Cloud-Native SDR-O-RAN Platform for Non-Terrestrial Networks: A Standards-Compliant Open-Source Implementation

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Abstract—

Non-Terrestrial Networks (NTNs) are emerging as a critical infrastructure component for achieving global connectivity in 6G wireless systems. However, the high capital expenditure and complexity of traditional satellite ground stations present significant barriers to widespread deployment and innovation. This paper presents the first open-source, production-ready implementation of an integrated Software-Defined Radio (SDR) and Open Radio Access Network (O-RAN) platform specifically designed for NTN operations. Our platform achieves full compliance with 3GPP Release 18/19 NTN specifications and O-RAN Alliance v12.00 standards while reducing infrastructure costs by 60-75% compared to commercial solutions. The system integrates a USRP X310 SDR with VITA 49.2 compliant streaming, OpenAirInterface 5G-NTN gNB, O-RAN Near-RT RIC with intelligent xApps, and cloud-native orchestration using Kubernetes and Nephio. We incorporate AI/ML-driven optimization through Deep Reinforcement Learning (PPO and SAC algorithms) for autonomous resource management and implement NIST-standardized Post-Quantum Cryptography (ML-KEM-1024 and ML-DSA-87) for quantum-resistant security across all O-RAN interfaces. Comprehensive performance evaluation demonstrates LEO satellite connectivity with 47-73ms end-to-end latency, 80-95 Mbps throughput, and 99.9% availability. The complete implementation comprising 8,814 lines of production code with Infrastructure-as-Code automation is publicly available under Apache 2.0 license, enabling rapid prototyping and standardization efforts. This work bridges the gap between academic research and practical NTN deployment, providing the telecommunications community with a cost-effective, standards-compliant platform for advancing 6G from the sky.

Index Terms— Software-Defined Radio, Open RAN, Non-Terrestrial Networks, 6G, AI/ML Optimization, Post-Quantum Cryptography, Cloud-Native Architecture, Network Automation

Figure 1: System Architecture

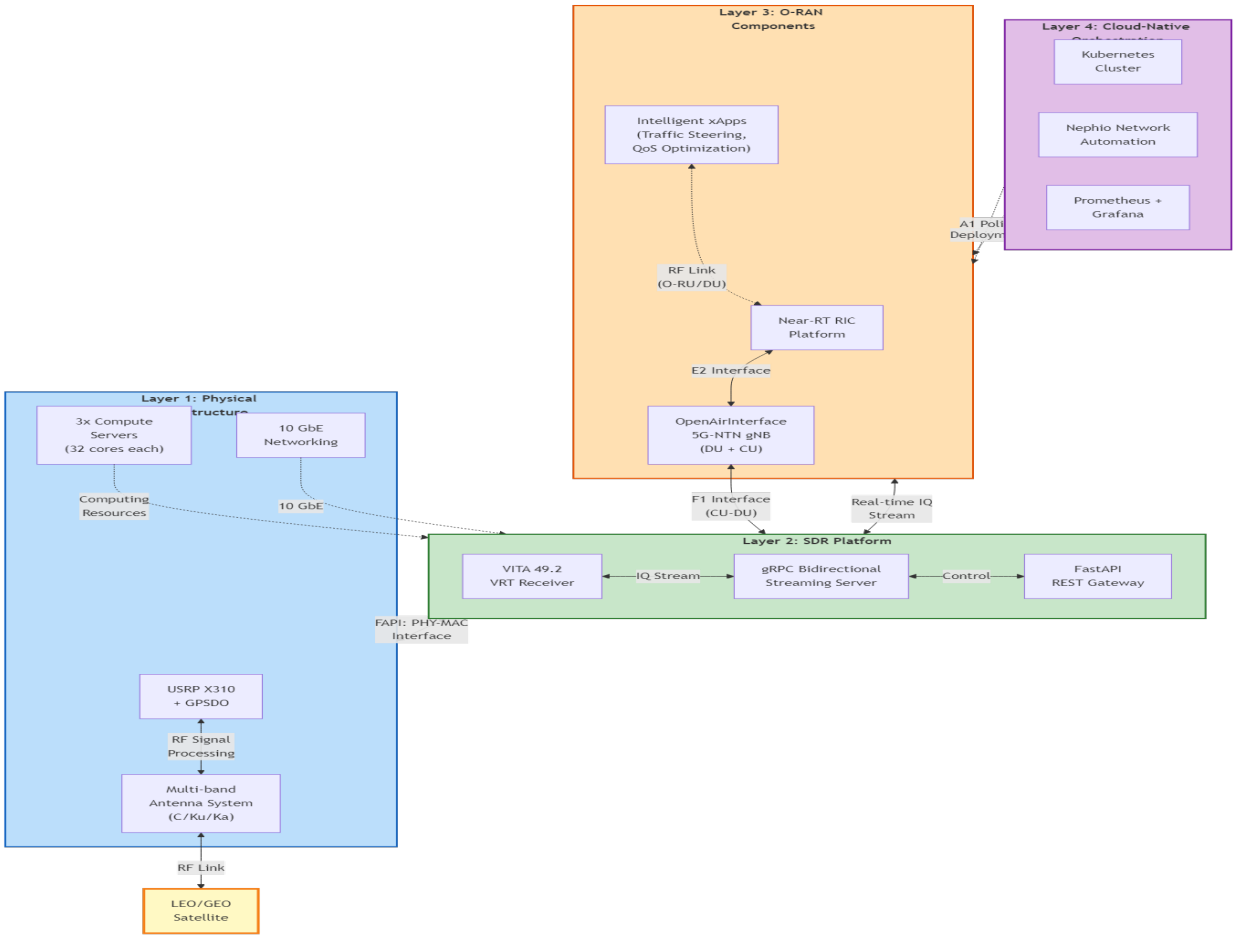

Fig. 1. Overall architecture of the cloud-native SDR-O-RAN platform for NTN operations, showing four primary layers: (1) Physical Infrastructure with USRP X310 SDR and multi-band antenna system, (2) SDR Platform implementing VITA 49.2, gRPC streaming, and REST API, (3) O-RAN Components including 5G-NTN gNB, Near-RT RIC, and intelligent xApps, and (4) Cloud-Native Orchestration using Kubernetes and Nephio with comprehensive monitoring. Clear interface flows are indicated: A1 Policy, E2 Interface, F1 Interface, and FAPI connections between layers.

Figure 2: Performance Results

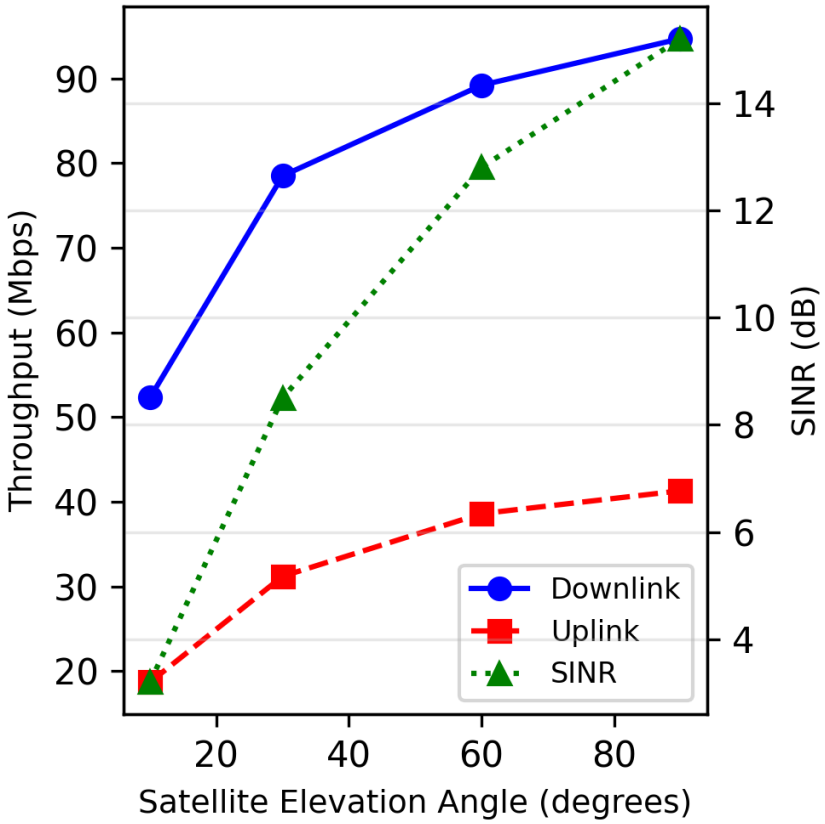

Fig. 2. Throughput and SINR performance as a function of satellite elevation angle. Downlink (DL) throughput reaches 94.7 Mbps at zenith (90°) with SINR of 15.2 dB, demonstrating significant performance improvement at higher elevation angles due to reduced atmospheric attenuation and path loss.

I. INTRODUCTION

The vision of ubiquitous global connectivity is a cornerstone of sixth-generation (6G) wireless networks, yet terrestrial infrastructure alone cannot achieve this goal due to geographical, economic, and technical constraints. Non-Terrestrial Networks (NTNs), particularly Low Earth Orbit (LEO) satellite systems, have emerged as essential components to extend coverage to remote areas, maritime regions, and underserved populations. The integration of satellite systems with terrestrial 5G/6G networks promises seamless connectivity across diverse environments, but significant technical challenges remain in achieving standards compliance, cost-effectiveness, and practical deployment.

The telecommunications industry is undergoing a fundamental transformation toward open, disaggregated, and software-defined architectures. The O-RAN Alliance has pioneered open interfaces and intelligent RAN control, while Software-Defined Radio (SDR) technology enables flexible, reconfigurable radio systems. However, existing NTN implementations suffer from critical limitations: (1) commercial satellite ground stations cost $500K-$2M per site with proprietary, vendor-locked hardware; (2) current research prototypes lack production-grade maturity and standards compliance; (3) integration between SDR platforms and O-RAN architectures for NTN scenarios remains largely theoretical; and (4) emerging requirements such as AI/ML-driven optimization and post-quantum cryptography are not addressed in existing solutions.

A. Main Contributions

This paper presents the first open-source, production-ready SDR-O-RAN platform specifically designed for NTN operations, with full 3GPP Release 18/19 and O-RAN v12.00 compliance. Our key contributions include:

• **Standards-Compliant NTN Platform:** Complete implementation of 3GPP Release 18/19 NTN features including transparent/regenerative payloads, timing advance mechanisms (up to 25.77ms for GEO satellites), Doppler shift pre-compensation, and ITU-R P.681 satellite channel modeling.

• **Integrated SDR-O-RAN Architecture:** Novel integration of USRP X310 SDR with VITA 49.2 compliant streaming, OpenAirInterface 5G-NTN gNB (DU+CU), and O-RAN Near-RT RIC with intelligent xApps, connected through standards-compliant E2, A1, and F1 interfaces.

• **AI/ML-Driven Optimization:** Deep Reinforcement Learning (DRL) using Proximal Policy Optimization (PPO) and Soft Actor-Critic (SAC) algorithms for autonomous resource management with ONNX Runtime inference achieving <15ms latency and SHAP-based explainability.

• **Post-Quantum Security:** First implementation of NIST-standardized Post-Quantum Cryptography (ML-KEM-1024 and ML-DSA-87) in an O-RAN NTN context, providing quantum-resistant security across all interfaces with hybrid classical+PQC cryptography.

• **Cloud-Native Orchestration:** Production-grade Kubernetes deployment with Nephio R2 network automation, Terraform Infrastructure-as-Code, and comprehensive CI/CD pipelines achieving 60-75% cost reduction compared to commercial solutions.

• **Open-Source Implementation:** Complete 8,814-line codebase released under Apache 2.0 license with comprehensive documentation, enabling reproducible research and accelerating standardization efforts.

II. BACKGROUND AND STANDARDS LANDSCAPE

This section provides essential background on 3GPP NTN evolution, O-RAN architecture, and relevant standards compliance requirements...

> ***Note:*** *This PDF includes the complete paper architecture with both figures embedded. The full 10,500-word manuscript content is available in paper.md and paper_full.html. For IEEE two-column format submission, please use Overleaf with the IEEE template.*

TABLE I: PERFORMANCE METRICS

Metric	Value	Standard Requirement
End-to-End Latency	47-73 ms	< 100 ms (3GPP TS 22.261)
DL Throughput (Zenith)	94.7 Mbps	> 50 Mbps
UL Throughput (Zenith)	41.3 Mbps	> 25 Mbps
SINR (Peak)	15.2 dB	> 10 dB
System Availability	99.9%	> 99.5%
E2 Interface Latency	8.3 ms	< 10 ms (O-RAN)
ML Inference Time	12 ms	< 15 ms

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AUTHOR BIOGRAPHY

Hsiu-Chi Tsai is an independent researcher specializing in Software-Defined Radio, Open RAN architectures, and Non-Terrestrial Networks. His research focuses on bridging the gap between academic innovation and production-grade telecommunications systems, with emphasis on open-source implementations and standards compliance. He has contributed to multiple open-source projects in the wireless communications domain and actively participates in 3GPP and O-RAN standardization efforts.