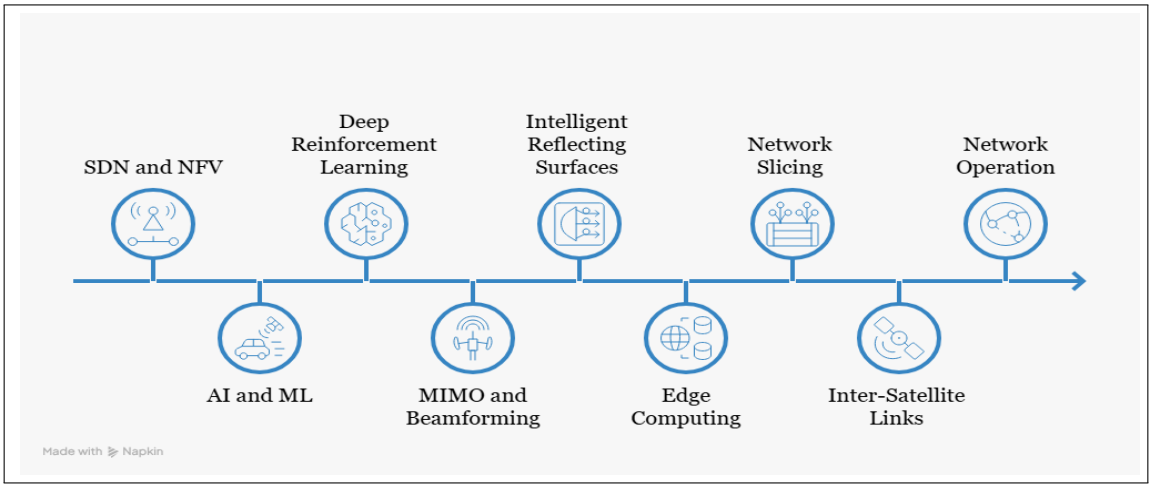

Figure 4. Enabling technologies for integrated networks

Software-Defined Networking (SDN) is the separation of the control plane from the data plane, allowing for programmable control of network resources through various satellites and ground systems. Network function virtualization (NFV) provides the ability for network functions to be implemented in software form. SDN and NFV enable the implementation of the end-to-end architecture requirements as described by Kerboeuf et al. [5].

AI and ML techniques can help enhance performance through analysis of traffic patterns, channel conditions, satellite visibility, and resource requirements. Applications of these technologies can be in the form of predictive resource management, satellite and beam selection, interference management, and mobility enhancement. The application of AI technology in non-terrestrial satellite-based networks is discussed by Mahboob and Liu [19]. The use of ML in real-time optimization of multi-beam for integrated satellite-terrestrial networks has been studied by Duong et al. [12]. Yin et al. [20] focused on DRL for joint scheduling and resource allocation in satellite systems, while Sun et al. [9] explored multi-objective DRL for reliable aerial cooperative communications. In comparison with traditional machine learning, which mainly facilitates prediction and classification, deep learning can better understand complicated network models. However, when applied to satellite-terrestrial networks, DRL faces some difficulties, such as insufficient onboard computing capabilities, heavy training load, delayed feedback, and a constantly changing network environment.

Massive multiple-input multiple-output (MIMO) and beamforming enhance spectral

efficiency and robustness through spatial multiplexing.. With integrated networks, MMIMO and beamforming can be used in satellite multibeam systems, HAPS, and terrestrial base stations. Joint user association and beamforming have been analyzed in [6], whereas ML-assisted multibeam optimization has been considered in [12]. Another promising technology for controlling signal propagation and mitigating interference is IRSs. Two-timescale beamforming optimization with IRS assistance was analyzed in [16], and DRL-assisted IRS-based cooperative jamming has been considered in [17]. Practical deployment in satellite-terrestrial networks needs more research on channel conditions, implementation constraints, and control overhead.

Edge computing enables data processing closer to users through resources deployed at terrestrial base stations, gateways, or suitable satellite and aerial platforms. Energy efficient satellite-terrestrial computing was studied by Wang et al. [7], where the authors emphasize the necessity of cooperation of communication and computing resources. Network slicing may be useful for providing various services with different performance requirements using logically separate resources in the network [5]. Moreover, inter-satellite links, especially optical ones, may allow direct communication among satellites and better backbone connections, but problems of pointing, acquisition, tracking, and availability change should be solved [3], [14].

Table 1. Enabling technologies and their roles in integrated networks

Technology	**Core function**	**Role in integrated networks**	**Ref**
SDN	Centralized and programmable network control	Coordinates routing, traffic management, and resource control across satellite, aerial, and terrestrial segments	[5]
NFV	Implements network functions as software-based services	Enables flexible deployment and management of network functions across heterogeneous infrastructure	[5]

AI/ML	Data-driven analysis and network optimization	Predicts traffic demand, analyzes channel conditions, and supports intelligent resource allocation	[12], [19]
DRL	Learning-based adaptive decision-making	Supports dynamic satellite scheduling, resource allocation, and coordination under changing network conditions	[9], [20]
Massive MIMO	Spatial multiplexing and directional signal transmission	Enables targeted beam coverage and coordinated transmission across satellite and terrestrial links	[6], [12]
IRS	Programmable control of wireless signal reflection	Potentially enhances propagation conditions and supports coverage improvement and interference control	[16], [17]
Edge computing	Distributed processing closer to network users	Supports local data processing at terrestrial base stations, gateways, and suitable network platforms	[7]
Optical inter-satellite links	High-capacity satellite-to-satellite communication	Establishes communication paths between satellites and supports connectivity with terrestrial gateways	[3], [14]

5. Spectrum Management and Resource Allocation

Spectrum sharing plays a vital role in the efficient use of frequency resources in STINs. Nevertheless, overlapping satellite and terrestrial coverage can lead to co-channel and adjacent-channel interference problems. Lee et al. [2] discussed the possibility and potential of spectrum sharing among terrestrial and non-terrestrial networks, emphasizing the importance of

coordinating spectrum usage. Interference is affected by transmission power, antenna features, frequencies, beam angles, and distance. Heydarishahreza et al. [4] studied spectrum sharing and interference management in 6G LEO satellite-terrestrial communication systems, whereas Ati et al. [11] studied interference management in the simultaneous operation of satellite and cloud-enabled terrestrial networks in the mmWave spectrum range. Some of the main interference management techniques are coordinated frequency assignment, adaptive power control, beamforming, spatial separation, and dynamic spectrum utilization [1], [4], [11].

Dynamic spectrum access allows for the dynamic allocation of frequencies depending on network traffic and interferences. Resource allocation can be further optimized with AI-assisted spectrum management, which would allow taking into consideration factors such as satellite visibility, user distribution, and network traffic [2], [4], [19]. Resource allocation includes allocating frequencies, power level, time slots, and spatial beams for users in the network. In the case of integrated networks, resource allocation is done taking into consideration satellite scheduling, terrestrial base station coordination, and user association [20].

Joint optimization schemes are highly critical to STINs due to the dependencies that exist between the processes of resource allocation, user association, beamforming, transmission power, and satellite scheduling. Some of the works on JO include Liu et al. [6] who considered user association and beamforming in hybrid satellite-HAPS-ground systems. Other work has been done by Yin et al. [20] where they looked into satellite scheduling and resource allocation via deep reinforcement learning. Optimization techniques in mathematics offer solutions with structure but can be computationally complex when multiple coupled parameters are considered. On the other hand, the DRL-based technique offers dynamic adaptation but suffers from training complexity, computational demands, and issues related to convergence.

Energy efficiency is of great importance since satellite payloads, air platforms, and ground infrastructures operate under diverse conditions regarding energy consumption. Wang et al. [7] studied the energy efficiency of satellite-terrestrial computing for 6G networks. Joint optimization of transmission power, computational workloads, and resource allocation will enable sustainable operation of the network. Satellite-enabled edge computing helps allocate computing operations among terrestrial edge nodes, gateways, and satellite nodes. Wang et al. [7] have also studied energy-efficient satellite-terrestrial computing and edge content broadcasting

in a hybrid terrestrial and non-terrestrial network.

Table 2. Spectrum sharing and interference management techniques

Technique	**Operating principle**	**Advantages**	**Limitations**	**References**
Static allocation	Predetermined frequency assignment	Simple implementation	Limited adaptability	[2], [4]
Dynamic sharing	Adaptive spectrum utilization	Flexible allocation	Requires coordination	[2], [4]
Power control	Transmission power adjustment	Interference reduction	May reduce coverage	[1], [11]
Beamforming	Spatially directed transmission	Spatial interference control	Requires channel information	[6], [12]
Interference cancellation	Suppression of unwanted signals	Improved signal quality	Computational complexity	[1],[4], [11]
AI-assisted allocation	Learning-based resource decisions	Adaptation to changing conditions	Training complexity	[12], [19], [20]

6. Mobility Management and Handover Mechanisms

The main aim of mobility management is to ensure connectivity as users roam from one coverage area to another. Mobility management in satellite–terrestrial networking is made even more complex due to the mobility of the satellite, its beam coverage areas, and the heterogeneous nature of access technologies [14], [18].

Figure 5 provides a conceptual handover process in STINs by presenting how a connected user is assessed for terrestrial coverage and, if required, handed over to an appropriate satellite or beam. This process includes assessing available satellite connections, assessing visibility and

link qualities, selecting the proper satellite or beam, performing handover, and ensuring session continuity. Satellite-to-terrestrial handover refers to a case where a user moves from satellite connection to an available terrestrial network, whereas terrestrial-to-satellite handover is used when no adequate terrestrial coverage is available.

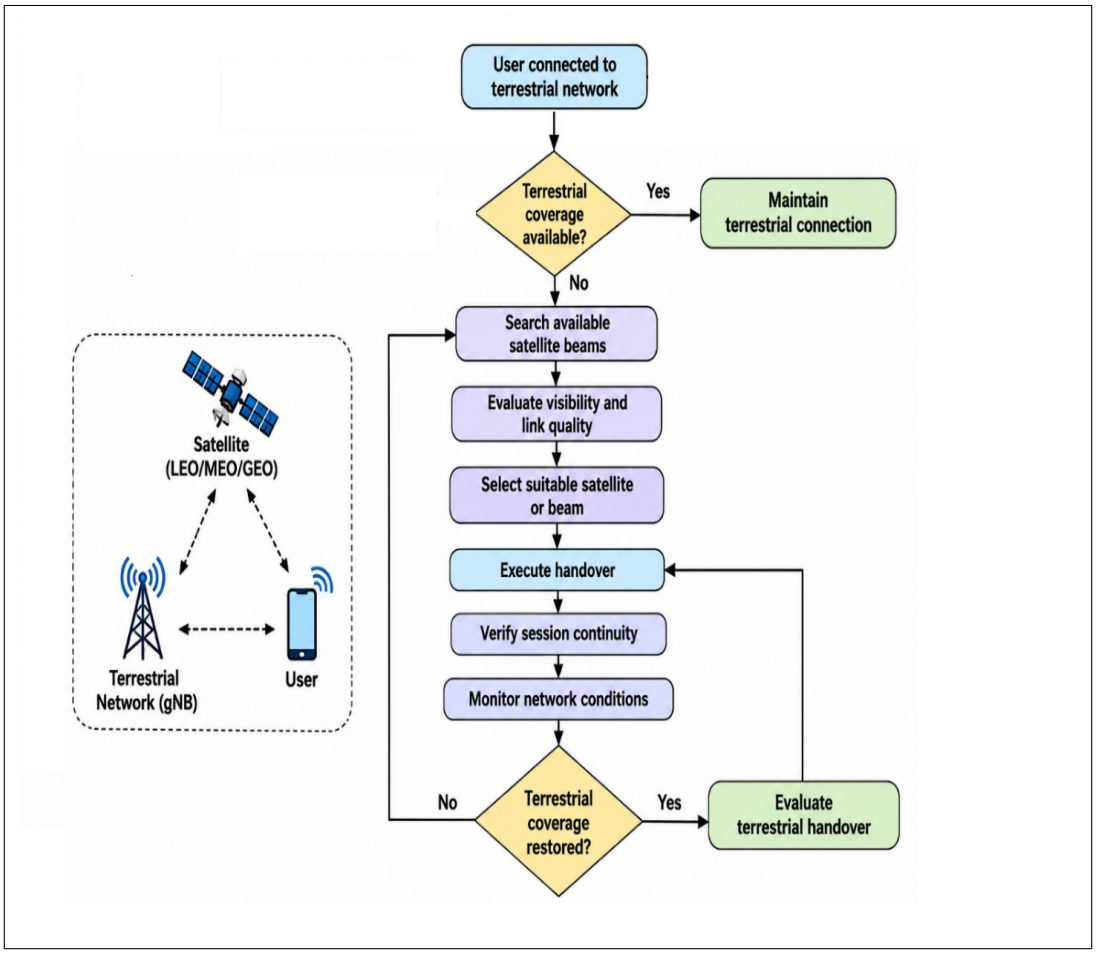

Figure 5. Conceptual handover procedure in STINs

Transitions between neighboring satellite beams or different satellites are needed for LEO systems to maintain connectivity. Eydian et al. [18] suggested a handover approach founded on the use of bipartite graphs and hysteresis margins. Association using graph theory can aid satellite selection, and the use of hysteresis is likely to help minimize unwanted handovers due to transient signal variations. Handover without interruption requires the existence of an ongoing session between communication networks. Aktas et al. [13] elaborated on the issues with regard to routing and the technologies that can be used to enable the deployment of satellites into 6G networks.

Mobility management for smooth handover in STINs involves mobility prediction, link quality estimation, ping pong phenomenon control, and service continuity. Mobility prediction is used to forecast future satellite visibility and link degradations prior to losing connection with the current serving link. Hysteresis and time-to-trigger parameters could avoid excessive handovers due to temporary changes in signals. Also, the target network must be selected depending on its signal quality, resource availability, and QoS requirements [13], [18], [19].

Table 3. Comparison of mobility and handover mechanisms

Mechanism	**Operating principle**	**Major challenges**	**Ref**
Satellite-to-satellite	Transfers an active connection from a serving satellite to another satellite when the serving link becomes unavailable or unsuitable.	Frequent satellite movement, changing link conditions, and coordination among satellites.	[14], [18]
Inter-beam	Transfers a user connection between adjacent beams of the same satellite or across satellite coverage regions to maintain an adequate communication link.	Beam overlap, fluctuating signal quality, and unnecessary handovers.	[12], [18]
Satellite-to-terrestrial	Transfers user connectivity from a satellite link to an available terrestrial base station when terrestrial coverage provides a suitable connection.	Coordination between satellite and terrestrial networks, session continuity, and access availability.	[13], [14]
Terrestrial-to-satellite	Transfers connectivity from a terrestrial network to a satellite link when terrestrial coverage becomes unavailable or insufficient.	Satellite link establishment, propagation delay, resource availability, and service interruption during transition.	[13], [14]

Predictive handover	Estimates future connectivity conditions and initiates handover preparation before the serving link deteriorates.	Prediction accuracy, changing network conditions, and the availability of reliable prediction information.	[18], [19]
AI-assisted mobility	Uses learning-based algorithms to support adaptive satellite selection, user association, and handover decisions under dynamic network conditions.	Computational complexity, training-data requirements, delayed feedback, and limited onboard processing resources.	[9], [19], [20]

7. Performance Analysis and Quality of Service

Satellite–terrestrial integration utilizes both the global coverage ability of satellite systems and the local capacity of the terrestrial system. In doing so, connectivity may be expanded to distant locations while enhancing network availability [1], [3], [14]. Latency will vary according to distance, processing, scheduling, gateway routing, and congestion in the network. Geostationary orbit systems typically incur higher propagation delays than Low Earth Orbit satellites, while Low Earth Orbit satellite networks have more Doppler effects and mobility issues. Throughput depends on bandwidth, SINR, antenna gain, interference, and resource allocation [1], [6], [12].

Factors affecting reliability include satellite visibility, link quality, interference, and the availability of gateways and terrestrial networks. Combining of the architecture may increase reliability by providing other ways of communication. Collaboration in aerial communication may provide an added advantage to ensure reliable connectivity for terrestrial mobile users [9]. Efficiency in energy use becomes vital due to different levels of power requirements in satellites and terrestrial systems [7], [20].

QoS measures such metrics as latency, bandwidth, packet loss rate, and reliability, while

QoE is the perceived level of quality. Applications have different requirements for performance metrics. Interactive applications need to provide low-latency connections, while content delivery systems should provide high bandwidth [8], [10]. The integration of the network takes into consideration the trade-off between coverage, throughput, energy, and latency. An increase in the power of transmission improves coverage but increases energy consumption and interference. Handover increases frequently for good link qualities. [1], [6], [9], [20]. Table 4 compares the complementary features of satellite and terrestrial networks and the advantages of their cooperation.

Table 4. Qualitative comparison of satellite, terrestrial, and satellite–terrestrial integrated networks

Performance parameter	**Satellite networks**	**Terrestrial networks**	**Integrated networks**
Coverage	Wide-area and remote-area coverage	Limited by terrestrial infrastructure	Extended coverage through complementary networks
Latency	Generally higher, particularly in GEO systems	Generally low	Depends on satellite type, routing, and access selection
Throughput	Depends on satellite capacity and available spectrum	Generally high in dense coverage areas	Improved resource utilization through coordinated access
Reliability	Affected by weather, link availability, and satellite visibility	Depends on infrastructure and coverage	Improved service availability through alternative links
QoS support	Constrained by propagation delay and resource availability	Supports diverse QoS requirements	Requires coordinated resource allocation and mobility management

8. Comparative Discussion and Research Gaps

Table 5. Comparative analysis of existing studies, research gaps, and potential future directions

Research Area	**Ref**	**Main contributions and research focus**	**Identified limitations and research gaps**	**Potential future research directions**
Satellie terrestrial network architecture and integration	[3], [5], [14], [15]	Review satellite communication technologies, NTN evolution, 6G system design, and integrated space–aerial–ground -sea architectures. Establish the architectural foundations for heterogeneous network connectivity.	Differences in network architectures, protocols, coverage characteristics, and operational requirements complicate seamless integration. Existing architectural studies do not fully resolve cross-layer coordination and interoperability.	Develop flexible and scalable architectures with common interfaces, coordinated control mechanisms, and seamless integration of satellite, HAPS, aerial, and terrestrial networks.
Spectrum sharing and interference management	[1], [2], [4], [11]	Investigate spectrum-sharing feasibility, coexistence, interference analysis, and mitigation techniques in satellite–terrestrial systems, including mmWave environments.	Dynamic spectrum conditions, overlapping coverage, beam interactions, and different transmission characteristics make interference coordination challenging. Joint treatment of interference and security threats remains limited.	Develop adaptive spectrum allocation, coordinated beamforming, intelligent power control, and joint interference detection and mitigation mechanisms.

User association and radio resource allocation	[6], [20]	Investigate joint user association and beamforming in satellite–HAPS–ground networks and reinforcement-learning-based satellite scheduling and resource allocation.	User association, scheduling, beam management, and resource allocation are often optimized under specific assumptions or separately from mobility and service requirements.	Develop joint optimization frameworks that consider user association, spectrum, power, beamforming, scheduling, and mobility across heterogeneous network layers.
Energy-efficient resource and computing management	[7]	Examine energy-efficient satellite–terrestrial computing and edge content broadcasting through integrated terrestrial and non-terrestrial networks.	Different power budgets, computing capabilities, and communication delays across platforms complicate network-wide energy optimization.	Investigate energy-aware workload distribution, adaptive transmission, satellite scheduling, and coordinated edge computing across satellite and terrestrial platforms.
Mobility management and handover	[13], [14]	Study NTN integration and routing challenges, as well as LEO handover strategies based on bipartite graphs and hysteresis margins.	Rapid satellite movement, changing beam coverage, variable link quality, and frequent handovers can cause service interruption. Handover decisions are not always jointly optimized within spectrum and resource allocation.	Develop predictive and AI-assisted handover strategies that jointly consider link quality, user mobility, traffic demand, beam availability, and service continuity.

AI-assisted network optimization	[9], [12], [19], [20]	Explore aerial collaborative communication, machine-learning-based multi-team optimization, AI-enabled NTN management, and deep reinforcement learning for scheduling and resource allocation.	AI models may require significant computational resources, training data, and feedback. Delayed observations, limited onboard processing, and changing network conditions affect practical deployment.	Develop lightweight, distributed, explainable, and adaptive AI models, including federated learning and multi-agent reinforcement learning for heterogeneous network coordination.
Aerial and multi-layer collaborative communication	[9], [15]	Investigate aerial collaborative communication and integrated space–aerial–ground–sea network architectures to improve connectivity and reliability.	Coordination among platforms with different mobility, coverage, and energy characteristics remains challenging.	Investigate hierarchical coordination, dynamic platform selection, and joint resource optimization across satellite, aerial, and terrestrial nodes.
Intelligent reflecting surfaces and physical-layer security	[16], [17]	Study two-timescale beamforming optimization for IRS-assisted wireless networks and deep reinforcement learning-based IRS cooperative jamming.	Practical deployment in satellite– terrestrial environments requires reliable channel estimation, control signaling, hardware feasibility, and energy-efficient operation.	Explore IRS-assisted satellite and aerial links for coverage enhancement, interference control, and physical-layer security under realistic channel conditions.

Routing and service continuity	[10], [13]	Examine satellite-based integrated access and backhaul and routing challenges associated with 6G satellite network integration.	Dynamic topology, propagation delay, gateway availability, and heterogeneous routing protocols complicate end-to-end service continuity.	Develop delay-aware, topology-adaptive routing and coordinated access and backhaul mechanisms with end-to-end QoS support.
Performance evaluation and QoS	[1], [3], [6], [9]	Examine network performance, optimization, beamforming, and reliable collaborative communication in heterogeneous environments.	Performance indicators such as coverage, latency, throughput, reliability, energy efficiency, and handover interruption are interdependent and may be evaluated under different assumptions.	Establish common evaluation frameworks and realistic scenarios that assess multiple QoS and energy metrics jointly.
Security, privacy, and network resilience	[4], [11], [17], [19]	Address interference-related challenges, IRS-assisted cooperative jamming, and AI-enabled NTN technologies relevant to secure and resilient network operation.	Authentication, spoofing, jamming, privacy, and AI-specific threats require coordinated protection across multiple network layers.	Develop integrated security frameworks incorporating lightweight authentication, secure handover, intrusion detection, privacy-preserving learning, and resilient control mechanisms.

Experimental validation and standardization	[5], [13], [14], [15]	Discuss 6G system design, NTN evolution, network integration, and enabling technologies for future heterogeneous networks.	Analytical and simulation-based evaluations may not fully represent real-world propagation, hardware limitations, mobility, interoperability, and operational constraints.	Develop integrated experimental testbeds, field trials, realistic channel models, interoperable interfaces, and coordinated standardization approaches.

The reviewed literature shows considerable advances in the integration of satellite-terrestrial networks in such aspects as spectrum sharing, interference management, resource allocation, mobility, intelligent optimization, and heterogeneous networks. However, past research usually deals with particular technical issues or optimization problems but not the whole integration process itself. Table 5 summarizes the comparison of representative studies in terms of their research contributions, weaknesses, and possible future research directions.

From the comparative study provided in Table 10, it can be observed that research into satellite–terrestrial integration has made considerable progress in a number of vital dimensions such as network architecture, spectrum sharing, interference coordination, resource management, mobility support, AI-enabled optimization, and energy-efficient computing. Architectural research [3], [5], [14], [15] lays the groundwork for heterogeneous networking while spectrum-based research [1], [2], [4], [11] underlines the significance of efficient coexistence and interference coordination. Similarly, research involving user collaboration, beamforming, scheduling, and computing [6], [7], [20] indicates how coordinated resource management can increase the efficiency of networks and their energy use. Mobility and routing research [10], [13], [18] additionally highlights the importance of handover and end-to-end service continuity in the dynamic conditions of satellites. Recent AI-oriented investigations [9], [12], [19], [20] offer encouraging solutions to adaptive network management, whereas IRS-based research [16], [17] suggests possibilities for improved beamforming and physical layer security.

Despite these advances, several important research gaps remain. In particular, while

most current techniques have been designed for specific optimization problems, practical network integration calls for consideration of spectrum assignment, interference management, user association, mobility, routing, computation, and power utilization at once. Practical implementation of AI methods is also complicated by their computational complexity, feedback delay, unreliability, and resource limitation. In addition to that, security techniques must cater to both traditional cyber-attacks and physical-layer attacks within heterogeneous network segments. As such, future research efforts must focus on cross-layer optimization, distributed and lightweight AI algorithms, mobility prediction and management, security and interference mitigation, energy-efficient network operations, and testbed experiments with practical systems. These issues must be addressed in order to facilitate the development of interoperable and sustainable satellite-terrestrial networks for 6G and beyond.

9. Conclusion

Satellite-terrestrial integration provides an architectural solution that can be adopted to extend wireless services over regions where terrestrial coverage is scarce, while maintaining the capacity benefits offered by terrestrial systems. The literature review indicates advancements made in terms of space-air-ground architecture integration, spectrum coexistence, beamforming, intelligent resource allocation, and mobility support. Nevertheless, coordinating these features over platforms with varying propagation, coverage, mobility, and power properties is challenging. The comparative analysis also indicates that most current studies focus on optimization problems in isolation; joint management of spectrum, interference, user association, routing, computing, and handover remains an open problem. AI approaches offer opportunities for adaptive control; however, they need to consider factors such as training issues, computational burden, delays, and resource constraints. Additional research should also be conducted on integrated security, realistic channel models, mobility models, interoperability, and experimental testing. Future work should focus on scalable cross-layer optimization, lightweight distributed intelligence, predictive mobility management, energy awareness, and security coordination. This can lead to the successful implementation of the proposed STIN paradigms in 5G Advanced and 6G.

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