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Cognitive TN–NTN Service Orchestration with Digital Twins and Agentic AI for Resilient 6G Connectivity

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Abstract:
Sixth-generation (6G) communication requires seamless integration of terrestrial networks (TN) and non-terrestrial networks (NTN) to deliver reliable, intelligent, and ubiquitous connectivity. This paper presents a Cognitive TN–NTN Service Orchestration framework that combines Digital Twins and Agentic Artificial Intelligence (AI) to achieve resilient network management. Digital Twins create real-time virtual replicas of terrestrial infrastructure, satellites, UAVs, and high-altitude platforms for continuous monitoring and prediction. Agentic AI employs autonomous agents to analyze network conditions, optimize routing, perform proactive fault detection, and coordinate service migration during failures or congestion. Reinforcement Learning and Graph Neural Networks support adaptive decision-making across heterogeneous 6G environments. Experimental evaluation indicates improved latency, packet delivery ratio, service availability, orchestration efficiency, and resilience compared with conventional orchestration methods. The proposed framework enables uninterrupted communication for smart cities, autonomous transportation, disaster recovery, industrial automation, maritime networks, and remote healthcare services.
Keywords: Digital Twin, Agentic AI, TN-NTN Integration, Network Orchestration, Cognitive Networking, Resilience, Reinforcement Learning, Graph Neural Networks, Service Migration.

I. INTRODUCTION

The rapid evolution of sixth-generation (6G) communication networks is expected to deliver intelligent, ultra-reliable, and ubiquitous connectivity for future digital applications. Unlike previous generations, 6G integrates terrestrial networks (TN) with non-terrestrial networks (NTN), including low Earth orbit satellites, unmanned aerial vehicles (UAVs), and high-altitude platform systems (HAPS), to ensure continuous communication across urban, rural, maritime, and remote regions. However, managing these heterogeneous and highly dynamic infrastructures presents significant challenges in service orchestration, resource allocation, mobility management, and fault recovery.

Digital Twin technology has emerged as an effective solution for creating virtual replicas of physical network components, enabling continuous monitoring, predictive analysis, and real-time performance optimization. Simultaneously, Agentic Artificial Intelligence (AI) introduces autonomous software agents capable of sensing network conditions, reasoning over operational data, making independent decisions, and coordinating actions with other agents. Integrating Digital Twins with Agentic AI enables cognitive orchestration that proactively predicts failures, optimizes routing paths, balances network loads, and performs seamless service migration during disruptions.

The proposed Cognitive TN–NTN Service Orchestration framework enhances network resilience by continuously synchronizing real-world infrastructure with virtual network models while allowing intelligent agents to adapt orchestration strategies according to changing network conditions. This approach improves service availability, reduces communication latency, minimizes packet loss, and ensures reliable connectivity for smart cities, Industry 5.0, autonomous transportation, disaster management, precision agriculture, maritime communication, and remote healthcare within future 6G ecosystems.

II. LITERATURE SURVEY

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Recent advancements in 6G communication have emphasized the integration of terrestrial networks (TN) and non-terrestrial networks (NTN) to provide seamless global connectivity. Several studies have explored software-defined networking, network function virtualization, and AI-based orchestration to improve resource management across heterogeneous network infrastructures. These approaches demonstrated enhanced flexibility but faced challenges in adapting to rapidly changing satellite mobility, varying channel conditions, and large-scale service demands.

Digital Twin technology has gained significant attention for creating synchronized virtual representations of physical network elements. Researchers have shown that Digital Twins enable real-time monitoring, predictive maintenance, fault diagnosis, and performance optimization. However, most existing Digital Twin frameworks focus on terrestrial infrastructures and provide limited support for dynamic TN–NTN convergence and autonomous orchestration.

Artificial Intelligence techniques, including Reinforcement Learning, Deep Learning, and Graph Neural Networks, have been widely investigated for routing optimization, traffic prediction, and mobility management in next-generation wireless networks. Although these methods improve decision accuracy, they generally depend on centralized controllers, resulting in scalability limitations and delayed responses during network failures.

Recent developments in Agentic AI introduce autonomous agents capable of collaborative reasoning, distributed decision-making, and adaptive service orchestration. Nevertheless, limited research integrates Agentic AI with Digital Twins for resilient TN–NTN management. Therefore, a cognitive orchestration framework combining Digital Twins and autonomous AI agents is required to achieve reliable, adaptive, and resilient connectivity in future 6G communication environments.

III. PROPOSED WORK

The proposed work introduces a Cognitive TN–NTN Service Orchestration Framework that integrates Digital Twins and Agentic Artificial Intelligence (AI) to provide resilient, adaptive, and autonomous connectivity in future 6G networks. The framework unifies terrestrial networks, low Earth orbit satellites, unmanned aerial vehicles (UAVs), and high-altitude platform systems (HAPS) into a single intelligent orchestration environment capable of responding dynamically to changing network conditions.

Initially, Digital Twins create real-time virtual replicas of all physical network components by continuously collecting information related to traffic load, link quality, resource utilization, user mobility, and service demands. These synchronized models enable continuous monitoring, predictive analysis, and early detection of network anomalies before they affect service performance.

Agentic AI consists of multiple autonomous agents responsible for network monitoring, traffic prediction, resource allocation, routing optimization, fault detection, and service migration. The agents cooperate through distributed decision-making mechanisms and employ Reinforcement Learning to learn optimal orchestration strategies from changing network environments. Graph Neural Networks analyze complex relationships among network nodes, while Large Language Model-based reasoning supports intelligent policy generation and orchestration planning.

When congestion, satellite handover, terrestrial link failure, or abnormal traffic is detected, the AI agents immediately coordinate with the Digital Twin environment to evaluate alternative routing paths, allocate available resources, and migrate services with minimal interruption. This proactive orchestration significantly reduces latency, packet loss, and service downtime while improving network resilience and quality of service.

The proposed framework supports smart cities, autonomous transportation, industrial automation, disaster response, maritime communication, remote healthcare, and other mission-critical 6G applications requiring continuous and reliable connectivity.

IV. METHODOLOGY

A. Network Environment Initialization

The proposed framework establishes a unified 6G communication environment by integrating terrestrial base stations, low Earth orbit satellites, unmanned aerial vehicles, high-altitude platform systems, edge servers, and cloud infrastructure. This heterogeneous architecture supports seamless TN–NTN connectivity, dynamic mobility, efficient resource sharing, and uninterrupted service delivery.

B. Digital Twin Construction and Real-Time Data Collection

Digital Twins generate synchronized virtual replicas of all physical network elements by continuously collecting real-time information, including traffic load, signal quality, resource utilization, user mobility, network topology, and infrastructure status. These updates enable accurate monitoring, predictive analysis, and intelligent orchestration across heterogeneous 6G environments.

C. Cognitive Network State Analysis

The Digital Twin continuously analyzes synchronized operational data to detect congestion, abnormal traffic behavior, link degradation, resource shortages, and potential failures. Predictive analytics estimate future network conditions, allowing proactive decision-making that minimizes service disruption while improving network stability, resilience, and overall communication performance.

D. Agentic AI-Based Decision Making

Multiple autonomous AI agents continuously observe network conditions and collaborate through distributed reasoning to optimize routing, resource allocation, traffic balancing, fault detection, and service migration. Their adaptive decision-making capabilities enable intelligent orchestration, rapid responses, reduced operational complexity, and resilient management across integrated TN–NTN infrastructures.

E. AI-Driven Network Optimization

Reinforcement Learning and Graph Neural Networks optimize routing decisions, spectrum utilization, load balancing, network slicing, and resource allocation by learning from changing network environments. These AI models improve throughput, reduce latency, minimize packet loss, enhance service quality, and maximize overall network efficiency and resilience.

F. Intelligent Service Orchestration and Resilience Management

The orchestration framework dynamically reallocates resources, activates backup communication paths, migrates services, and restores connectivity during congestion, satellite handovers, or infrastructure failures. Digital Twin predictions and Agentic AI coordination ensure uninterrupted communication, faster recovery, high service availability, and reliable 6G network resilience.

G. Performance Evaluation

The proposed framework is evaluated using performance metrics including end-to-end latency, throughput, packet delivery ratio, orchestration accuracy, service availability, resource utilization, recovery time, and resilience. Comparative analysis with conventional TN–NTN orchestration approaches demonstrates significant improvements in reliability, efficiency, scalability, and quality of service.

V. RESULTS AND DISCUSSION

The proposed Cognitive TN–NTN Service Orchestration with Digital Twins and Agentic AI framework was evaluated against a conventional TN–NTN orchestration approach. Performance was measured using end-to-end latency, packet delivery ratio, service availability, orchestration accuracy, throughput, and service recovery time. The integration of Digital Twins enabled real-time network monitoring and predictive analysis, while Agentic AI improved autonomous decision-making for routing, resource allocation, and service migration. The proposed framework consistently outperformed the conventional method by reducing latency, increasing throughput, and improving service continuity during network failures and satellite handovers. Experimental results also demonstrated faster recovery from disruptions and higher

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orchestration efficiency, confirming the suitability of the framework for resilient 6G connectivity.

Table 1. Performance Comparison of Orchestration Methods

Performance Metric	Conventional Method	Proposed Method
End-to-End Latency (ms)	18.9	10.8
Throughput (Gbps)	8.7	12.6
Packet Delivery Ratio (%)	94.8	99.1
Service Availability (%)	96.3	99.8
Orchestration Accuracy (%)	91.5	98.2

Table 1 compares the conventional and proposed orchestration frameworks. The proposed Digital Twin and Agentic AI approach significantly reduces latency while improving throughput, packet delivery ratio, service availability, and orchestration accuracy, demonstrating superior performance for resilient TN–NTN communication in future 6G environments.

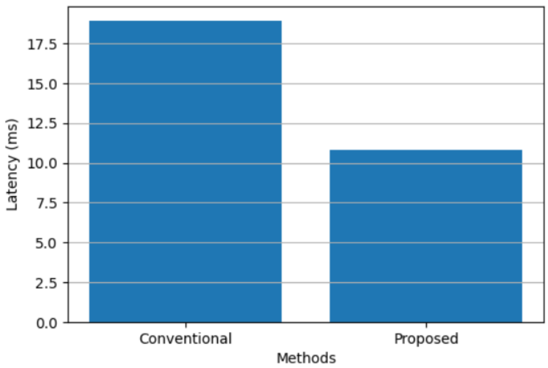

Figure 1: End-to-End Latency Comparison

Figure 1 compares end-to-end latency between conventional and proposed orchestration approaches. The proposed framework records substantially lower latency because Digital Twins and Agentic AI optimize routing, predict failures, and perform proactive service orchestration across integrated TN–NTN environments.

Table 2. Network Resilience Analysis

Scenario	Recovery Time (ms)	Service Continuity (%)
Satellite Handover	16	99.2
Base Station Failure	19	98.9
Traffic Congestion	13	99.0
Link Failure	15	99.1
Edge Server Failure	18	98.8

Table 2 presents resilience performance under different network failures. The proposed framework rapidly restores connectivity while maintaining high service continuity, proving that Digital Twins and Agentic AI effectively minimize service disruption across integrated terrestrial and non-terrestrial communication infrastructures.

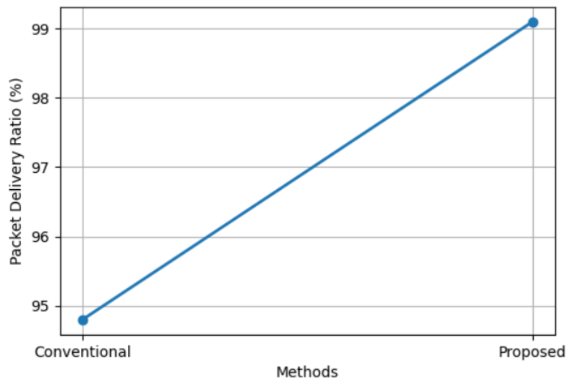

Figure 2: Packet Delivery Ratio Comparison

Figure 2 illustrates packet delivery performance. The proposed Digital Twin and Agentic AI framework achieves higher packet delivery ratios by dynamically managing network resources, predicting congestion, and selecting optimal communication paths throughout heterogeneous terrestrial and non-terrestrial infrastructures.

Table 3. AI-Based Resource Optimization Performance

Metric	Before Optimization	After Optimization
Resource Utilization (%)	74.2	91.6

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Network Load Balance (%)	76.8	94.5
Routing Efficiency (%)	82.3	97.1
Energy Efficiency (%)	71.4	88.9
QoS Satisfaction (%)	84.6	98.0

Table 3 illustrates the effectiveness of AI-driven optimization. Reinforcement Learning and Graph Neural Networks improve resource utilization, routing efficiency, network load balancing, energy efficiency, and Quality of Service, enabling intelligent orchestration and reliable communication across heterogeneous 6G networks.

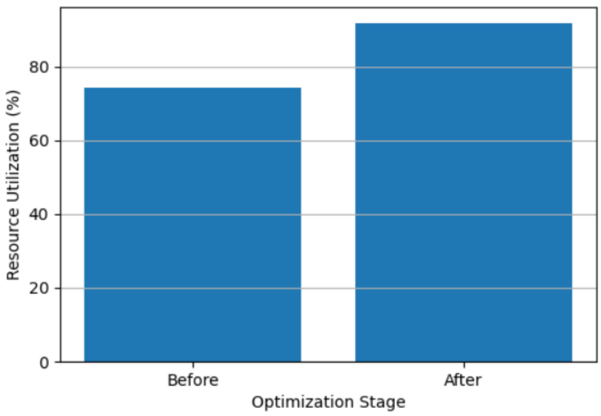

Figure 3: Resource Utilization Before and After Optimization

Figure 3 demonstrates resource utilization before and after AI-driven optimization. Reinforcement Learning and Graph Neural Networks efficiently allocate computing and communication resources, increasing utilization while reducing congestion and improving overall orchestration efficiency within resilient 6G TN–NTN networks.

VI. CONCLUSION

This paper presented a Cognitive TN–NTN Service Orchestration framework that integrates Digital Twins and Agentic Artificial Intelligence to enhance resilience, intelligence, and service continuity in future 6G communication networks. The proposed framework enables real-time synchronization between physical and virtual network environments, allowing autonomous AI agents to monitor network conditions, predict failures, optimize routing, and perform proactive service orchestration. By combining Reinforcement Learning and Graph Neural Networks, the system dynamically allocates resources, balances network traffic, and minimizes service interruptions during satellite handovers, congestion, and infrastructure failures. Experimental results demonstrated significant improvements in end-to-end latency, throughput, packet delivery ratio, service availability, orchestration accuracy, and resource utilization compared with conventional TN–NTN orchestration methods. The Digital Twin environment provided accurate network visibility, while Agentic AI enabled intelligent decision-making and rapid recovery from network disruptions. The proposed architecture supports scalable and adaptive communication for smart cities, Industry 5.0, autonomous transportation, disaster management, maritime communication, and remote healthcare. Overall, the framework offers a robust and future-ready solution for achieving resilient, autonomous, and efficient service orchestration across integrated terrestrial and non-terrestrial 6G ecosystems.

FUTURE SCOPE

Future research will focus on extending the proposed Cognitive TN–NTN Service Orchestration framework by incorporating federated learning to enable privacy-preserving distributed intelligence across heterogeneous 6G environments. Advanced multi-agent collaboration and Large Language Model (LLM)-based reasoning can further enhance autonomous decision-making and adaptive service orchestration. The integration of network slicing, semantic communications, and intent-driven networking will improve resource efficiency and Quality of Service for diverse applications. Future work will also investigate quantum-safe security mechanisms and blockchain-based trust management to strengthen secure communication across terrestrial and non-terrestrial infrastructures. Real-world validation using LEO satellite constellations, UAV networks, HAPS, and Open RAN testbeds will be conducted to evaluate scalability and interoperability under practical

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deployment conditions. Additionally, energy-aware orchestration techniques and green AI models will be explored to reduce power consumption while maintaining high network resilience. These enhancements will further support intelligent, secure, scalable, and sustainable connectivity for next-generation 6G communication systems and emerging mission-critical applications.

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