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Research Article

Software-Defined Networking (SDN) in Satellite-Terrestrial Mobile Communication Integration

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ABSTRACT

The rise of 5G networks demands advanced solutions to provide seamless connectivity, even in remote or underserved areas. Integrating Software-Defined Networking (SDN) into hybrid satellite-terrestrial networks creates a programmable, centralized architecture capable of dynamically allocating resources and reducing latency. This paper examines the application of SDN in satellite-terrestrial systems, focusing on mobility management, network slicing and dynamic resource optimization. Finally, we propose future directions such as the role of AI-based SDN orchestration and edge computing in minimizing delays across networks with multiple orbits.

This paper proposes a novel SDN-based orchestration framework, enhanced with AI-driven predictive analytics, to optimize resource allocation across hybrid satellite-terrestrial networks. Additionally, it introduces an adaptive mobility management mechanism to reduce latency and improve handover performance in dynamic network environments.

Keywords: Software-Defined Networking (SDN), Satellite Networks, 5G, Network Slicing, Mobility Management in SDN orchestration Layer

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1. Introduction

5G networks extend beyond terrestrial coverage, aiming for low-latency connectivity in environments where traditional network infrastructure cannot reach. Non-terrestrial networks (NTNs)- including low-earth orbit (LEO) and medium-earth orbit (MEO) satellite constellations-serve as essential components to close these gaps. Integrating these satellite systems with terrestrial networks, however, presents several challenges such as latency, frequent handovers and efficient bandwidth management. Software-Defined Networking (SDN) addresses these challenges by decoupling the control plane from the data plane, enabling control over resource management[1].

SDN provides programmability and centralized network visibility, which are crucial for adapting routing policies dynamically between terrestrial and non-terrestrial components. The potential for SDN to operate in tandem with network slicing is particularly transformative in enabling Quality of Service (QoS) differentiation across both terrestrial and satellite segments.

The paper is structured as follows: Section II discusses traditional hybrid satellite-terrestrial communication, highlighting its challenges. Section III presents SDN architecture for integrated networks. Section IV introduces the orchestration layer framework, while Section V focuses on mobility management and latency optimization[2,3].

2. Traditional Hybrid Satellite and Terrestial Communication

Hybrid satellite-terrestrial communication systems integrate satellite and terrestrial networks to provide ubiquitous coverage, especially in remote areas where terrestrial infrastructure is limited. Satellite links, including Low Earth Orbit (LEO), Medium Earth Orbit (MEO) and Geostationary Earth Orbit (GEO) systems, connect underserved regions via radio transmissions to ground stations, which interface with the broader internet through terrestrial fiber or microwave backhaul[4,5].

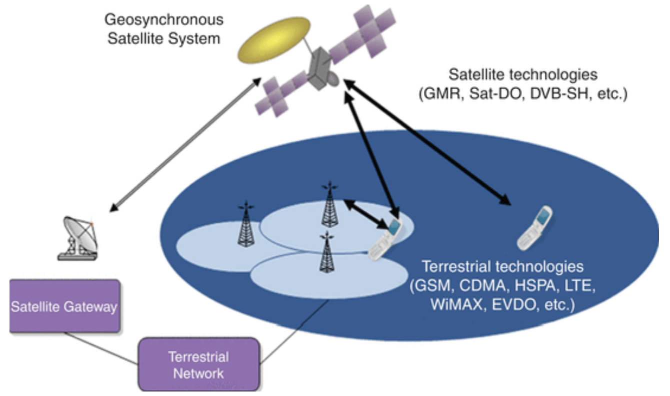


Figure 1: Traditional Hybrid Satellite Terrestrial Network[10].

A. Latency Challenges

Traditional hybrid systems encounter high latency due to the physical distance between satellites and ground stations, particularly in GEO networks, where round-trip delays can reach 600 ms. LEO constellations mitigate latency but introduce challenges with frequent handovers between satellites as they move rapidly across the sky. These latencies affect real-time applications, such as video calls or IoT services, where even minimal delays can degrade Quality of Service (QoS).

B. Inefficient Handovers

Seamless handovers between satellites and terrestrial stations are often inefficient, resulting in service disruptions. These issues arise from the static nature of traditional routing protocols, which cannot adapt quickly to changing network conditions. Without intelligent control, users moving across satellite beams or switching between terrestrial and non-terrestrial segments experience dropped connections or degraded performance.

C. QoS Constraints

Conventional systems struggle to maintain consistent QoS across both satellite and terrestrial segments, as routing paths are typically predefined. This leads to suboptimal bandwidth usage, congestion and reduced service reliability in dynamic environments.

D. SDN as a Solution

Software-Defined Networking (SDN) addresses these challenges by providing a centralized control plane that decouples network control from data forwarding. SDN enables real-time traffic management and dynamic resource allocation, ensuring optimal latency, seamless handovers and enhanced QoS across hybrid networks. For instance, when a satellite handover is imminent, the SDN controller can pre-emptively route traffic to a different satellite or terrestrial path, avoiding service disruptions.

This paper proposes a SDN-based orchestration framework with AI-driven predictive analytics for resource management and mobility. These contributions aim to overcome the limitations of traditional hybrid systems by dynamically adjusting routing paths and optimizing handover processes.

3. SDN Architecture

Software-Defined Networking (SDN) enables dynamic, scalable and programmable control of networks by separating the control plane from the data plane. This decoupling allows for centralized network management and dynamic configuration, which is essential for hybrid satellite-terrestrial communication systems.

This enables network controllers to make global routing decisions and reconfigure data paths in real time without manual intervention. SDN controllers interact with both satellite and terrestrial networks through Control Logic, N**orthbound APIs (NBI)** and **Southbound APIs (SBI)**.

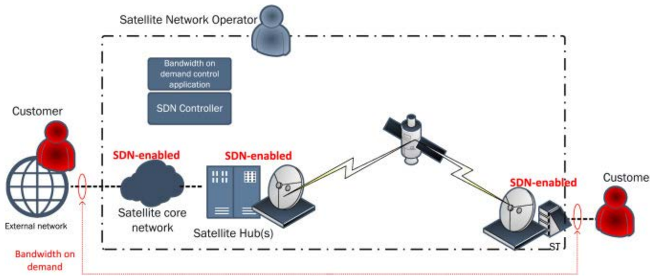


Figure 2: SDN based Hybrid Satellite Terrestrial Network Architecture[9].

The SDN controller acts as the brain of the network, using protocols such as OpenFlow to manage forwarding tables across satellite ground stations, terrestrial base stations and gateways[8].

A. Control Logic

The control plane in SDN architecture serves as the brain of the network. It makes routing decisions and manages traffic flows based on real-time conditions.

Controllers in this plane communicate with the underlying infrastructure through the Southbound Interface (SBI), ensuring the continuous adaptation of the data plane. This design enables programmable network management, facilitating seamless handovers and traffic optimization across hybrid systems.

B. Southbound Interfaces (SBIs)

The SBI is responsible for transmitting instructions from the control plane to the network devices in the data plane. It uses protocols such as **OpenFlow**, NETCONF or gNMI to configure routers, switches and satellite gateways. The flexibility provided by the SBI ensures efficient resource allocation, particularly during satellite handovers, which often demand rapid adaptation to changing network topologies.

Protocols

- **OpenFlow:** The most widely used SBI protocol for configuring switches and routers.
- **NETCONF/YANG:** Used to manage the configuration and state of devices.
- **BGP-LS (Border Gateway Protocol Link State):** For satellite-ground station routing.

C. Northbound APIs (NBIs):

The NBI connects the SDN controller to **external applications and orchestration frameworks**, such as AI modules or QoS management platforms. It allows the control logic to interact with higher-level services by exposing APIs. This interaction provides **end-to-end visibility** of network resources and predictive traffic management, ensuring optimized performance for latency-sensitive applications.

The NBI allows external applications (such as AI-based network monitoring systems, load balancers or network slicing orchestration platforms) to communicate with the SDN controller.

In satellite-terrestrial networks, this could involve predictive models to anticipate beam switching or disruptions due to weather conditions, allowing the controller to adjust routing dynamically.

Protocols: RESTful APIs, gRPC.

Example: An AI system sends requests via the NBI to predict congestion in satellite links and redirects traffic accordingly.

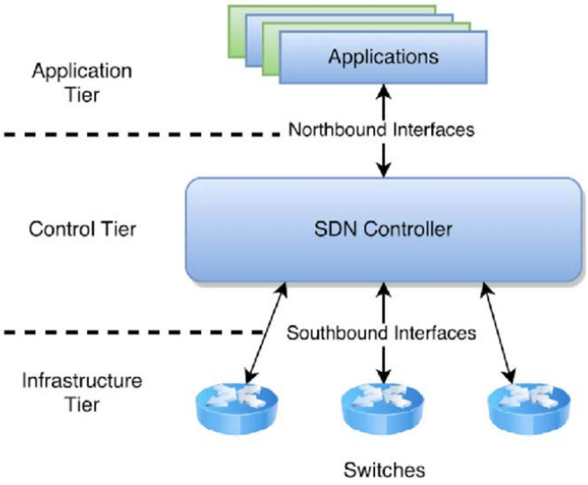


Figure 3: SDN Controller Architecture[8].

D. AI-Enhanced Orchestration

The integration of **AI-powered algorithms** with SDN provides predictive insights for network traffic and resource management. AI models deployed at the orchestration layer predict satellite handovers and proactively adjust routing paths, avoiding disruptions. Furthermore, the orchestration framework dynamically reallocates bandwidth to meet varying QoS demands across hybrid networks[3,7,8].

The integration of **AI-powered algorithms** within SDN-based orchestration provides advanced predictive insights and adaptive resource management. Several AI techniques can address key network challenges:

1. Predictive Modeling for Satellite Handovers:

- Recurrent Neural Networks (RNNs) or Long Short-Term Memory (LSTM) models can predict satellite movement and anticipate handover events, ensuring smooth transitions without service interruptions.

2. Traffic Forecasting and Dynamic Routing:

- Time Series Models (like ARIMA) and Graph Neural Networks (GNNs) can analyze network traffic patterns, enabling dynamic routing adjustments to avoid congestion across both terrestrial and satellite links.
- Reinforcement Learning (RL) algorithms can adapt routing policies based on real-time network conditions, optimizing path selection for latency-sensitive applications.

3. Bandwidth Allocation with QoS Guarantees:

- Deep Q-Networks (DQNs) or Multi-Agent Reinforcement Learning (MARL) models can dynamically reallocate bandwidth to meet changing Quality of Service (QoS) demands across hybrid networks, improving throughput and resource efficiency.

4. Anomaly Detection and Fault Management:

- Autoencoders and Generative Adversarial Networks (GANs) can detect anomalies or potential failures in the network by learning baseline behaviors and identifying deviations in traffic or device performance.

E. Benefits of SDN in Hybrid Systems

- **Dynamic Resource Allocation:** Real-time adjustments to network resources improve efficiency and reduce latency.
- **Seamless Handovers:** SDN minimizes service disruptions by pre-emptively managing satellite and terrestrial transitions.
- **Improved QoS:** SDN ensures consistent quality across the network by balancing loads and rerouting traffic.

4. SDN Based Orchestration Framework

The orchestration layer sits above the individual SDN controllers in the network hierarchy. It acts as a global decision-making entity that coordinates multiple controllers operating across different domains, such as terrestrial networks, satellite constellations and cloud infrastructure. It ensures end-to-end service delivery by providing cross-domain visibility, dynamic resource allocation and policy enforcement[8].

Key components of the orchestration layer include:

- **Network Function Virtualization (NFV):** This technology enables the decoupling of network functions from hardware, allowing for greater flexibility and scalability in deploying network services[9].
- **Software-Defined Networking (SDN):** SDN provides a centralized control mechanism that enhances network management and enables real-time adjustments to network configurations based on current conditions[9].
- **AI-Enhanced Orchestration:** The incorporation of AI algorithms facilitates advanced predictive insights and adaptive resource management. Key algorithms include:
- **Reinforcement Learning (RL):** Optimizes routing decisions and resource allocation through real-time learning from network performance feedback.
- **Supervised Learning Models:** Utilizes Support Vector Machines (SVM) and Random Forest for traffic pattern forecasting and anomaly detection based on historical data.
- **Unsupervised Learning:** Employs clustering algorithms like K-Means and DBSCAN to identify anomaly prone behavior in network traffic.
- **Neural Networks:** Uses Long Short-Term Memory (LSTM) networks for accurate time series forecasting of network traffic and user demand.
- **Genetic Algorithms (GAs):** Optimizes configuration parameters of network functions to enhance overall performance while maintaining QoS.

In addition, the orchestration layer should support interoperability among different technologies and protocols to ensure cohesive operation across the network. The architecture must be designed to accommodate various interfaces and standard protocols, facilitating effective communication between terrestrial and satellite segments.

The orchestration framework's ability to balance flexibility and efficiency is crucial. It must dynamically adapt to varying demands, leveraging AI for real-time decision-making and resource allocation while maintaining optimal performance and service continuity.

5. Mobility Management and Dynamic Control in Hybrid Satellite-Terrestrial Networks

The integration of satellite and terrestrial networks necessitates sophisticated mobility management to ensure seamless service continuity, particularly as users transition between different connectivity options. The orchestration layer, empowered by Software-Defined Networking (SDN), plays a pivotal role in facilitating this process through advanced management techniques[5,7].

A. Predictive Handover Algorithms

The orchestration layer employs **predictive handover algorithms** to anticipate the need for handovers between satellite beams or from satellites to terrestrial base stations. By utilizing predictive models that analyze user mobility patterns, the orchestration layer can determine optimal timing for handovers.

Make-Before-Break Handover: This technique establishes a new connection before severing the old one, minimizing packet loss and jitter during transitions.The optimal handover timing T_h can be modeled as

$$T_h = f(P_{mobility}, T_{signal\_strength}, D_{handover\_distance})$$

where:

$P_{mobility}$ represents the user mobility pattern,

$T_{signal\_strength}$ is the signal strength of the current connection,

$D_{handover}$ is the distance to the next access point.

B. Dynamic Routing and Path Optimization

SDN controllers use multi-hop routing algorithms to forward traffic efficiently between satellites, terrestrial stations and core networks.

For example, in case of congestion in one LEO satellite link, the SDN controller can switch traffic dynamically to a terrestrial fiber route or a backup satellite (MEO or GEO) path.

Routing Objective: Minimize total latency (L) across multiple links.

$$L_{\text{total}} = \sum_{i=1}^{n} \left(L_{\text{satellite}_i} + L_{\text{terrestrial}}\right)$$

The controller selects the route with the smallest L_{total} using **shortest-path algorithms** (e.g., Bellman-Ford).

C. Latency Optimization

In hybrid networks, **latency is a critical factor**, particularly for applications demanding low response times. Low Earth Orbit (LEO) satellite networks, provide round-trip times of approximately **20-40 ms**

$$L = L_{LEO} + L_{processing} + L_{transmission}$$

where:

L_{LEO} is the inherent latency of the LEO satellite,

$L_{processing}$ represents the processing delay at the ground station,

$L_{transmission}$ is the transmission delay over terrestrial links.

The orchestration layer dynamically routes latency-sensitive applications through LEO satellites while directing less time-sensitive data through Medium Earth Orbit (MEO) satellites.

D. Seamless Handover Management

In LEO satellite networks, satellites frequently move out of the communication window. The SDN controller facilitates make-before-break handovers to establish new links before old ones are disrupted.

Predictive handover is usually used where the controller uses Kalman filters to predict the precise moment a satellite will move out of range, triggering a seamless transition to the next satellite.

The handover delay must be less than the transmission time of an active data packet to avoid packet loss.

E. Load Balancing and Congestion Control

SDN controllers use **traffic engineering algorithms** to distribute loads evenly across satellite and terrestrial links.

In a scenario where multiple satellites serve the same ground station, the controller applies **Equal-Cost Multi-Path (ECMP)** routing to balance traffic.

For example: 50% of the traffic is routed through **Satellite A (LEO)** and the rest through **Fiber Link B**, ensuring optimal performance and avoiding congestion.

$$w_i = \frac{1}{n} \text{ for } i = 1, 2, \ldots, n$$

where w_i is the weight of traffic assigned to each path and n is the total number of available paths.

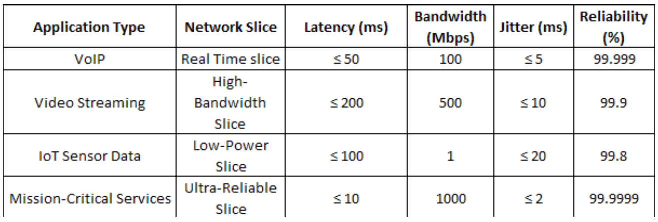
F. QoS and Network Slicing

The SDN controller ensures that each flow in the network receives the required Quality of Service (QoS). For hybrid networks, the controller configures end-to-end slices that extend across both terrestrial and satellite domains, continuously monitoring performance metrics and reallocating resources dynamically if performance degrades.

6. Network Slicing Across Satellite and Terrestrial Networks

As telecommunications evolve, the integration of satellite and terrestrial networks through network slicing becomes imperative. This approach facilitates customized network resources tailored to diverse applications, enhancing service quality, flexibility and operational efficiency[2,6].

Table 1: Network slice depending on applications



Application Type	Network Slice	Latency (ms)	Bandwidth (Mbps)	Jitter (ms)	Reliability (%)
VoIP	Real Time slice	≤ 50	100	≤ 5	99.999
Video Streaming	High-Bandwidth Slice	≤ 200	500	≤ 10	99.9
IoT Sensor Data	Low-Power Slice	≤ 100	1	≤ 20	99.8
Mission-Critical Services	Ultra-Reliable Slice	≤ 10	1000	≤ 2	99.9999

A. Slice Orchestration

Slice orchestration involves the coordination and management of multiple network slices, ensuring that they operate efficiently across different network domains.

Key considerations:

- **Cross-Domain Management:** Orchestration must manage the unique characteristics of satellite and terrestrial networks, addressing latency, bandwidth and propagation delays specific to each type.
- **Resource Allocation:** Dynamic allocation of resources among slices is essential to optimize performance. Orchestration algorithms should consider real-time data on network conditions and user demands to adjust resources dynamically.
- **Policy Enforcement:** Establishing policies that govern resource allocation, service-level agreements (SLAs) and quality of service (QoS) metrics ensures that each slice adheres to its defined requirements, regardless of underlying network differences.

B. Performance Differentiation

Performance differentiation allows for tailored Quality of Service (QoS) metrics across various applications and user requirements. This involves:

- **Service-Level Agreements (SLAs):** Defining specific performance metrics (e.g., latency, throughput, jitter) for each slice based on its application needs. For example, low latency is critical for real-time applications like VoIP, while high bandwidth may be prioritized for video streaming.
- **Resource Prioritization:** Employing algorithms that dynamically prioritize resources based on application criticality. For instance, mission-critical applications might receive guaranteed bandwidth, while less critical services could be deprioritized during congestion.
- **Monitoring and Feedback Loops:** Implementing monitoring tools to continuously assess the performance of each slice and utilizing feedback loops for adaptive adjustments in resource allocation, ensuring optimal performance based on real-time conditions.

C. Dynamic Slice Reallocation

Dynamic slice reallocation enables the adjustment of resources among slices based on changing network conditions and user requirements.

- **Real-Time Analytics:** Utilizing AI-powered analytics to monitor traffic patterns and resource utilization across slices, allowing for timely reallocation of resources in response to demand fluctuations.
- **Load Balancing:** Implementing algorithms that ensure an even distribution of traffic across slices, preventing bottlenecks and improving overall network performance. This may involve redirecting traffic from overloaded slices to those with available capacity.
- **User-Centric Approaches:** Ensuring that reallocations consider individual user needs and experiences, adjusting resources based on user location, device type and application requirements to enhance overall user satisfaction.

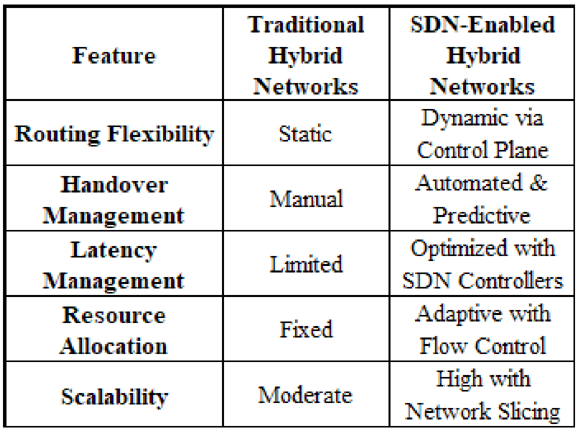
This structured approach to **network slicing** across satellite and terrestrial networks underscores its critical role in optimizing network performance, meeting diverse user needs and facilitating seamless integration between different network types.

7. Comparative Analysis: SDN vs. Traditional Hybrid Networks

Software-Defined Networking (SDN) and traditional hybrid networks differ significantly in terms of architecture, flexibility and performance. SDN decouples the control plane from the data plane, offering centralized management and programmability, whereas hybrid networks rely on distributed control through static, device-specific configurations. This centralized approach in SDN allows for dynamic resource allocation, real-time traffic management and faster fault recovery, making it ideal for cloud-native applications and environments with rapidly changing demands. In contrast, hybrid networks, while stable and reliable for legacy operations, lack the agility required to adjust network behavior on the fly.

Another key distinction lies in scalability and operational efficiency. SDN enables automated provisioning and policy enforcement across the network from a single control point, reducing manual configurations and streamlining operations. Traditional hybrid networks, however, require more manual intervention for updates, making them more labor-intensive to manage. Furthermore, SDN improves security by allowing rapid deployment of threat mitigation strategies across the entire network, while hybrid networks, with their fragmented control, can face challenges in maintaining consistent security policies. Despite these limitations, hybrid networks remain relevant in cases where gradual modernization is needed, especially when older systems coexist with newer technologies[8].

Table 2: Comparison of Traditional and SDN enabled Hybrid Networks.



Feature	Traditional Hybrid Networks	SDN-Enabled Hybrid Networks
Routing Flexibility	Static	Dynamic via Control Plane
Handover Management	Manual	Automated & Predictive
Latency Management	Limited	Optimized with SDN Controllers
Resource Allocation	Fixed	Adaptive with Flow Control
Scalability	Moderate	High with Network Slicing

8. Challenges and Future Directions

- **Security Vulnerabilities:** SDN's centralized architecture introduces single points of failure. Blockchain-based authentication or distributed control models can mitigate this issue.
- **Standardization Issues:** Interoperability across SDN controllers for terrestrial and satellite systems requires alignment with 3GPP and ETSI standards.
- **AI-Enhanced Orchestration:** AI models integrated into SDN controllers can predict satellite availability and optimize resource allocation, enhancing service continuity[20].

9. Conclusion

In this paper, we explored the integration of Software-Defined Networking (SDN) within hybrid satellite-terrestrial networks, emphasizing its potential to enhance network performance and efficiency. Key points discussed include:

- **SDN's Role in Mobility and Latency Management:** We highlighted how SDN can optimize mobility management and significantly reduce latency in hybrid networks. By leveraging its programmable architecture, SDN enables dynamic resource allocation and seamless handovers, which are crucial for maintaining service quality in diverse environments.
- **Integration of AI and Orchestration Frameworks:** The potential of AI-powered algorithms was underscored as a vital element in improving orchestration and resource management in these networks. AI can enhance decision-making processes, enabling real-time adaptations to network conditions and user demands, which is essential for future-proofing hybrid satellite-terrestrial systems.
- **Future Research Directions:** As the telecommunications landscape evolves, future research should focus on developing advanced algorithms for SDN and AI integration, exploring interoperability challenges and addressing security issues inherent in hybrid networks. Additionally, further investigation into the scalability of SDN solutions in various operational environments will be pivotal.

In summary, the synergistic application of SDN and AI in hybrid satellite-terrestrial networks presents a promising avenue for advancing telecommunications infrastructure, paving the way for enhanced connectivity and user experience.

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