VIEWS & COMMENTS

Key technologies for networking in satellite-terrestrial integrated network

1. Introduction

As a key development of the next-generation spatial information infrastructure,[1] the Satellite-Terrestrial Integrated Network (STIN) has become a strategic priority actively pursued by major spacefaring nations and regions, including the United States, Europe, China, and Russia. Specifically, SpaceX's Starlink project has deployed over 6 750 satellites,[2] while OneWeb has completed its initial phase of satellite constellation deployment with more than 600 satellites.[3] With a strategic vision, China has incorporated the space internet into the national key research and development focus for "new infrastructure construction".[4] Notably, the 14th Five-Year National Informatization Plan explicitly mandated accelerating the integration and innovation of satellite communication networks with terrestrial 5G networks. The breakthrough and strategic deployment of networking technologies for STIN constitute a critical foundation for achieving global leadership in the digital economy. Furthermore, it demonstrates significant value in maintaining territorial integrity in physical airspaces and defending sovereign rights within virtual network environments. However, the existing STIN networking technology is still limited by integrating heterogeneous networks. At the same time, the lightweight protocols must be optimized to adapt to resource constraints. At the resource coordination level, conflicts between spectrum dynamic sharing and cross-domain interference suppression must be resolved, as must the scheduling of multi-domain resources globally under highly dynamic topologies.

2. Key challenges of networking in STIN

Recently, the 3rd Generation Partnership Project (3GPP) R18 has focused on dynamic satellite backhaul, on-board edge computing, and local data exchange technology, and supports UPF on-board deployment to realize satellite edge computing. Based on further improvement of satellite network coverage, capacity, and energy consumption, it also researches new application scenarios such as artificial intelligence, drones,

and mobile Integrated Access Backhaul (IAB). The STIN's networking continues to face several challenges, including protocol architecture disparities, resource allocation constraints, orbital dynamics management, and service demand volatility. Due to the interaction of these diverse factors, the following major technical challenges must be addressed.

2.1. Protocol integration challenges in STIN architectures

The STIN system comprises multi-orbit satellites, terrestrial base stations, High-Altitude Platforms (HAPs), and other multi-source heterogeneous nodes. This architectural heterogeneity poses significant standardization challenges. Current implementations predominantly employ proprietary protocols that exhibit fundamental incompatibility with 3GPP's Non-Terrestrial Network (NTN) protocols. While 3GPP Release 17 has defined protocol frameworks for transparent payload architectures,[5] significant gaps persist in standardizing regenerative payload systems. This standardization delay primarily stems from the complex tradeoffs required among technical feasibility, economic viability, and regulatory compliance during NTN specification development.

2.2. Function and protocol lightweight challenges on satellite

The lightweight functions and protocols on the satellite have emerged as a cornerstone technology for STIN, enabling optimized resource utilization and enhanced dynamic adaptability. However, this technology still faces three primary challenges: resource constraints, security vulnerabilities, and reliability concerns. The first challenge stems from severe satellite resource limitations. Current spacecrafts have significantly lower processing power and storage capacity than terrestrial systems. It highlights the gap between finite orbital resources and the growing demand for high-performance computing. The second challenge involves security-reliability tradeoffs in protocol design. Simplified protocols may compromise encryption robustness. Meanwhile, the satellite environment presents unique challenges, such as extended maintenance cycles for orbital assets and performance degradation under extreme thermal vacuum conditions. These collectively necessitate the

protocols with intrinsic fault tolerance and adaptive error correction.

2.3. Spectrum coordination challenges in STIN

As the critical enabler for seamless STIN coverage, frequency coordination technology faces spectrum scarcity in Low Earth Orbit (LEO) user links and the need for global dynamic adaptation challenges.[6] Furthermore, based on the "first come, first served" principle, the current International Telecommunication Union (ITU) framework lacks in-orbit verification mechanisms, enabling undeployed constellations to claim orbital slots and frequency resources strategically. The disparities in national spectrum policies also amplify the challenges of coordination.

2.4. Interference challenges of STIN

The spatial–temporal coupling effect of satellite-spectrum resources, triggered by high-speed satellites and the complex physical field distortion of trans-orbit signal propagation, presents substantial challenges for interference mitigation in STIN.

The high-speed LEO satellites cause the insufficiency of inter-satellite safety distance and the spatial–temporal dynamics of spectrum interference. The conventional static interference coordination mechanisms exhibit limited adaptability to dynamic interference scenarios. Furthermore, cross-orbit signal coupling between High Earth Orbit (HEO) and LEO satellites induces nonlinear propagation path distortions. Existing interference prediction models, based on static environmental assumptions, face inherent limitations in accurate predictions.

2.5. Mobility management and cross-domain resource management challenges

The satellite's periodic motion, non-spatial and temporal uniform distribution of user services, and heterogeneity of satellite-terrestrial resources result in distributed and time-varying network resources. Current frequency offset compensation mechanisms and time domain synchronization techniques are difficult to adapt to satellite communication scenarios. Firstly, the frequency bias caused by satellite high-velocity dynamics far exceeds the correction capability of traditional terminals. Secondly, the substantial disparity in signaling latency between satellite-terrestrial links and terrestrial connections creates an insurmountable challenge for precise time–frequency synchronization acquisition. These will lead to inefficient multi-mode access handover, delayed network topology maintenance, and compromised end-to-end Quality of Service (QoS) guarantees, and fundamentally restrict the resource management algorithms' effectiveness.

3. Key technologies to address the challenges

As illustrated in Fig. 1, the key networking technology architecture is divided into 3 parts. First, architectural convergence is realized at bottom layer. The ground infrastructure includes Base Station (BS), core network equipment, ground relay station, ground gateway, edge node, and mobile terminal. Cen-
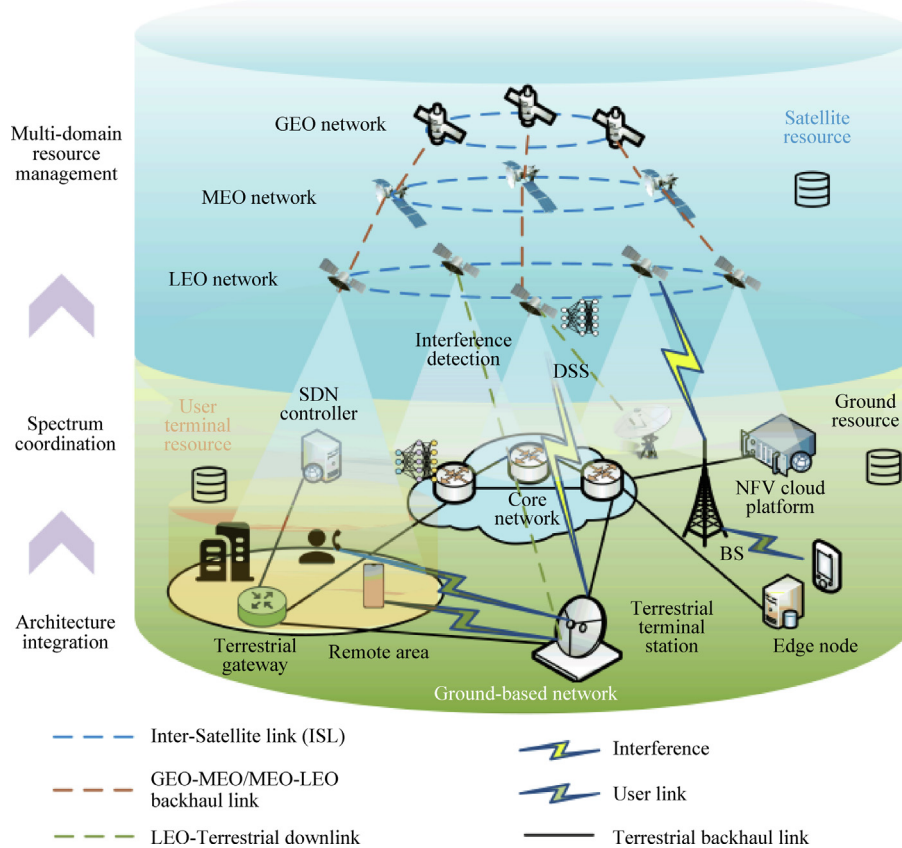

Fig. 1 Networking framework in STIN.

tralized and dynamic control of network traffic is achieved through Software Defined Network (SDN). Network Function Virtualization (NFV) is adopted to reduce satellite payload hardware dependency and support on-board edge computing and on-demand service deployment. Second, Dynamic Spectrum Access (DSA) is used to allocate spectrum promptly to improve utilization. Interference detection uses machine learning to monitor interference and schedule resource allocation. Finally, user terminal, ground, and satellite resources are integrated through a multi-domain resource pool for unified scheduling.

3.1. Heterogeneous integration of the satellite-terrestrial network

Heterogeneous integration, as the core technology paradigm of STIN, effectively addresses the inherent contradiction between dynamic space-based networks and statically deployed terrestrial infrastructures by establishing standardized protocols and hierarchical topological structures.[7] This study suggests a three-level architecture framework that includes a Geostationary Earth Orbit (GEO)-based core layer, a Medium Earth Orbit (MEO) integration layer, and a LEO access layer to address the challenges related to compatible protocols and lightweight satellite systems.

It supports transparent forwarding and on-planet regeneration operational modes, specified in 3GPP NTN R16. These modes can be dynamically switched through SDN, enabling adaptive resource allocation in response to service demands immediately.

First, this architecture incorporates the air interface protocol adaptation scheme from 3GPP Release 17 to accommodate distinctive propagation delays and significant Doppler shifts. Second, machine-learning-driven trajectory prediction algorithms and lightweight protocols are employed to reduce delay and co-frequency interference between satellites and terrestrial systems.

3.2. Resilient spectrum coordination for STIN

This study proposes a dynamic spectrum coordination optimization to address the spectrum coordination challenges in STIN, based on cross-domain cognition, dynamic gaming, and interference suppression. It aims to break the spatial and temporal asymmetry of satellite-terrestrial spectrum management through the hybrid architecture of centralized global optimization and distributed dynamic adjustment. The real-time seizure of spectrum cavities can be realized by adopting cognitive radio technology based on DSS to overcome the frequency band overlap and the significant rain fade effect of high-frequency band signals.

Facing the interference challenges, superframe scheduling in the temporal domain, sparse separation in the transform domain, and beam null steering in the spatial domain are constructed to form a multi-dimensional interference suppression system. This system provides an elastic spectrum supply for the STIN and accomplishes the double leap of spectrum reuse efficiency and interference suppression capability.

3.3. Multi-domain efficient resource management of STIN

The STIN multi-domain resource management technology creates a ubiquitous resource pool of the ground station and the orbiting satellite load by establishing a multi-domain coupling joint optimization model across space, time, frequency, energy, and orbit.[8]

First, the high-dimensional state space created by combining interstellar link status, satellite orbit dynamics parameters, and service requirements establishes the ubiquitous resources characterization model. Second, an artificial intelligence-driven dynamic resource scheduling mechanism has been developed to achieve multi-objective optimization of interstellar link configuration, multi-beam dynamic switching, and computational task offloading. To address the energy efficiency bottleneck of compute-intensive tasks, the lightweight machine learning models' edge computing offloading strategy is adopted to reduce the computational power consumption and communication overhead. To address QoS guarantees in dynamic topologies, a pre-switching mechanism using guide frequency signal strength is implemented. The target satellite negotiates resource reservations with neighboring satellites, allowing users to trigger conflict-free switching based on signal strength thresholds. It utilizes ephemeris-driven trajectory prediction and mobility-aware resource reservation, based on a predictive switching control framework of deep reinforcement learning, to meet the demand for resource utilization and QoS enhancement under highly dynamic service loads in STINs.

4. Prospects

The breakthroughs in STIN's key technologies will promote the satellite-terrestrial communication paradigm from situational complementarity to intelligent integration. As 6G and satellite-terrestrial technology are deeply integrated, the STIN will evolve into a new paradigm of global digital infrastructure.

CRediT authorship contribution statement

Haijun ZHANG: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Sichen LU:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Xiaoqi ZHANG:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Haijun ZHANG [a,b,*]
Sichen LU [a,b]
Xiaoqi ZHANG [a,b]

[a] *Hebei Key Laboratory of Space-Air-Ground Intelligent Communication, University of Science and Technology Beijing, Beijing 100083, China*

[b] *Beijing Engineering and Technology Research Center for Convergence Networks and Ubiquitous Services, University of Science and Technology Beijing, Beijing 100083, China*

* Corresponding author.

E-mail address: zhanghaijun@ustb.edu.cn (H. ZHANG).