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Review

SDN-Based Integrated Satellite Terrestrial Cyber–Physical Networks with 5G Resilience Infrastructure: Future Trends and Challenges

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Abstract: This paper reviews the state-of-the art technologies and techniques for integrating satellite and terrestrial networks within a 5G and Beyond Networks (5GBYNs). It highlights key limitations in existing architectures, particularly in addressing interoperability, resilience, and Quality of Service (QoS) for real-time applications. In response, this work proposes a novel Software-Defined Networking (SDN)-based framework for reliable satellite–terrestrial integration. The proposed framework leverages intelligent traffic steering and dynamic access network selection to optimise real-time communications. By addressing gaps in the literature with a distributed SDN control approach spanning terrestrial and space domains, the framework enhances resilience against disruptions, such as natural disasters, while maintaining low latency and jitter. Future research directions are outlined to refine the design and explore its application in 6G systems.

Keywords: software-defined networking (SDN); satellite and terrestrial integration; quality of service; intelligent traffic steering; multi-attribute decision-making; resilient communication networks

1. Introduction

The advent of robust, integrated satellite–terrestrial networks holds the promise of revolutionising global communication connectivity and accessibility for large-scale communications. A primary aspiration of 5G and Beyond Networks (5GBYNs) is to deliver ubiquitous coverage and resilient connectivity, aiming to provide a minimum of 50 Mbps everywhere, irrespective of location [1]. However, achieving these objectives using current terrestrial technologies designed for 5G goals, such as low latency and ultra high-speed, poses challenges in terms of excessive Capital Expenditure (CAPEX) and Operational Expenditure

(OPEX) [2,3]. Deploying telecommunication equipment in harsh or remote terrains with sparse populations may not yield commensurate Return on Investments (ROIs).

Integrating satellites with 5G networks has emerged as a solution to achieve ubiquitous and resilient connectivity [4]. However, the divergent evolution of satellite technologies and terrestrial systems, along with their incompatible underlying protocols, presents a challenge in unifying the two networks [5]. To address this issue, the concepts of Software-Defined Networking (SDN) [6,7] and Network Function Virtualization (NFV) have been adopted to perform protocol translation and ensure smooth interoperation of the networks [8]. Nevertheless, leveraging the heterogeneous architecture presents another challenge. The 3rd Generation Partnership Project (3GPP) standard body has introduced a framework for satellite–terrestrial integration called Access Traffic Steering Switching and Splitting (ATSSS) [9], where the 5G network serves as the 3GPP access network (AN) and the satellite serves as the non-3GPP AN. The ATSSS framework provides a structured approach for services to exploit the integrated architecture.

Recent works, such as [10,11], have demonstrated the feasibility of all three modes of ATSSS. Ref. [10] illustrated traffic steering, where traffic can be redirected from one network path due to factors like congestion, Quality of Service (QoS) requirement mismatches, or link unavailability. Conversely, the study in [11] showcased traffic splitting to enhance the goodput of transmitted data traffic. However, while their efforts demonstrated the splitting aspects of the ATSSS framework, this can lead to packet reordering induced by complementary delay in end-to-end (E2E) communication [12]. Complementary delay refers to the variation in latency between two concurrently utilised network paths, each exhibiting notably different latency characteristics in an end-to-end data transmission scenario. This relationship is mathematically represented as follows (1):

$$T_t = \max_{x,y \in b}\left(\sum_{b1=1}^{x} {}^{b1}t_{p1}, \sum_{b2=1}^{y} {}^{b2}t_{p2}\right) \tag{1}$$

where b is the total number of application data bits transmitted, which is divided into sub-flows x and y via both paths $p1$ and $p2$. $b1$ and $b2$ are the application traffic that traverse terrestrial and satellite paths ($p1$ and $p2$), respectively. x and y represent the total number of bits in the sub-flows transmitted via $p1$ and $p2$. ${}^{b1}t_{p1}$ and ${}^{b2}t_{p2}$ depict the time taken to transmit each bit $b1$ and $b2$ belonging to sub-flow x and y.

While the ATSSS approach is well suited for elastic traffic [13] such as hypertext transfer protocol (HTTP) and simple mail transfer protocol (SMTP), due to its capacity to enhance goodput, it falls short when handling real-time traffic, such as voice. This limitation arises from the vulnerability of real-time traffic to issues such as packet reordering [12] and jitter [14]. Thus, there is a compelling case for investigating the steering and switching modes of the ATSSS framework as presented in the multi-connective design in [11]. In this manner, the problem of jitter and packet reordering for real-time traffic can be addressed. Table 1 summarises QoS expectations of interactive or conversational applications in terms of E2E latency, jitter, and packet loss rate (PLR).

Table 1. End-user performance expectations—conversational services [15].

Medium	Application	Degree of Symmetry	Data Rate (kbps)	Key Performance Parameters and Target Values: E2E One-Way Delay (ms)	Delay Variation Within a Cell (ms)	Information Loss (%)
Audio	Interactive voice	Two-way	4–25	<150 preferred [16] <400 limit	<1 ms	<3 FER
Video	Video phone	Two-way	32–384	<150 preferred <400 limit Lip-synch: 100	NA	<1 FER
Data	Telemetry-two-way control	Two-way	<28.8	<250	NA	Zero

Table 1. *Cont.*

Medium	Application	Degree of Symmetry	Data Rate (kbps)	Key Performance Parameters and Target Values		
				E2E One-Way Delay (ms)	Delay Variation Within a Cell (ms)	Information Loss (%)
Data	Interactive games	Two-way		<250	NA	Zero
Data	Telnet	Two-way		<250	NA	Zero

The existing integrated satellite–terrestrial network (ISTN) architecture for multi-connective User Equipment (UE) presents resilience and reliability challenges. For instance, the multi-connective SDN-based ISTN design outlined in [11] may not provide a high degree of resilience/reliability, as the satellite component relies on the SDN component in the terrestrial region to execute network functions. Although the SDN controlling satellite operations may be distinct from the 5G core network and located at satellite ground operation centres, any disruption affecting terrestrial network facilities can render the satellite networks inactive since they depend on terrestrial SDN for network direction. This network design can be seen as a logically serial connected network architecture.

To address this reliability issue, a parallel designed SDN-based ISTN is proposed. With modern satellite's inter/intra satellite links (ISLs) capable of facilitating in-space routing, a parallel-oriented ISTN design becomes feasible. The space segment can be outfitted with SDN controllers in space, eliminating the need to rely on terrestrial regions for network directions. This design can ensure high reliability that would enable network service operations to persist during situations like natural disasters or sabotage incidents. The proposed parallel SDN-based ISTN design is illustrated in Figure 1.

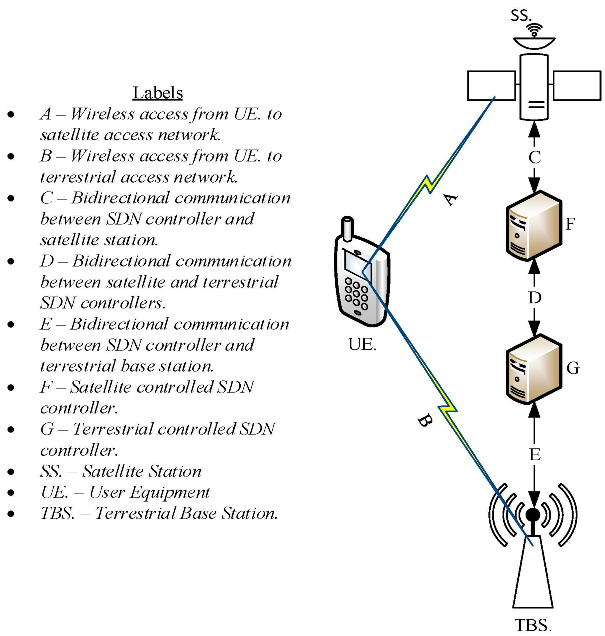

Figure 1. Proposed parallel-oriented SDN-based ISTN design for a multi-connective UE.

In the context of the proposed framework as depicted in Figure 1, it is crucial to assess the limitations of existing protocols such as transmission control protocol–internet protocol (TCP/IP), multipath transmission control protocol (MPTCP), and similar ones to enhance the transmission process within this architecture. By identifying these limitations, a new protocol design can be formulated to optimise the transmission process within the proposed framework. A well-designed protocol architecture has the potential to greatly enhance the reliability of 5G systems and minimise associated delays, leading to an improved Quality of Service/Experience (QoS/QoE).

This article aims to provide an overview of various literature that highlight the state-of-the-art, limitations, and relevant technological concepts relevant to addressing the problem. Drawing insights from the literature, we propose a conceptual design for a reliable ISTN that leverages the Steering mode of the ATSSS framework for real-time communication.

The contributions of this article are significant and can be summarised as follows:

1. Proposes a novel SDN-based framework for integrated satellite–terrestrial networks to enable resilient and ubiquitous real-time communications.
2. Proposes both traffic steering and switching within the user-plane connectivity model to intelligently select optimal AN based on dynamic network conditions and application QoS requirements.
3. Incorporates QoS aware multi-attribute decision-making for AN selection, accounting for metrics such as latency, jitter, and available bandwidth.
4. Demonstrates how distributed SDN control can enable seamless satellite network operation during terrestrial network disruptions.
5. Proposes a cooperative SDN control framework spanning terrestrial and space domains for intelligent traffic routing and AN switching decision.
6. Synthesises insights from an extensive set of prior works on SDN-based traffic engineering, QoS provisioning, and integrated satellite–terrestrial networking.
7. Lays out an agenda for future research by identifying key performance factors, algorithms, and mechanisms needed to realise the proposed SDN-based integration framework.

The subsequent sections are organised as follows: "Traffic Transmission Architecture" presents two ISTN traffic steering models derived from literature, where it was mathematically proven that the reliability of a parallel-oriented architecture offers high reliability. "Overview of 5G Technology" outlines the evolution and current state of 5G and beyond networks. "Satellites and their Role in 5G" examines the critical role of satellites in 5G infrastructures, discussing the challenges and benefits of integrating satellite and terrestrial systems. "SDN and NFV Concepts for Programmable Infrastructure" explores these key technologies. "Framework for a Reliable SDN-Based ISTN for Real-time Communication" proposes a framework for a dependable SDN-based ISTN. A comprehensive literature review follows, identifying global research gaps. The final section highlights future trends and applications, concluding with insights into the future landscape of communication networks.

2. Traffic Transmission Architecture

The implementation of the splitting mode implied from the literature in [11] is depicted in Figure 2a. This offers high reliability compared to the implementation portrayed in [10], which is depicted in Figure 2b.

In general, the implementation of the ATSSS can be categorised into two models: the ser-plane connectivity (UPC) model (Figure 2a) and the Network-Plane Connectivity (NPC) model (Figure 2b). The UPC model represents a multi-connective system [17,18] where a UE can possess two or more network interfaces (NIs) connecting to different radio access technologies/networks (RANs/RATs). Conversely, the NPC model illustrates data transmission where for instance a UE is unaware of how or where its traffic is being transmitted; instead, the core network (CN) determines the route for its data. In this model, the UE typically has only one NI for transmitting its information. A simple reliability model for both the UPC and NPC models can be expressed as follows:

If we denote the probability of system failure as $P(f)$, then the probability of the system not failing, referred to as R, can be expressed as in (2):

$$R = 1 - P(f) \tag{2}$$

Considering the reliability of a parallel connected system R_p, then the expression (3) is given [19].

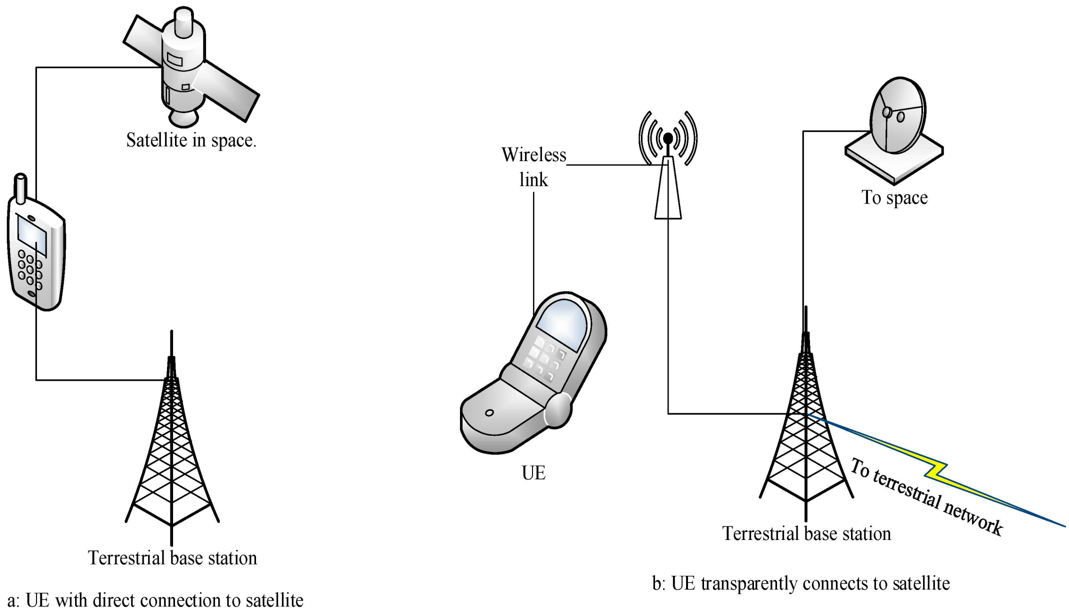

Figure 2. User-plane versus network-plane connectivity architecture.

$$R_p = 1 - (1 - P(f)_1) \times (1 - P(f)_2 \times \ldots \times (1 - P(f)_n) = 1 - (R_1 \times R_2 \times \ldots \times R_n) \quad (3)$$

Conversely, the reliability of a serially connected system R_s, can be given as (4).

$$R_s = R_1 \times R_2 \times \ldots \times R_n \quad (4)$$

where the terms $R_1, R_2, \ldots R_n$ denote the reliability of the individual component of a system.

Since the UE in the UPC model has a parallel access/connection to the satellite and terrestrial AN, then the reliability of this model can be obtained in (5), as derived from (3).

$$R_{upc} = 1 - (1 - P(f)_{sat}) \times (1 - P(f)_{terst}) = 1 - (R_{sat} \times R_{terst}) \quad (5)$$

In the same vein, the UE in the NPC model has a serial access/connection to the satellite and terrestrial AN thus the reliability of this model can be depicted in (6), as derived from (4).

$$R_{npc} = P(f)_{sat} \times P(f)_{terst} = R_{sat} \times R_{terst} \quad (6)$$

For $0 < R < 1$, the R_{upc} will be greater than R_{npc}. By implication, the UPC model will offer a higher reliability than the NPC model.

However, the conceptual design in the work of Giambene et al. [11] is not a truly reliable system, since the satellite operation still depends on the control actions coming from terrestrial networks, and any shutdown of the latter would mean the satellite cannot continue to offer communication services. Thus, there is a need for a new architectural design where satellite can be completely isolated when issues arise but can work in synchrony with terrestrial systems when they are both active.

3. Overview of 5G Technology

The emergence of 5G technology has created a remarkable spike in mobile broadband demand and connected devices. The proliferation of smartphones, tablets, wearables, and the Internet of Things (IoT) highlights the necessity for robust and high-speed connectivity, particularly as IoT applications heavily rely on mobile broadband for seamless data transmission [20]. A significant contributor to the increasing demand for vehicular broadband is data-intensive applications. The widespread adoption of vehicular computing (Vehicle-to-

Vehicle (V2V), Vehicle-to-Infrastructure (V2I), and Vehicle-to-Everything (V2X)) has led to a substantial leverage in data consumption. These applications necessitate swift and stable connections to deliver an uninterrupted user experience, a need quickly addressed by the high data rates and low latency of 5G technology [21].

Moreover, various industries are increasingly turning to high traffic broadband to drive their operations. For instance, the transportation sector is harnessing 5G to enable remote vehicular monitoring, and real-time data transmission for IoT devices [22]. Similarly, these industries are leveraging mobile broadband for connected vehicles, intelligent transportation systems, and road traffic management [23]. These sectors demand reliable and high-speed connectivity to support their critical applications.

To meet the escalating demand for edge location broadband, 5G/6G technology was advanced for seamless integrations. Fifth-generation networks offer substantially higher data rates, lower latency, and enhanced capacity compared to their predecessors [24]. Leveraging advanced techniques such as non-orthogonal multiple access (NOMA), 5G enhances spectral efficiency and supports massive connectivity [25]. Additionally, technologies like Multiple-Input Multiple-Output (MIMO) and beamforming are employed to optimise coverage and capacity [26].

Also, of utmost importance is the need for ubiquitous coverage. The terrestrial networks are limited in the areas they can cover due to factors like cost of deploying terrestrial facilities in a very remote area, geographically harsh terrains such as mountains, hard to reach areas such as the seas, and the likes. Satellites has been brought into the picture to offer ubiquity. The assurance of making satellites to work side by side with terrestrial networks is premised on the success of SDN and NFV in 5G mobile wireless networks, which have brought about flexible deployment and management of network infrastructures.

On this note, the subsequent discussions will delve into the evolution of 5G and its enablers (such as cloud computing, network slicing, SDN, NFVs, etc.), the need for satellites, and its viability, applications, and benefits. The role the SDN and NFV technologies have played in the evolution of 5G terrestrial network will further be discussed, and the role it can play in ensuring seamless interworking between satellites and terrestrial network to provide global connectivity will also be discussed.

3.1. Evolution of 5G Terrestrial Network

The evolution of terrestrial networks in 5G and beyond encompasses several key aspects, including the deployment of 5G technology, the concept of network slicing, and the adoption of cloud radio access network (RAN) architectures. These advancements aim to enhance network performance, flexibility, and scalability to meet the diverse requirements of emerging applications and services. The deployment of 5G technology represents a significant milestone in terrestrial network evolution. Fifth-generation networks offer higher data rates, lower latency, and increased capacity compared to previous generations. They enable a wide range of applications, including enhanced mobile broadband, massive machine-type communications, and ultra-reliable low-latency communications [27]. The deployment of 5G networks involves the deployment of new infrastructure, including base stations and small cells, to provide seamless coverage and support the increasing demand for high-speed connectivity.

Network slicing is a key concept in 5G and beyond networks, enabling the creation of virtual networks tailored to specific use cases and requirements. Network slicing allows the allocation of dedicated resources and services to different applications, ensuring optimal performance and QoS for each slice [28]. This approach enables efficient resource utilisation, improved scalability, and the ability to support diverse applications with varying requirements within a single physical network infrastructure.

Cloud RAN (C-RAN) is an architectural approach that centralises baseband processing and intelligence in a cloud-based infrastructure. C-RAN enables more efficient resource allocation, dynamic network optimisation, and centralised management of radio resources [29].

By separating the baseband processing from the Remote Radio Units (RRUs), C-RAN reduces the complexity and cost of deploying and maintaining radio access networks.

The integration of network slicing and C-RAN architectures offers significant benefits in terms of network flexibility and resource optimisation. Network slicing allows the creation of dedicated slices for different services, while C-RAN provides centralised control and management of radio resources. This integration enables efficient resource allocation, dynamic service provisioning, and improved QoS for different applications and use cases [30,31]. Furthermore, network slicing and C-RAN architectures will provide avenues to ensuring energy efficiency in 5G and upcoming 6G networks. Particularly, [32] discussed the various strategies where network slicing can achieve energy efficiency, which include dynamic resource management, AI integration, and the effective prioritisation of services. Also, as highlighted in [33], various energy saving schemes leveraging on SDN such as SD Optical Network (SD-ONU) can be emulated in various access technologies in 5G and beyond networks. While ISTN implementation can ensure energy distribution across the terrestrial and satellite networks, it will be worthwhile to explore some of these energy saving strategies within the ISTN framework.

3.2. Satellites in 5G and Beyond Networks

Satellites have in the past played significant roles in various aspects like weather monitoring, tracking, and communications. Satellites in communications systems have operated independently of other wireless access technologies and thus have evolved divergently along different underlying protocols and operational principles. In this section, we discuss how satellites systems can be exploited to enhance 5G and beyond mobile communications networks when integrated together; this is done by providing different discourse as follows.

A. Satellites and Their Roles in 5G and Beyond Networks

In the context of 5th Generation Broadband Wireless Networks (5GBYNs), Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary Earth Orbit (GEO), satellite communication networks play vital roles, offering distinctive characteristics and capabilities that complement terrestrial networks, facilitating global connectivity.

LEO satellite networks, positioned at relatively low altitudes (typically around 1200 km or less), are poised to be integrated into future wireless networks, including 5GBYNs, to furnish global wireless access with augmented data rates [34]. Notably, LEO satellites, exemplified by initiatives like Starlink and OneWeb, hold promise for expansive 3D wireless connectivity when seamlessly integrated with Unmanned Aerial Vehicles (UAVs) and ground terminals [35]. However, integrating LEO satellite networks into 5G and beyond networks presents challenges and opportunities, including resource allocation and network management [36].

GEO satellite networks, situated at fixed points above the equator, offer global coverage but contend with notable delays due to their high altitude [37]. Integrating GEO satellites with terrestrial systems can prove advantageous for global large-capacity coverage, albeit the high latency poses challenges that necessitate mitigation [37]. Post-5G and future mobile communication systems are expected to integrate different radio access technologies, including satellite components [11].

MEO satellite networks, positioned at intermediate altitudes between LEO and GEO, offer advantages such as enhanced coverage and reduced latency compared to GEO satellites [38]. In a hybrid communications architecture complemented by MEO and GEO satellites alongside terrestrial network components, these constellations can enable universal 5G service while accommodating diverse use cases [38]. The orbital placements of LEO, MEO, and GEO satellites are diagrammatically described in Figure 3 [39].

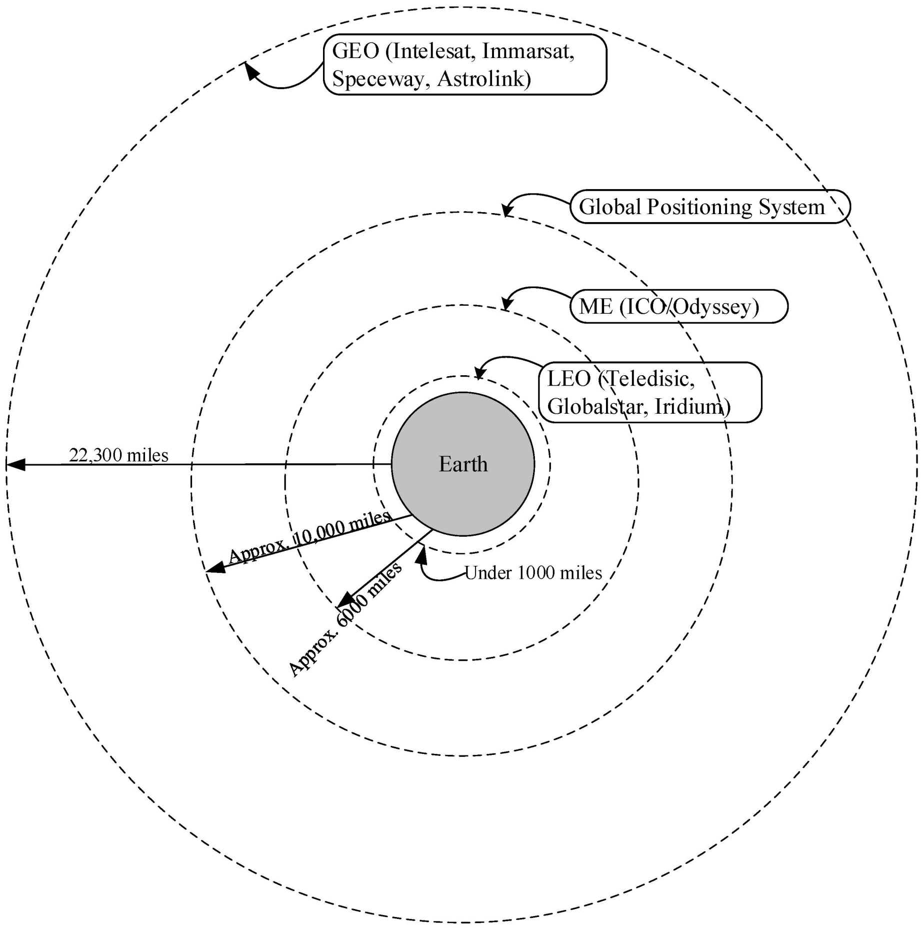

Figure 3. Types of satellites and their orbital positions [39].

The integration of satellite communication networks, whether LEO, MEO, or GEO, with terrestrial networks in 5GBYN systems unlocks opportunities for global connectivity, improved data rates, and enhanced coverage. However, challenges such as resource allocation, network management, latency, and synchronisation must be addressed to fully exploit the potential of these integrated networks [39–42]. Table 2 provides a summary of the features and applications of LEO, MEO, and GEO satellites.

Table 2. A summary of the various satellite types and their features.

S/N	Features	LEO	MEO	GEO
1.	Altitude	500–2000 km [36]	2000–35,780 km [43]	>35,780 km [43]
2.	One-Way Latency	<30 ms [36,38]	112 ms [44]	≥250 ms [45]
4.	Coverage/visibility period	~20 min [46]	~2 h	24 h
5.	Coverage area	0.45% of earth's surface at 30 deg inclination [36]	Several thousand kilometres in diameter per satellite	1/3 of the earth's surface
6.	Speed	7.6 km/s at 500 km altitude [36]	3.07 km/s at 20,000 km altitude	Synchronous with earth's rotational speed
7.	Capacity			
8.	Design	Walker, Delta	Walker	Fixed
9.	Application	Communications, scientific, weather monitoring	Navigation (GPS), observation, weather monitoring	Weather monitoring, communication, tracking
10.	Examples	Starlink, Oneweb, Kepler, Telesat	O3b, mPOWER, Telstar	Inmarsat, ViaSat, SES

B. Benefits of Integrated Satellite Terrestrial Networks

The integration of satellite and terrestrial networks in 5G and next-generation networks brings several important aspects to consider, including increased capacity [5], ubiquitous coverage, resilience, mobility, and edge access. This contributes to the achievement of key performance indicators (KPIs) in 5G networks. Ubiquitous coverage is a key requirement for integrated satellite–terrestrial networks. Satellite networks provide wide-area coverage, which is particularly beneficial in remote and underserved areas where terrestrial networks may have limited reach [37,47]. The combination of satellite and terrestrial networks can ensure seamless connectivity across different geographical locations, enabling users to stay connected regardless of their location [1,48]. Resilience is another important aspect of integrated networks. Satellite networks are known for their inherent resilience to natural disasters and other disruptions, making them a reliable backup option for terrestrial networks [37]. In the event of a terrestrial network failure or congestion, satellite networks can provide alternative connectivity, ensuring uninterrupted communication [49].

Mobility is a critical requirement in today's connected world. Integrated satellite–terrestrial networks can support seamless mobility, allowing users to maintain connectivity while moving across different coverage areas [11]. This is particularly important for applications such as connected vehicles where uninterrupted connectivity is essential for safety and efficiency [50]. Edge access is an emerging concept that brings computing and storage capabilities closer to the network edge. Integrated networks can leverage edge computing to enable low-latency and high-bandwidth applications [50]. By offloading computing tasks to the edge, satellite–terrestrial networks can reduce latency and improve the overall user experience [51]. To achieve these goals, several technical challenges need to be addressed. These challenges include the design and optimisation of network architectures that seamlessly integrate satellite and terrestrial components [37]. Additionally, the joint exploitation of multiple paths and the use of network coding techniques can enhance the performance of integrated systems [11]. Furthermore, the use of Software-Defined Networking (SDN) and Network Function Virtualization (NFV) can enable the flexible and efficient management of the integrated networks [52].

C. Satellite Communication Use Cases

Satellite communication networks play a crucial role in various usage scenarios within 5GBYNs, including backhaul, direct access, broadcast, and mobility. It enables the seamless integration of satellite and terrestrial networks, ensuring connectivity in remote and rural regions [53]. Backhaul extends coverage to underserved areas beyond terrestrial infrastructure [50]. Direct access provides global coverage for the IoT and remote sensing [54,55]. Broadcast delivers high-quality content to wide audiences [53], while mobility ensures continuous connectivity for moving platforms [54]. Integrating satellite and terrestrial networks enhances coverage, capacity, and connectivity, albeit with challenges such as resource allocation and security [56], opening doors to diverse applications and services. A number of specific use cases of satellite communication are highlighted in view of the emerging technologies such as 6G, AI, edge computing, etc.

i. Vision of Future 6G Network: Sixth-generation networks are poised to revolutionise connectivity, offering unparalleled speed, reliability, and scalability. These networks will serve as the backbone for a myriad of applications, ranging from smart cities to autonomous vehicles, ushering in an era of ubiquitous connectivity and unprecedented innovation.
ii. Smart and Connected Vehicular Life in 6G: In the 6G era, vehicles will be seamlessly integrated into a connected ecosystem, communicating not only with each other but also with the surrounding infrastructure and pedestrians. This interconnectedness will pave the way for safer roads, optimised traffic flow, and enhanced passenger experiences.
iii. Vehicle–Road–Human Integrated Network: The integration of vehicles, road infrastructure, and human interaction will form a cohesive network aimed at enhancing transportation efficiency, safety, and sustainability. Through advanced sensors, communication technologies, and AI algorithms, this network will enable real-time data exchange and decision-making, creating a more responsive and adaptive transportation system.

iv. Vehicular Communications in 6G: Sixth-generation vehicular communications will transcend traditional boundaries, leveraging satellite communication networks alongside terrestrial infrastructure to deliver seamless connectivity in even the most remote or challenging environments. From backhaul to direct access, broadcast, and mobility, satellites will play a pivotal role in extending coverage and ensuring uninterrupted communication for vehicles on the move.
v. Cloud, Fog, and Edge Computing: The convergence of cloud, fog, and edge computing will empower 6G networks with unprecedented computational capabilities, enabling real-time data processing, analytics, and decision-making at the network's edge. This distributed computing paradigm will reduce latency, enhance privacy, and unlock new opportunities for edge-based applications and services.
vi. Centralised and Distributed AI: AI will be at the heart of 6G networks, driving intelligent automation, optimisation, and decision-making across various domains. From centralised AI platforms orchestrating network resources to distributed AI algorithms running on edge devices, AI will enhance network efficiency, reliability, and adaptability, ushering in an era of autonomous networking and intelligent services.
vii. Data Security and Privacy Protection: As connectivity proliferates and data volumes soar, robust security and privacy measures will be paramount in safeguarding sensitive information and preserving user trust. Sixth-generation networks will employ advanced encryption techniques, decentralised authentication mechanisms, and privacy-preserving technologies to ensure the confidentiality, integrity, and availability of data across the network.

Satellite Communication Networks

D. Challenges in Integration of Satellite with Terrestrial Networks

The integration of satellite and terrestrial networks faces several limitations and hindrances that need to be addressed for seamless operation and optimal performance. These limitations include hardware compatibility, standardisation challenges, interference constraints, management plane convergence, and routing complexities. One limitation is the proprietary hardware used in many current satellite communication networks, which hinders integration with future 5G and future terrestrial networks and the adoption of new protocols and algorithms [5]. This hardware incompatibility poses challenges in achieving seamless interoperability and efficient resource management between satellite and terrestrial components. Standardisation efforts are crucial for the integration of satellite and terrestrial networks. Standardisation issues need to be addressed to ensure interoperability, efficient management, and seamless integration of satellite and terrestrial networks. However, the lack of common interfaces for resource management and control between these networks hampers their convergence [57].

The convergence of management planes between satellite and terrestrial networks is a complex task. The absence of convergence in management planes poses challenges in coordinating and controlling network resources effectively [57]. Efforts are needed to develop common management frameworks and interfaces that enable seamless coordination and resource allocation across satellite and terrestrial components. Routing complexities arise in integrated satellite–terrestrial networks due to the unique characteristics of satellite communication, such as long propagation delays and non-uniform coverage [58]. Routing strategies need to be designed to address these challenges and optimise the routing paths in the integrated network.

Interference constraints are another limitation in the integration of satellite and terrestrial networks. Where both systems share the same spectrum, the proper consideration of interference is essential in the carrier allocation algorithm design [59]. Managing interference and optimising spectrum usage are critical for achieving efficient and reliable communication in integrated networks.

Emerging solutions are being developed to overcome these limitations and enhance the integration of satellite and terrestrial networks. For example, hyperbolic geometry-based routing strategies have been proposed to improve the efficiency and robustness of integrated networks [58]. By leveraging hyperbolic coordinates, greedy forwarding algorithms can be employed to achieve efficient packet routing in complex network topologies. The concept of reconfigurable SDN Low Earth Orbit (LEO) constellations has been explored as a potential solution for backhauling in integrated networks [60]. LEO constellations offer high coverage and relatively low delays, making them suitable for providing backhaul connectivity in integrated systems. Furthermore, the use of NOMA (non-orthogonal multiple access) techniques and pilot-based channel estimation can mitigate the impact of imperfect channel state information in integrated satellite–terrestrial networks [61]. Also, ref. [62] provides a framework for managing scarce spectrum resources between the two networks and the mitigation of the consequent interference. These techniques improve the spectral efficiency and reliability of the communication links. Projects like H2020 SANSA (Shared Access Terrestrial–Satellite Backhaul Network enabled by Smart Antennas) have worked on seamless integration solutions to boost the performance of mobile wireless networks [11,63].

3.3. SDN and NFV Concepts for Programmable Infrastructure

SDN and NFV are two key concepts that have revolutionised the design and management of modern network infrastructures. These concepts provide programmable and flexible architectures, enabling efficient resource allocation, dynamic network control, and service agility. SDN decouples the control plane from the data plane, allowing the centralised control and management of network resources. It provides a programmable network infrastructure where the control logic is separated from the underlying hardware devices [64]. SDN enables network administrators to dynamically configure and manage network behaviour through open interfaces and programmable controllers. Figure 4 depicts the contrast between the SDN and traditional network architecture.

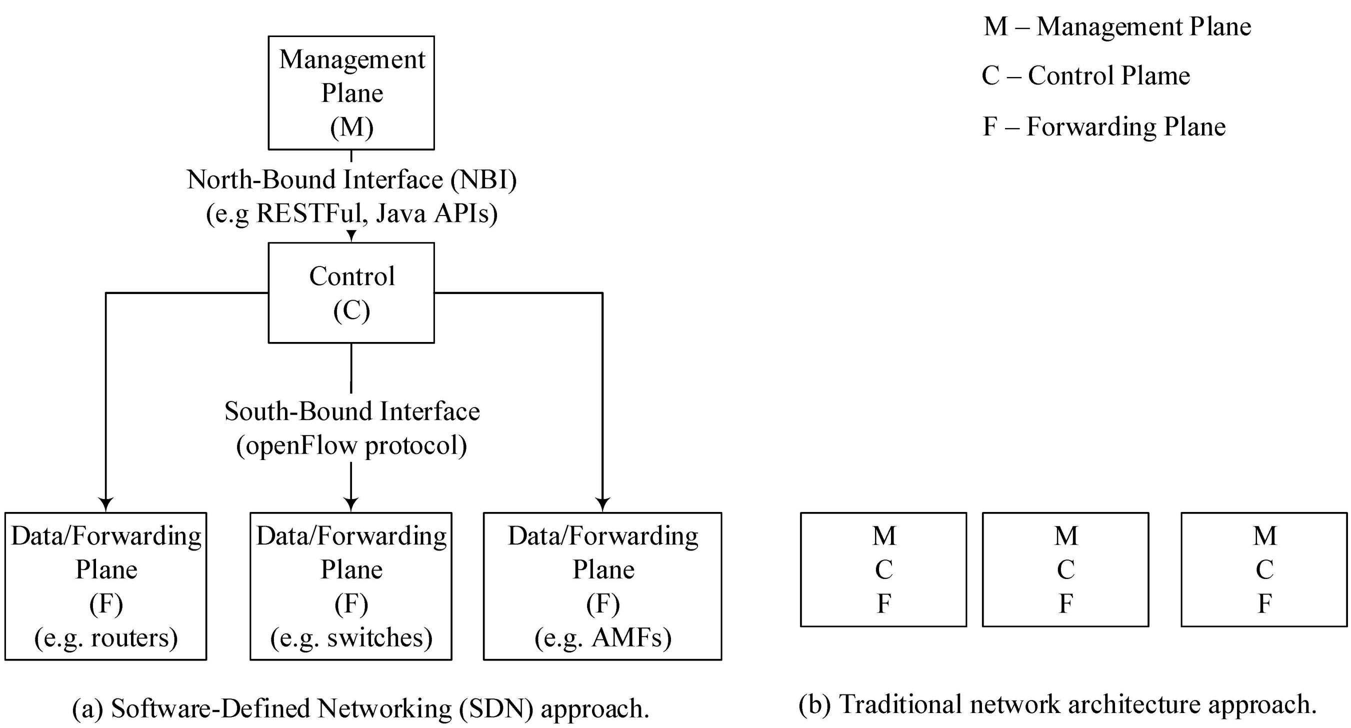

Figure 4. SDN versus traditional network architecture.

NFV, on the other hand, virtualises network functions, such as firewalls, routers, and load balancers, by running them as software instances on commodity hardware or commercial off the shelf (COTS) [65,66]. NFV eliminates the need for dedicated hardware appliances, enabling flexible deployment, scalability, and cost savings. It allows network functions to be dynamically instantiated, scaled, and migrated based on demand. Figure 5 shows the NFV framework in contrast to PNF.

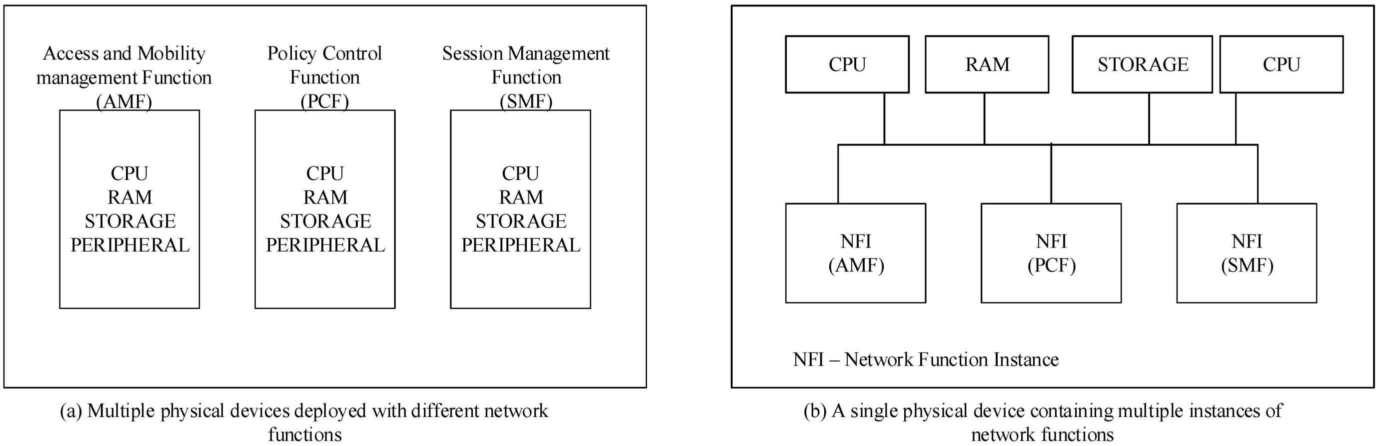

Figure 5. Network function virtualisation versus physical network functions.

The combination of SDN and NFV provides a programmable infrastructure that offers numerous benefits. It enables network operators to efficiently allocate resources, optimise network performance, and rapidly deploy new services. SDN and NFV facilitate network automation, allowing for dynamic provisioning, service chaining, and traffic steering based on real-time requirements [67].

The programmable infrastructure provided by SDN and NFV is particularly relevant in the context of 5G and beyond networks. These networks require flexible and scalable architectures to support diverse use cases, such as enhanced mobile broadband, massive machine-type communications, and ultra-reliable low-latency communications. SDN and NFV enable network slicing, where dedicated virtual networks are created to meet the specific requirements of different applications and services. C-RAN is an architectural approach that leverages SDN and NFV to centralise baseband processing and intelligence in a cloud-based infrastructure. C-RAN enables efficient resource utilisation, dynamic network optimisation, and centralised management of radio resources. It provides a flexible and scalable solution for cost-effectively managing the radio access network.

The adoption of SDN and NFV concepts for programmable infrastructure has implications across various domains, including the IoT, security, edge computing, and virtualisation [68–71]. These concepts enable the virtualisation and orchestration of network functions, leading to increased flexibility, scalability, and efficiency in network operations [72–74].

4. Proposed Framework for Reliable SDN-Based ISTN for Real-Time Communication

In this section, we proposed a conceptual framework that can implement traffic steering suitable for real-time communication. The framework is aimed to eliminate dependency on terrestrial SDN control systems, ensuring uninterrupted network operation during terrestrial outages. This framework differs from existing work wherein satellite operations are dependent on the terrestrial SDN control systems. Any issue that arises on the terrestrial end of the network would affect the SDN controller that dictates the operation of the satellite segment. In order to have an independent yet cooperative ISTN system, we formulate the framework depicted in Figure 6, which is an expanded proposition of the framework depicted in Figure 1.

For real-time communication, voice, latency, and jitter are paramount. Thus, the network design for such communication must minimise the factors that will aid high latency and jitter. In this text, one consideration is using only one AN rather than the simultaneous use of multiple ANs where traffic is split onto each AN as demonstrated in the work of Giambene et al. [11]. We consider traffic splitting to be unsuitable for voice traffic due to complementary delay as depicted in (1). Complementary delay, as described under the "Introduction" section, can induce packet reordering, which in turn would induce jitter.

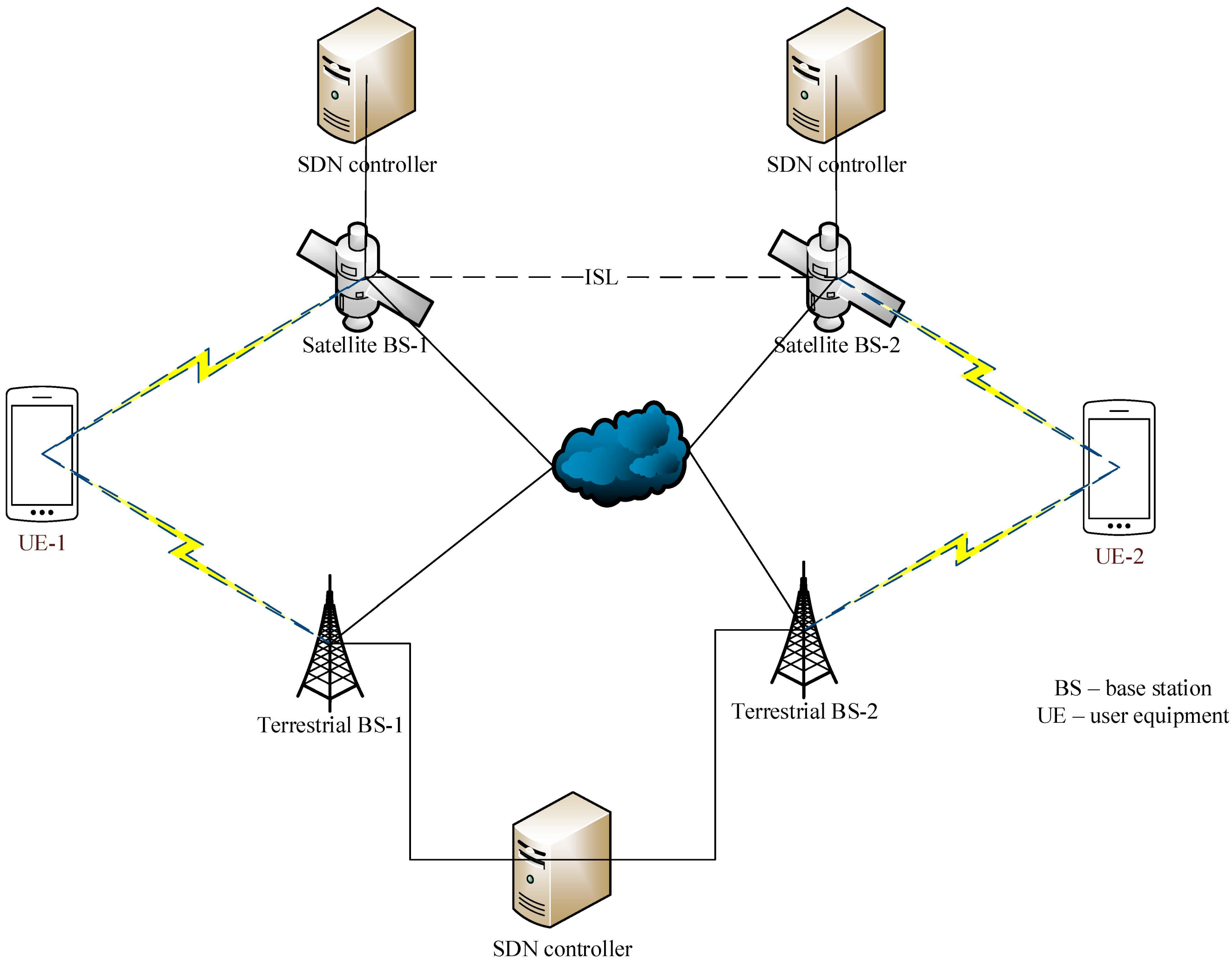

Figure 6. A reliable SDN-based framework of real-time traffic steering.

Considering the design shown in Figure 6, we want the UE-1 equipped with two NIs, satellite and terrestrial, to select one out of the two (or multiple for other case studies). Also, a situation that eliminates or minimises network downtime or unavailability due to congestion or resources is desired. For this reason, we have SDN controllers in both the space and terrestrial domains where they can cooperatively make network and routing decisions for UE-1 traffic. In this manner, when situations such as sabotage or natural disaster occur in the terrestrial region, the satellite network can continue operation without the need for terrestrial SDN controllers. Thanks to modern satellite capabilities such as On-Board Processing and inter satellite links (ISLs), routing can easily be achieved in space without the help of a satellite earth station.

So, how can communication be achieved between UE-1 and UE-2 as shown in the framework in Figure 6?

To ensure communication is achieved between UE-1 and UE-2, the following are envisioned:

1. The assessment of the Reference Signal Received Power (RSRP) for both ANs interfaced with User Equipment 1 (UE-1) through its Nis is essential. If only one NI of UE-1 meets the RSRP threshold for the available radio access technology (RAT), UE-1

will automatically utilise that NI for data transmission. The RSRP can be measured based on the expression in (7) [75,76].

$$RSRP = P_{bs} - L_{pl} - L_{fad} \quad (7)$$

where P_{bs} is the transmit power of a base station, L_{pl} is the path loss between a base station and a UE, and L_{fad} is the shadow fading with a log-normal and a standard deviation of 3 dB.

2. If both NIs of UE-1 meet the RSRP threshold of their respective RATs, UE-1 will transmit a control signal to the network requesting assistance with AN selection based on specific network criteria. Criteria such as latency, available bandwidth, jitter, and PLR may be considered.
3. The network will need to perform multi-attribute/criteria decision-making (MADM/MCDM) to select a suitable AN for UE-1 using a multi-objective function as depicted in (8) [77].

$$MOF = W_1 \times D + W_2 \times B + W_3 \times P + W_4 \times J \quad (8)$$

where weights W_1, W_2, W_3, and W_4 are weights associated with delay, bandwidth, PLR, and jitter, respectively.

Notably, UE-1's traffic QoS expectation must be communicated in the control signal to enable proper MADM selection.

Table 3 depicts different MADM techniques adopted in the literature for applications in telecommunication systems.

Table 3. MADM techniques.

S/N	Technique	Application	Advantage	Drawbacks
1.	Analytical Hierarchical Process (AHP) Habbal et al. [78]	Weighting and ranking.	Offers a way to check for judgement error by evaluating consistency index. Works with both objective and subjective criteria.	Requires pre-defined criteria weights provided by user/operator. Difficult to ensure consistency with increased number of elements. Pairwise comparisons result in lengthy subjective opinions for weight assignment if there are many criteria and alternatives.
2.	Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [78,79]	Ranking.	Scales well with objective measurable criteria. Exhibits a simple and rational way of choosing alternative closest to ideal solution.	Requires pre-defined criteria weights provided by user/operator. Exhibits ranking abnormalities.
3.	Analytical Network Process (ANP) [80,81]	Weighting and ranking.	Offers a network of relationships among criteria, which leads to more reliable results.	Requires pre-defined criteria weights provided by user/operator.
4.	Simple Additive Weighting (SAW) [82]	Ranking.	Simple and transparent.	Sensitive to attributes scaling and normalisation can adversely affect scores.
5.	Fuzzy-AHP [83,84]	Weighting and ranking.	Considers the vagueness of judgement made in weight assignment. Can handle imprecise and uncertain information.	Computationally complex and time intensive.

In MADM computation, the weights are determined subjectively by the network providers. A better alternative is to seek customers' preferences to determine the weights, wherein the preferences can be grouped. Based on these groupings, modern computing automation provision, such as a network slice [85,86], can be exploited for the different preference groups. Aside from the user indicating their preference, there can be a machine learning model that can automatically determine the QoS requirement of the application and determine their level of importance to form weights.

4. The network, aided by SDN controllers situated in both space and terrestrial domains, will cooperatively select the AN by evaluating network conditions along the path between UE-1 and UE-2.

After AN selection for UE-1, the real-time assessment of the end-to-end path for both satellite and terrestrial ANs must be continuously monitored. If one path fails, the network can initiate a seamless transition between RAT paths and corresponding NIs on UE-1. Table 4 summarises the possible link assessment or QoS monitoring employed in the literature.

Table 4. Link monitoring techniques.

S/N	Technique	Measured Metric	Pros	Cons	SDN-Implemented
1.	Self-Loading Periodic Streams [87,88]	Available bandwidth	Non-intrusive, i.e., no increase in network utilisation or delay is induced.	Accuracy is dependent on variables like stream length.	No
2.	Variable Packet Size (VPS) probing [89]	Available bandwidth, delay	Requires no prior knowledge of network path and requires control of only the source node.	Being an active method, it requires tests packet to be injected into the network while actual traffic is being transmitted.	Yes
3.	Packet pair/train probing [90]	Link capacity	Simple and low overhead. Compensates for errors induced by revers cross traffic using SDN flow statistics.	Overhead [91] and accuracy is a trade-off based on chosen train length. Cross traffic interleaving probe packets can lead to inaccurate link capacity measurement.	Yes
4.	LLDP-looping [92]	Latency	Minimises overhead by leveraging SDN controller as monitoring point.	Incurs failures caused by timestamping of probe packets.	Yes
5.	PacketBurst [91]	Bandwidth			No
6.	OpenNetMon [93]	Packet loss and delay	Exploits the OpenFlow features to measure per flow metrics without requiring additional hardware resources.	Incurred overhead due to injection of probe packets.	Yes
7.	E2E SDN-based ABW measurement [94]	Available bandwidth	Obtains available bandwidth for any paths in real-time. Exploits OpenFlow messages for monitoring thereby reducing overhead.	Accuracy is limited to OpenFlow counter timestamps.	Yes

However, for the proposed framework, there is a need to develop schemes for the cooperative AN decision-making, which would be hinged on convergence. For convergence to take place, there is a need to investigate existing protocols that can be adapted or develop a new protocol that can aid convergence of the proposed ISTN framework.

Based on the highlighted points above, utilising an existing and appropriate control protocol or developing a new control signal protocol may be necessary. Furthermore, to achieve the points highlighted, future work will examine various scheme propositions and conduct theoretical analyses to inform the selection of an optimal scheme. Additionally, adopting or developing a real-time measurement scheme is critical to ensure QoS-based AN selection and traffic steering. Real-time link assessment predicated on QoS metrics will be an essential component of integrated satellite–terrestrial networks. Existing works have concentrated on backhaul, convergence, SDN-based routing, QoS provisioning, and traffic offload. Reviewing these works contributes to comprehending and enhancing real-time communication in integrated networks, elucidating potential constraints, and proposing adaptable solutions for efficient and reliable connectivity in an ISTN system.

5. Related Works on Foundational Concepts and Evidence Gaps

In this subsection, we present the studies whose concepts or solutions can be of help to aid the implementation of the user-plane multi-connective traffic steering conceived in this work. The technical definition of steering as specified by [9] is the selection of ANs. However, in this work, the steering refers to the process of selecting an AN by/for a UE and the process of switching network paths along an E2E communication as the current path falls shorts of the QoS expectations of the traversing traffic. In other words, traffic steering is a combined act of the Steering and Switching aspect of the ATSSS framework. In order to achieve this feat, it is essential to examine the AN's QoS offerings in relation to the QoS demand of an application that is about to traverse the network. This section explores foundational studies and recent advancements that can guide the development of a user-plane multi-connective traffic steering for an ISTN system. The studies reviewed encompass topics such as QoS considerations, SDN-based frameworks, protocol optimisations, and real-time network assessments, all of which can be critical in surmounting the challenges of E2E communication across dynamic and heterogeneous networks. Therefore, these studies identify gaps and opportunities that underpin the proposed ISTN architecture.

5.1. QoS Considerations in Satellite and Terrestrial Networks

Various studies have emphasised the need for QoS considerations for the efficient utilisation of an ISTN. QoS is a pivotal factor in the integration of satellite and terrestrial systems, ensuring reliable and effective communication. Understanding how QoS provisioning impacts user experience and network efficiency in heterogeneous environments will aid in developing solutions for improved resource utilisation and service reliability of an ISTN system.

Lee and Park [95] discussed the overall design of satellite networks for internet services with QoS support. They proposed a QoS architecture for the satellite network and highlighted the considerations for providing QoS support. Zeydan and Turk [96] analysed the impact of satellite communications over mobile networks. They identified technical challenges in achieving QoS similar to high-bandwidth terrestrial networks for end-users. Niephaus et al. [10] discussed traffic offload in converged satellite and terrestrial networks. They demonstrated that offloading traffic can improve the user's Quality of Experience (QoE) with limited overhead. Ravishankar et al. [38] proposed a next-generation global satellite system with mega-constellations. They emphasised the need for an end-to-end multilayer protocol architecture to analyse and ensure QoS and mobility in the integrated network.

Wang et al. [48] conducted a comprehensive survey on the convergence of satellite and terrestrial networks. They emphasised the importance of QoS in ensuring effective and reliable communication in integrated networks. They further discussed the opportunities, scenarios, and challenges of SDN/NFV-enabled satellite communication networks. They highlighted the potential of satellite services to supplement terrestrial links during peak times or failures, ensuring QoS for critical applications.

Boero et al. [5] explored the integration of satellite networking in the 5G ecosystem. They discussed the physical layer frames and the importance of QoS provisioning in the integrated network.

Guo et al. [97] proposed an SDN-based end-to-end fragment-aware routing for elastic data flows in LEO satellite–terrestrial networks. They focused on QoS optimisation in the terrestrial network with satellite relay.

Niephaus et al. [98] conducted a survey on QoS provisioning in converged satellite and terrestrial networks. They discussed traffic requirement identification, link characteristics identification, traffic engineering, and execution functions for QoS provisioning.

5.2. Software-Defined Networking (SDN) Approaches for QoS-Based Traffic Steering and Routing

The adoption of SDN and NFV in ISTN systems introduces new possibilities for dynamic and scalable traffic management. This subsection examines frameworks that leverage SDN to enable adaptive and real-time routing decisions for optimal network performance.

Li et al. [99] proposed a software defined framework for integrated space–terrestrial satellite communication (SERvICE) to address problems of the traditional satellite network such as inflexible traffic engineering and coarse-grained Quality of Service (QoS) guarantee. The framework provided two schemes: QoS-oriented Bandwidth Allocation (QBA) and QoS-oriented Satellite Routing (QSR) algorithm. The QSR algorithm provides routes to a destination, while the QBA allocates bandwidth within the satellite segment of the integrated system for different services. Two experiments were performed, which include traffic steering within the space segment and traffic steering between the space and the terrestrial segment. In the former, upon simulating bad weather conditions, traffic was able to find another route within the space segment in order to reach its destination, while in the latter, upon simulating a broken connection, traffic was able to reroute to the space segment. The following problems were identified by the authors: (i) the inability to track QoS changes due to time-varying topology of LEO satellites, and (ii) safety concerns as there is one centralised control mechanism where, in the event of breaching on the control link, the whole system could be grounded.

Xu et al. [100] presented a software-defined architecture for the next-generation satellite networks tagged SoftSpace where the SDN/NFV paradigm was exploited to facilitate the integration of upcoming applications into satellite technologies. They presented an approach to achieve Cooperative Traffic Classification (CTC) within a multi-layered controller architecture. They proposed the use of Deep Packet Inspection (DPI) to achieve the CTC system. The proposed classification system comprises local traffic classifiers situated within a distributed SD-satellite terminal, and a global traffic classifier located at the super controller. The global classifier uses Machine Language (ML) techniques to build mapping functions that can make formidable QoS classifications. The caveat however in using DPI for traffic identification violates data privacy hence another approach is needed to achieve identification.

Wang and Yu [101] applied virtualisation and SDN in satellite network. They developed a scheme called Dynamic Global Payload Balance Routing (DGPBR) by implementing a multi-layered SDN-based satellite system where an SDN controller is distributed and coordinated across LEO, MEO, and GEO satellites. An experiment was carried out to evaluate the delay and throughput performance of the scheme. The results showed that the scheme exhibits lower delay and higher throughput than the conventional routing scheme, even when the network load is relatively high. It should however be noted that the two parameters considered, hop number and bandwidth, are not enough to give the correct indication of the network resources. A more in-depth analysis of access network's condition for metrics like available bandwidth, jitter, and so on, is required to attain better dynamic load balancing.

Bao et al. [102] proposed a novel architecture called OpenSAN, which is based on SDN-based multi-layer satellite. The architecture comprises a terminal router, which makes up the data plane, a group of GEO satellites, which make up the control plane, and a Network Operations and Control Centre (NOCC), which makes up the management plane. The centralised topology of the OpenSAN potentially offers significant reduction in the bandwidth required to route packets compared to traditional dynamic routing protocol such as Open Shortest Path First (OSPF). The idea presented in this study can be examined and adopted in a reliable ISTN framework.

5.3. Protocol Consideration for Traffic Steering in SDN-Based ISTN

Considering there is a need for a converged SDN-based ISTN for effective traffic steering, there is a need for a new protocol to be considered. Existing protocols that deal with multiple paths needs to be studied and examined for adaptation or be re-engineered for future ISTN systems. This subsection examines literature on multipath transmissions.

Cola et al. [103] presented texts on multipath transmission control protocol (MPTCP), a useful tool for systems having the capabilities of more than one AN. In this scenario, hosts are assigned multiple IP addresses corresponding to individual network interfaces (NIs). In situations where the NIs are used alternatively, that is, where one is explicitly used while the other is unused until the former is no longer active, there is the problem of unsmooth transition from one link to another. In order to overcome this problem, the idea of multipath was established to exploit multiple paths simultaneously rather than alternatively. Since packets would arrive at different times at the destination host with MPTCP, a packet reordering is required, which constitutes another form of delay. The packet reordering is only suitable for a TCP-based application but not for real-time application as it would have adverse effects.

5.4. QoS-Based Traffic Steering and Data Offload Consideration for ISTN

To be able to achieve AN selection and traffic steering based on the QoS requirement of the application, there is a need to obtain in real-time the QoS offerings of access links associated to a UE; then the application's QoS expectation can be correlated or matched with the AN's or links the QoS offering. On this premise, we present studies that offer ideas to implement this correlation. Al-Najjar et al. [89] proposed an SDN-based load balancing scheme where link selection is made based on the real-time assessment of heterogeneous links' capabilities. The Variable Packet Size (VPS) probing was used to estimate the links' metrics, which were deemed suitable for all kinds of access networks (4G/LTE, WiFi, etc.). The experimental result shows that the SDN-based VPS probing offers better performance in terms of time to process packet sizes. Other metrics that were used include available bandwidth. While these metric assessments can be exercised in an ISTN system, additional metrics such as jitter and packet loss rate need to be measured.

Di et al. [104] proposed ultra-dense Low Earth Orbit (LEO) integration into 5G and beyond networks for data offloading. They considered the joint optimisation of the data rate and backhaul capacity constraints to maximise the efficiency of the integrated network.

Priscoli et al. [18] worked on traffic steering by means of network selection using Reinforcement Learning (RL), which is to be implemented within a network controller such as an SDN controller. RL was claimed to be opted for due to its ability to address complex issues without the involvement of an explicit model. Like in many other studies, the authors consider QoS requirements that characterise service applications in making network selection decision. The traffic steering problem was modelled based on the Markovian Decision Process (MDP).

Bi et al. [105] proposed an architectural framework to integrate space and terrestrial networks using SDN in order to achieve convergence, and to bring about flexible management of the two networks. An SDN-based traffic steering framework was presented where network selection can be made based on the dynamically identified traffic's QoS demand.

Shu et al. [106] provided a framework for integrating traffic engineering (TE) in SDN. The TE framework comprises the Traffic Measurement (TME) and Traffic Management (TMA) schemes. The TMA monitors, measures, and analyses network status and traffic in real-time, and then feeds them into the TME. The TME performs scheduling of QoS guarantees, traffic load balancing, energy management, etc. based on the input fed into it. The network status information captured is the connection status of the current network topology, the ports' statuses, packet counters, link bandwidth utilisation ratio, end-to-end network latency, and traffic matrices. All these make up the network performance parameters.

5.5. Real-Time QoS and Link Assessment Mechanisms

Real-time network monitoring and assessments are indispensable for maintaining QoS in dynamic ISTN environments. There is a need to investigate tools and protocols that would enable accurate and scalable network resource evaluations. This segment is aimed at identifying methods that would provide insights into network performance that aid adaptive decision-making.

Al-Najjar et al. [107] developed a Weighted Round Robin (WRR) load balancing scheme for SDN-based multi-homed end hosts. This scheme addresses the unfair link resource utilisation of the existing load balancing schemes, which do not consider the state of the network before making link selection or always opt for the best network while ignoring their eligibility thus rendering them redundant until the best network becomes unavailable.

Sato et al. [108] developed a Never Die Network (NDN) system that is able to deliver network services under any situation, even in the wake of disaster. They proposed a method to autonomously derive optimum packet flow by measuring the communication state of the individual member of heterogeneous access network, which an end host is equipped with. Parameters such as throughput, packet loss rate, etc. are used to determine the suitability of a given access link to transmit packets. The performance of heterogeneous access networks, which include 3G/LTE, WiMax and satellite, were assessed at periodic interval using Cognitive Radio (CR). The system as a whole performs network measurement, link selection, and sets communication priority to a given traffic type. While the system demonstrates service continuity in the wake of failure of one of the links, prioritising emergency traffics fails the 5G expectation of network availability for every service.

To enable real-time link monitoring and efficient network capacity assessments in an SDN-based ISTN system, the work of Curtis et al. [109] is examined. Their work developed a DevoFlow (DFL) protocol by modifying the OFL protocol to achieve scalable flow management. This is achieved by keeping flows within the data plane thereby keeping minimal the overhead experienced by the control plane of the OFL. The DFL's controller has and maintains enough visibility of network flows, which affords it the ability to obtain aggregation of flow statistics. This makes DFL suitable for real-time link monitoring and thus suitable for a reliable ISTN system. For efficient link monitoring or network capacity assessment, the DFL can be considered over the OFL.

Jain and Dovrolis [87] performed link estimations by developing a scheme called Self-Loading Periodic Streams (SLoPS). In the scheme, an artificial traffic is created and sent across an E2E path in order to estimate the E2E available bandwidth (ABW). This is carried out by measuring the one-way delay of the transmitted traffic. Through simulation and internet experiments, it was shown at the time that the method can accurately measure ABW under any load condition. As noted, the experiment was performed on a wired network. Adaptation of this technique to the wireless and satellite systems can be further studied for possible adaptation into a reliable SDN-based ISTN system.

Studying the work of Davy et al. [110] can be beneficial in a reliable SDN-based ISTN systems. It involves a method of empirical estimation of the effective bandwidth required to satisfy the QoS of an admitted traffic. A measurement-based admission control technique was performed where traffic is admitted based on a real-time assessment of the network's bandwidth capability. Other admission controls evaluated in this text include Parameter Based Admission Control (PBAC) and Experience Based Admission Control (EBAC). However, the PBAC and EBAC were proven to be inferior in performance compared to the one developed by the authors. While the experiments show an accurate estimation of the bandwidth commensurate with admitted traffic requirement, the same performance cannot be shown for burst traffic. Examining this study for adaptation into a reliable SDN-based ISTN system is essential as the experiment was exercised under the assumption of uninterrupted flow, a situation often not obtainable in practice.

5.6. Strategies and Algorithms Considerations for Access Network Selection

Considering there are multiple QoS criteria that may be considered for AN selection or traffic steering, there is a need to perform multi-criteria/attribute decision-making (MCDM/MADM). Thus, this section explores studies that could offer insights into developing future SDN-based traffic steering for an ISTN system.

Ahuja et al. [77] presented a novel algorithm for the optimal selection of heterogeneous network architecture where they considered UMTS, WLAN, WiMAX, and GPRS. They developed a multi-objective function (MOF), where QoS parameters (such as delay, bandwidth, PLR, and cost per byte) and their weights are inputs in the function. The MOF was then used to obtain the optimal link best suitable to transport a particular application traffic. The weights were obtained using TOPSIS and entropy technique and the QoS demands were determined based on prior knowledge of the application traffic. The technique presented here may fit heterogeneous networks involving satellite systems, and additional QoS factors like jitter can be considered and implemented in an SDN context.

Giambene et al. [11] proposed a network coding (NC) scheme where an optimal traffic split between links of a heterogeneous network is obtained based on a split probability value. The probability value is obtained based on the capacity of the individual links characterised by delay, PLR, and bandwidth. While the split probability model was used to determine the traffic volume ratio to be split across multiple ANs before being simultaneously transmitted, this could be studied and be adapted for AN selection.

Hossen and Jamalipour [111] proposed a universal traffic steering (TS) framework based on the current network conditions and the user's profile, which comprises the user's location, time, connection type, mode of connection, mobility condition, device power level, traffic type, and QoS requirement. With the help of SDN, the global view and the network status of a cellular network were obtained in order to make dynamic steering decision. Steering decision was achieved based on the highest utility value obtained from the policy defined by the network operator. The performance evaluation was based on handover events where the experiments showed that network access points were optimally identified for users to redirect traffic based on the set TS policies.

Li et al. [112] introduced a comprehensive framework for an integrated space–ground satellite communication system with multiple layers, leveraging software-defined networking (SDN) and network function virtualization (NFV). The experimentation involved a scenario where a user uploaded data to a data centre (DC) via a satellite path allocated by the network. In the simulation, adverse weather conditions led to elevated Bit Error Rate (BER) and PLR. To address these challenges, the Satellite Network Management Centre (SNMC) within the management plane proactively scheduled traffic rerouting through an alternate satellite path. The results demonstrate the effectiveness of this approach in mitigating the impact of deteriorating BER and PLR. The success was attributed to the SNMC initiating traffic rescheduling through the controller in the Geostationary Earth Orbit (GEO) satellite, ultimately ensuring the provision of satisfactory Quality of Service (QoS).

5.7. Distributed SDN Controller Architecture for Converged ISTN

For a reliable SDN-controlled ISTN, there would be a need for the cooperative interworking of SDN controllers within and beyond a region (i.e., within and outside space and terrestrial regions). On this note, we present literature that can be examined and adopted in an ISTN architecture.

Yu et al. [113] proposed a West–East Controller Associated Network (WECAN) to address scalability and single points of failure in SDN control planes. The distributed approach of WECAN could improve reliability for large-scale integrated space–ground networks. However, the terrestrial focus of WECAN needs to be adapted to consider satellite link characteristics. Overheads from coordinating satellite and terrestrial controllers should be examined.

Almadani et al. [114] introduced a distributed SDN framework (DSF) using a standardised east–west interface protocol to improve interoperability. Adopting such standardised protocols could benefit space–ground network integration. However, DSF was designed for data centres, so a satellite-optimised protocol likely needs development.

Bhardwaj and Panda [115] evaluated Ryu SDN controller performance for data centres. While informative for general SDN assessment, focusing on satellite connections rather than data centres, would be more relevant for space–ground networks. Testing multiple controller options over satellite links can reveal their strengths and weaknesses in this context.

Koulouras et al. [116] compared four SDN controller options based on performance metrics using emulation. Their approach demonstrates a methodology for comparative SDN controller evaluation. However, their simple topology likely does not reflect satellite network complexities. Testing over more realistic space–ground network configurations would improve applicability.

Each study addresses specific aspects of QoS, network management, and integration, providing valuable considerations for developing an efficient and adaptable network architecture. Table 5 shows the summary of the reviewed efforts. The purpose of this study is to build on existing literature to achieve the proposed ISTN architecture presented in this work.

Table 5. Summary of related works on SDN/NFV and links' QoS/metric measures.

S/N	Reference	SDN/NFV Implementation	Link QoS/Metric Measure	Satellite–Terrestrial Integration
1.	Lee and Park [95]	Yes	Yes	Yes
2.	Zeydan and Turk [96]	No	Yes	Yes
3.	Niephaus et al. [10]	Yes	Yes	Yes
4.	Ravishankar et al. [38]	Yes	Yes	Yes
5.	Li et al. [99]	Yes	Yes	Yes
6.	Xu et al. [100]	Yes	No	Yes
7.	Cola et al. [103]	Yes	Yes	No
8.	Al-Najjar et al. [107]	Yes	Yes	No
9.	Sato et al. [108]	Yes	Yes	Yes
10.	Shu et al. [106]	Yes	Yes	No
11.	Wang and Yu [101]	Yes	No	Yes
12.	Ahuja et al. [77]	No	Yes	No
13.	Bao et al. [102]	Yes	No	Yes
14.	Curtis et al. [109]	Yes	Yes	No
15.	Bi et al. [105]	Yes	No	Yes
16.	Li et al. [112]	Yes	No	Yes
17.	Wang et al. [48]	Yes	No	Yes
18.	Boero et al. [5]	Yes	No	Yes
19.	Guo et al. [97]	Yes	No	Yes
20.	Niephaus et al. [98]	Yes	Yes	Yes
21.	Di et al. [104]	No	No	Yes
22.	Al-Najjar et al. [89]	Yes	Yes	No
23.	Hossen and Jamalipour [111]	Yes	Yes	No
24.	Giambene et al. [11]	Yes	Yes	Yes
25.	Priscoli et al. [18]	No	Yes	No
26.	Davy et al. [110]	No	Yes	No
27.	Jain and Dovrolis [87]	No	Yes	No
28.	Almadani et al. [114]	Yes	No	No
29.	Yu et al. [113]	Yes	No	No
30.	Bhardwaj and Panda [115]	Yes	No	No
31.	Koulouras et al. [116]	Yes	Yes	No

6. Global Research Gaps

Based on the literature review, the following research gaps are identified:

1. Quality of Service (QoS) Frameworks for ISTN Environments: The importance of QoS considerations in integrated ISTN has been emphasised but there is currently no standardised QoS framework tailored specifically for ISTN environments. Therefore, there is a need for a unified QoS architecture that considers ISTN-specific factors like latency, jitter, reliability, and diverse link capacities across both satellite and terrestrial networks.
2. Adaptive Traffic Engineering and Management: Mechanisms for dynamic traffic engineering that adapt in response to fluctuating network conditions owing to dynamic LEO satellite topologies are lacking. Thus, there is a need to explore joint optimal traffic distribution, routing, and load balancing across a heterogeneous ISTN link.
3. Privacy-Preserving Traffic Analysis: While techniques like Deep Packet Inspection (DPI) enable traffic identification, they pose privacy risks. Hence, an alternative AI approach needs to be explored to balance between reliable traffic classifications and user privacy protections.
4. Service Resilience and Continuity: Although studies demonstrated certain capabilities in disaster/failure scenarios, limitations persist in meeting 5G expectations for service availability. Therefore, advanced methods or policies are needed to guarantee resilient

service continuity for all applications without compromising network availability for critical and emergency use cases.

5. Efficient Resource Estimation and Management: Gaps exist in developing adaptive admission control, capacity estimation, and bandwidth management techniques specifically tailored for ISTN environments. Existing link measurement and modelling techniques in both wireless and wired environments need to be studied and adapted toward satellite channels.
6. Energy Efficiency and Management: One of the many critical areas considered by standard organisations in the energy saving (ES) capability of a network. While the use of SDN/NFV technologies has helped in conserving energy for network infrastructure, there is need for more techniques to be investigated for an ISTN system.

7. Future Trends and Applications

In this section, we look into future trends and applications. Currently, there is a gradual transition from 5G systems to 6G systems, with various research activities underway across different application areas. The deployment of reliable SDN-ISTN real-time traffic steering presents promising technologies for 5G and beyond networks. These technologies include radio access networks (RAN) intelligent controllers (RIC) for cell-free massive MIMO (CF-mMIMO), reconfigurable intelligent surfaces (RIS), also known as intelligent reflecting surfaces (RIS), fluid antenna systems (FAS) [117,118], and numerous others. While massive MIMO will continue to find applications in current and future generation networks, especially at the service provider end, the new FAS paradigm will significantly advance future communications at the mobile end, such as User Equipment (UE) [117]. FAS represents an innovative approach with software-controlled fluidic conductive structures, encompassing movable mechanical antenna structures or adaptable radio frequency (RF) pixels capable of altering their shape and position [118]. This dynamic capability allows for the reconfiguration of operating frequency, gain, radiation pattern, and various other characteristics. Through near-continuous repositioning within a pre-defined area, the antenna can effectively adapt to optimal channel conditions. This adaptability enables FAS to leverage spatial diversity, capitalising on fading opportunities to mitigate interference in multiuser communications [118]. Based on this, FAS can implement a single antenna to access different radio access technologies (RATs) [113].

Future research holds the potential to investigate how FAS can leverage its dynamic and adaptable characteristics to connect with both terrestrial access points of 5G/6G networks and satellite access points, particularly for optimising traffic flow. Through this exploration, FAS can be dynamically configured to prioritise traffic based on specific needs such as bandwidth demands, latency constraints, and user locations, ensuring effective utilisation of resources across both satellite and terrestrial networks. Cell-free massive MIMO is another interesting area that future networks can benefit from [119,120]. Rather than having cell- or boundary-oriented networks, a UE can associate with one or more base stations or access points (AP) based on various network conditions like Reference Signal Received Power (RSRP) and the QoS offerings of surrounding base stations, eliminating cell-edge or inter-cell interference [121]. While cell-free massive MIMO is a distributed network of terrestrial access points (AP), future research can delve into incorporating satellites as part of the network to achieve omnipresent network service. With the aid of RIC, CF-mMIMO can be coordinated. RIC is an SDN-aided RAN control where RAN operation/activities are made open, programmable, and flexible. Through the O-RAN alliance, the RAN, which has been a monolithic entity, can now be disaggregated, and different RAN components from different vendors can interoperate [122,123]. The RIC can aid in bringing various RATs under common control and aid traffic steering between heterogeneous APs, which can include 5G/6G cell-free MIMO APs, Wi-Fi, and even satellites. Another interesting area is the Metasurface antenna for 5G/6G minimization of cross-polarization and ensures stable radiation patterns [124,125].

8. Lessons Learned

Having deliberated on various technologies aiding the integration of satellites with next-generation SDNs, the following key takeaways are highlighted:

1. Resilience and Continuity: The investigation underscored the significance of guaranteeing service resilience and continuity within integrated networks, especially during disaster or failure scenarios. Advanced methodologies and policies are imperative to ensure resilient service continuity for all applications without compromising network availability for critical and emergency use cases. Techniques such as network redundancy, fast failover mechanisms, and dynamic rerouting can enhance resilience by ensuring that services remain available even in the event of network failures or disruptions. Continuity measures may include seamless handover mechanisms, session persistence, and backup communication paths to maintain connectivity and service availability during transitions or outages.
2. Efficient Resource Management: The document identified gaps in the development of adaptive admission control, capacity estimation, and bandwidth management techniques tailored for integrated satellite–terrestrial networks. Efficient resource estimation and management are crucial for optimising network performance and ensuring seamless connectivity. Techniques such as dynamic spectrum allocation, load balancing, and traffic prioritisation can optimise resource usage and improve network efficiency. Adaptive algorithms that monitor network conditions in real-time and adjust resource allocation dynamically can address fluctuations in demand and maximise resource utilisation.
3. Integration Challenges: Addressing technical challenges in designing and optimising network architectures that seamlessly integrate satellite and terrestrial components is essential. The joint exploitation of multiple paths and the utilisation of network coding techniques can enhance the performance of integrated systems. Challenges may include synchronisation issues, protocol interoperability, and coordination between satellite and terrestrial networks. Hybrid routing protocols, cross-layer optimisation techniques, and protocol translation mechanisms can help overcome integration challenges and improve system performance.
4. Mobility and Edge Computing: Seamless mobility support and leveraging edge computing capabilities are critical for enabling low-latency and high-bandwidth applications in integrated networks. Offloading computing tasks to the edge can reduce latency and enhance the overall user experience. Mobility management protocols, such as Mobile IP and Proxy Mobile IPv6, facilitate seamless handovers between different access technologies and network domains. Edge computing platforms, such as cloudlet and fog computing, bring computing resources closer to the users, enabling faster processing and response times for latency-sensitive applications.
5. Quality of Service Considerations: Real-time link assessment based on Quality of Service (QoS) metrics is essential for ensuring efficient and reliable communication in integrated networks. Traffic steering and switching within the user-plane connectivity model play a crucial role in selecting optimal Access Nodes (ANs) based on dynamic network conditions and application QoS requirements. QoS-aware routing protocols, admission control mechanisms, and traffic shaping algorithms ensure that network resources are allocated efficiently to meet application-specific QoS requirements. Techniques such as traffic prioritisation, packet scheduling, and Quality of Experience (QoE) monitoring enhance user satisfaction and improve overall network performance.

9. Conclusions

This paper discussed the integration of satellite and terrestrial networks, highlighting the potential for expanded coverage and improved reliability in the context of 5G and beyond. The synergy between these domains, though promising, demands solutions to challenges such as interoperability, seamless handovers, optimal resource allocation, and end-to-end Quality of Service (QoS) provisioning. We showed new innovations in Software-Defined Networking, network function virtualisation, and intelligent traffic engineering and how the above issues can be addressed. The use of machine learning has been identified to support network automation and management while enhancing mobility and traffic complexities. Open research problems were identified, including developing common control and management planes for heterogeneous components and investigating optimal network slicing across multi-domain topologies. We highlighted key directions for future research, emphasising standardised interfaces, PL, AI-driven autonomous optimisation, joint load balancing, seamless mobility, and verifiable QoS enforcement. Our conclusion is that addressing these challenges through cross-layer approaches will bring in the next-generation of intelligent integrated networks, transforming global communications' connectivity and accessibility as envisioned in the 5G/6G era and beyond.

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