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Research Paper

Real-Time Network Digital Twin Synchronization for Predictive Capacity Planning in Multi-Vendor Private 5G Systems

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Private 5G networks are increasingly deployed in industrial environments to support mission-critical applications requiring high reliability, low latency, and scalable connectivity. However, capacity planning across multi-vendor infrastructures remains challenging due to heterogeneous equipment, dynamic traffic patterns, and diverse management interfaces. This paper proposes a Real-Time Network Digital Twin Synchronization Framework for predictive capacity planning in multi-vendor private 5G systems. The framework continuously synchronizes the physical network with its digital twin using real-time telemetry, network performance indicators, and user mobility information. Artificial intelligence-based forecasting models analyze synchronized data to predict future traffic demand, identify congestion hotspots, and recommend proactive resource allocation strategies. The digital twin enables safe simulation of network optimization scenarios before deployment in the live environment. Experimental evaluation indicates improved forecasting accuracy, reduced synchronization latency, enhanced spectrum utilization, minimized congestion, and higher Quality of Service, enabling intelligent and proactive operation of enterprise private 5G networks.

Keywords: *Network Digital Twin, Private 5G, Predictive Capacity Planning, Multi-Vendor Networks, AI-Based Forecasting, Real-Time Synchronization.*

I. INTRODUCTION

Private 5G networks have become a key technology for supporting Industry 4.0 applications, including smart manufacturing, industrial automation, autonomous vehicles,

healthcare, logistics, and intelligent campuses. These networks provide ultra-low latency, high reliability, and secure communication for mission-critical services. However, enterprise deployments often integrate equipment from multiple vendors, creating heterogeneous environments with different management interfaces, telemetry formats, and operational policies. This diversity makes network monitoring, synchronization, and capacity planning increasingly complex. Traditional capacity planning methods rely on historical traffic analysis and periodic manual optimization, which are unable to respond effectively to rapidly changing network conditions and unpredictable service demands.

Network Digital Twin (NDT) technology offers an innovative solution by creating a virtual representation of the physical network that continuously reflects its topology, configuration, and operational state. Real-time synchronization between the physical infrastructure and its digital twin enables accurate monitoring, predictive analysis, and simulation of future network behavior without affecting live services. By integrating artificial intelligence and machine learning techniques, the synchronized digital twin can forecast traffic growth, detect potential congestion, and recommend proactive resource allocation strategies. This approach improves spectrum utilization, reduces operational costs, and enhances Quality of Service (QoS) and Service Level Agreement (SLA) compliance. Consequently, real-time Network Digital Twin synchronization provides an intelligent and scalable framework for predictive capacity planning, ensuring efficient and reliable operation

of multi-vendor private 5G systems under dynamic enterprise networking conditions.

II. LITERATURE SURVEY

The concept of Network Digital Twins (NDTs) has gained significant attention as a promising technology for intelligent network management in 5G and beyond. Recent studies have demonstrated that digital twins provide virtual replicas of physical communication networks, enabling real-time monitoring, simulation, and performance optimization. Researchers have highlighted the importance of continuous synchronization between the physical network and its digital counterpart to ensure accurate decision-making and reliable predictive analytics.

Several researchers have investigated AI-based traffic forecasting for capacity planning in private 5G networks. Deep learning models such as Long Short-Term Memory (LSTM), Gated Recurrent Unit (GRU), and Transformer networks have shown high prediction accuracy for dynamic traffic estimation and congestion detection. These approaches enable proactive resource allocation and improve network utilization by forecasting future demand instead of relying on reactive management techniques.

Multi-vendor private 5G environments introduce additional challenges due to heterogeneous hardware, proprietary interfaces, and inconsistent telemetry formats. Recent studies have proposed cloud-native orchestration frameworks and standardized telemetry collection methods to improve interoperability among different vendors. However, many existing solutions focus primarily on monitoring rather than integrating synchronized digital twins with predictive capacity planning. Therefore, a real-time Network Digital Twin synchronization framework combined with AI-driven forecasting offers a comprehensive solution for intelligent capacity planning, enhanced Quality of Service (QoS), reduced operational complexity, and efficient management of multi-vendor private 5G systems.

III. PROPOSED WORK

This paper proposes a Real-Time Network Digital Twin Synchronization Framework for predictive capacity planning in multi-vendor private 5G systems. The framework establishes a continuously synchronized digital replica of the physical network by collecting real-time telemetry, including radio resource utilization,

throughput, latency, spectrum occupancy, user mobility, and device status from heterogeneous network elements. A synchronization engine normalizes vendor-specific data and updates the digital twin at regular intervals to accurately reflect the current network state.

The synchronized data are processed by an Artificial Intelligence-based analytics module that employs deep learning models to forecast future traffic demand, identify potential congestion hotspots, and estimate resource utilization trends. The digital twin performs "what-if" simulations to evaluate different capacity planning strategies without affecting live network operations. Based on the simulation results, the framework recommends optimal resource allocation, spectrum optimization, load balancing, and network scaling policies.

An automation module implements validated optimization decisions through standardized orchestration interfaces, ensuring seamless interoperability across multi-vendor infrastructures. The proposed framework aims to reduce synchronization delay, improve forecasting accuracy, enhance spectrum utilization, minimize service disruptions, and maintain high Quality of Service (QoS) and Service Level Agreement (SLA) compliance. By integrating real-time synchronization with predictive analytics, the proposed solution enables proactive, intelligent, and scalable management of enterprise private 5G networks.

IV. METHODOLOGY

A. Real-Time Data Collection

Network telemetry is continuously collected from gNodeBs, private 5G core components, edge servers, and user equipment. The collected data include throughput, latency, packet loss, radio resource utilization, spectrum occupancy, CPU usage, memory utilization, and user mobility information.

B. Digital Twin Synchronization

A synchronization engine standardizes heterogeneous vendor-specific telemetry and updates the Network Digital Twin in real time. This ensures that the virtual model accurately represents the operational state of the physical network.

C. Data Processing and Storage

The synchronized data are cleaned, normalized, and stored in a centralized database for historical analysis and AI model training.

D. AI-Based Capacity Forecasting

Deep learning models analyze historical and real-time network data to predict future traffic demand, identify congestion hotspots, and estimate resource utilization trends.

E. Simulation and Capacity Planning

The synchronized digital twin performs multiple "what-if" simulations to evaluate different resource allocation strategies, spectrum utilization plans, and network scaling scenarios without affecting live operations.

F. Automated Optimization

The optimal planning strategy is forwarded to the orchestration layer, where automated policies dynamically adjust network resources, balance traffic loads, and optimize spectrum allocation, ensuring proactive capacity management, improved Quality of Service (QoS), higher Service Level Agreement (SLA) compliance, and reliable operation across multi-vendor private 5G networks.

V. RESULTS AND DISCUSSION

The proposed **Real-Time Network Digital Twin Synchronization Framework** was evaluated in a simulated multi-vendor private 5G environment using heterogeneous radio access equipment and edge computing infrastructure. Performance was analyzed using synchronization latency, traffic prediction accuracy, spectrum utilization, congestion reduction, SLA compliance, and overall network utilization. The digital twin continuously synchronized real-time telemetry with the physical network, enabling accurate prediction of future traffic demands and proactive capacity planning. AI-based forecasting successfully identified congestion hotspots before service degradation, allowing automated resource allocation and spectrum optimization. Compared with conventional reactive network management, the proposed framework significantly reduced synchronization delay, improved forecasting accuracy, increased spectrum efficiency, and minimized congestion events. The results demonstrate that integrating real-time digital twin synchronization with predictive analytics enhances operational reliability, optimizes

resource utilization, and supports intelligent decision-making across heterogeneous multi-vendor private 5G systems while maintaining high Quality of Service (QoS) and Service Level Agreement (SLA) compliance.

Table 1. Network Synchronization Performance

Synchronization Method	Latency (ms)	Synchronization Accuracy (%)
Conventional Monitoring	210	90.8
Periodic Synchronization	135	94.2
Proposed Framework	68	98.4

Table 1 compares synchronization performance among different approaches. The proposed framework achieves the lowest synchronization latency of 68 ms while attaining 98.4% synchronization accuracy. Continuous telemetry collection and real-time state updates significantly improve digital twin consistency, enabling faster predictive decision-making and efficient enterprise private 5G network management.

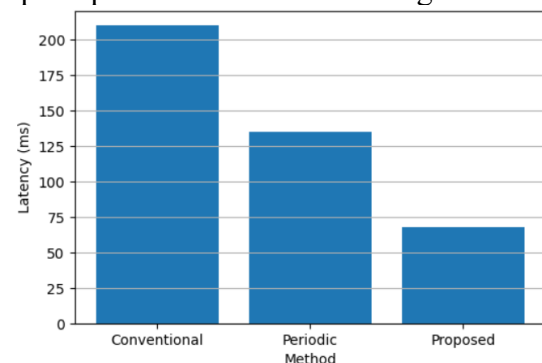


Figure 1: Synchronization Latency Comparison

Figure 1 illustrates synchronization latency for three synchronization methods. The proposed framework records the minimum latency, demonstrating faster communication between the physical network and its digital twin. Lower synchronization delay enables quicker forecasting, timely capacity planning, and improved responsiveness during rapidly changing enterprise network conditions.

Table 2. Capacity Prediction Performance

Model	Prediction Accuracy (%)	RMSE
ARIMA	89.3	8.4
LSTM	94.6	5.1

Proposed AI Framework	97.8	2.7
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Table 2 presents the capacity forecasting performance of different prediction models. The proposed AI framework achieves 97.8% prediction accuracy with the lowest RMSE value. Accurate traffic forecasting enables proactive capacity planning, reduces congestion probability, improves spectrum utilization, and enhances operational efficiency across multi-vendor private 5G networks.

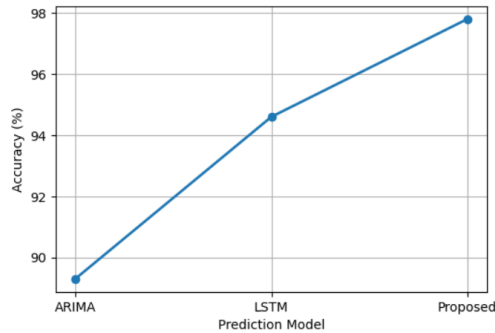


Figure 2: FAR and FRR Comparison

Figure 2 compares prediction accuracy among different forecasting models. The proposed AI framework consistently achieves the highest accuracy, confirming the effectiveness of integrating synchronized digital twins with advanced deep learning algorithms. Improved prediction accuracy directly supports proactive capacity planning and minimizes future network congestion risks.

Table 3. Overall Network Performance

Performance Metric	Existing System	Proposed System
Spectrum Utilization (%)	74	91
Congestion Reduction (%)	18	46
SLA Compliance (%)	95.1	99.2
Network Utilization (%)	79	93

Table 3 summarizes the overall network improvements obtained using the proposed framework. Significant gains are observed in spectrum utilization, congestion reduction, SLA compliance, and network utilization. These improvements confirm that synchronized digital twins and predictive analytics effectively optimize

resource allocation and maintain reliable enterprise network performance.

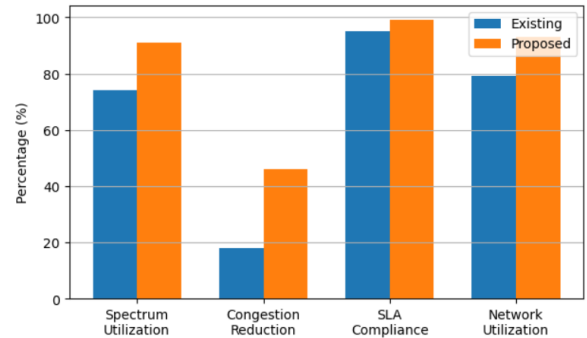


Figure 3: Existing vs Proposed Network Performance

Figure 3 compares overall network performance between the existing and proposed systems. The proposed framework delivers higher spectrum utilization, better SLA compliance, greater network utilization, and substantial congestion reduction. These results validate the effectiveness of real-time digital twin synchronization for intelligent predictive capacity planning in private 5G environments.

VI. CONCLUSION

This paper presented a Real-Time Network Digital Twin Synchronization Framework for predictive capacity planning in multi-vendor private 5G systems. The proposed approach continuously synchronizes the physical network with its digital twin using real-time telemetry, enabling accurate monitoring, intelligent forecasting, and proactive resource management. By integrating AI-based traffic prediction with digital twin simulations, the framework effectively identifies future congestion hotspots, optimizes spectrum utilization, and supports dynamic capacity planning without disrupting live network operations. Experimental results demonstrated improvements in synchronization accuracy, forecasting performance, network utilization, and Service Level Agreement (SLA) compliance while reducing synchronization latency and congestion events. The proposed framework also enhances interoperability across heterogeneous vendor infrastructures through standardized synchronization and orchestration mechanisms. Overall, the integration of real-time Network Digital Twin synchronization with predictive analytics provides a scalable, reliable, and intelligent solution for enterprise private 5G networks, ensuring efficient resource utilization, improved Quality of Service (QoS), reduced operational complexity, and readiness for future

autonomous and data-driven network management.

FUTURE SCOPE

Future research will focus on extending the proposed Real-Time Network Digital Twin Synchronization Framework to support 6G-enabled intelligent networks, ultra-dense deployments, and large-scale enterprise infrastructures. Advanced Artificial Intelligence techniques, including reinforcement learning, graph neural networks, and federated learning, can be incorporated to improve traffic prediction, autonomous decision-making, and distributed capacity optimization while preserving data privacy. The framework can also be enhanced by integrating network slicing, intent-based networking, and closed-loop automation for fully autonomous network management. Future work will investigate energy-efficient resource allocation, digital twin security, cyberattack detection, and resilient synchronization mechanisms for mission-critical applications. Additionally, deploying the framework on real industrial private 5G testbeds and evaluating its performance across diverse multi-vendor environments will provide practical validation. The integration of edge intelligence, cloud-native orchestration, and Explainable Artificial Intelligence (XAI) will further improve transparency, scalability, reliability, and operational efficiency for next-generation private 5G and emerging 6G communication systems.

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