UNITY-6G: UNified archITecture for Open RAN-enabled Distributed, Scalable and SustainabilitY-enhanced 6G Networks

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***Abstract*—This paper proposes a highly sustainable and scalable integrated AI-native architecture defining UNified archITecture for Open RAN-enabled Distributed, Scalable and SustainabilitY-enhanced 6G Networks (UNITY-6G) project that can support the diverse requirements of 6G networks by relying on advanced technologies, such as distributed ledger technology, semantic communications, digital network twinning to enhance the performance, cost-efficiency and trustworthiness of integrated 6G network services and applications. The focus is on scalability and sustainability for integrated networks (Non-Terrestrial and Terrestrial Networks, xHaul, Open RAN, Non-Public Networks, Edge, Core and Cloud). Furthermore, we aim to evolve to real-time distributed and network state-aware Open RAN that can leverage the integration of distributed applications in the integrated architecture. This will enable fine-grained data-driven management and control via incorporating dApps, distributed applications that complement existing xApps/rApps and use cases with stricter timing requirements in an integrated network. Common interfaces and protocols will be defined so that different heterogenous domains can communicate seamlessly. To better guide the design, This paper also use the principles of service based architecture for integrated networks and leverage digital twins for network evaluation and considers four use cases targeting: i) Sustainable networks for disaster handling, (ii) Immersive Experience with Real-time XR/holographic communications, (iii) Digital Twin for Integrated 6G Network Evaluation, (iv) Multi-RAT O-RAN enabled NPN for supporting time sensitive applications for Industry 4.0.**

Keywords—6G; NTN; O-RAN; NPN; Sustainability

I. INTRODUCTION

The increasing energy consumption of Information and Communication Technology (ICT) networks, predicted to account for 21% of global electricity use by 2030 [1], has highlighted the urgent need for sustainable and energy-efficient solutions. As 6G networks emerge, it is vital to integrate renewable energy sources, efficient protocols, and advanced network management techniques to support applications like eXtended Reality (XR) and holographic communications [2]. These applications demand low latency, high bandwidth, reliability, and energy efficiency, requiring new architectures and resource management strategies. Key technological trends include the adoption of softwarization, modularization, Software Defined Networking (SDN), and Network Function Virtualization (NFV) [8]. The edge-cloud continuum has also gained prominence, leveraging distributed computing and Artificial Intelligence (AI) for resource-intensive tasks, real-time decision-making, and scalability [3]. And non-public networks operating in license-exempt spectrum, mainly Wi-Fi, are also evolving towards high reliability [14]. However, challenges such as interoperability, resource allocation, and maintaining Quality of Service (QoS) for mission-critical applications remain critical.

A. Related Work

The UNified archITecture for Open RAN-enabled Distributed, Scalable and SustainabilitY-enhanced 6G Networks (UNITY-6G) project stands apart from existing projects by integrating advanced technologies and adopting a holistic approach to sustainability, scalability, and automation in 6G networks. Unlike its predecessors, UNITY-6G focuses on creating an *AI-native, data-driven network management system* with distributed intelligence, semantic communication, and sustainability as its core pillars. UNITY-6G employs distributed AI for real-time, multi-domain resource

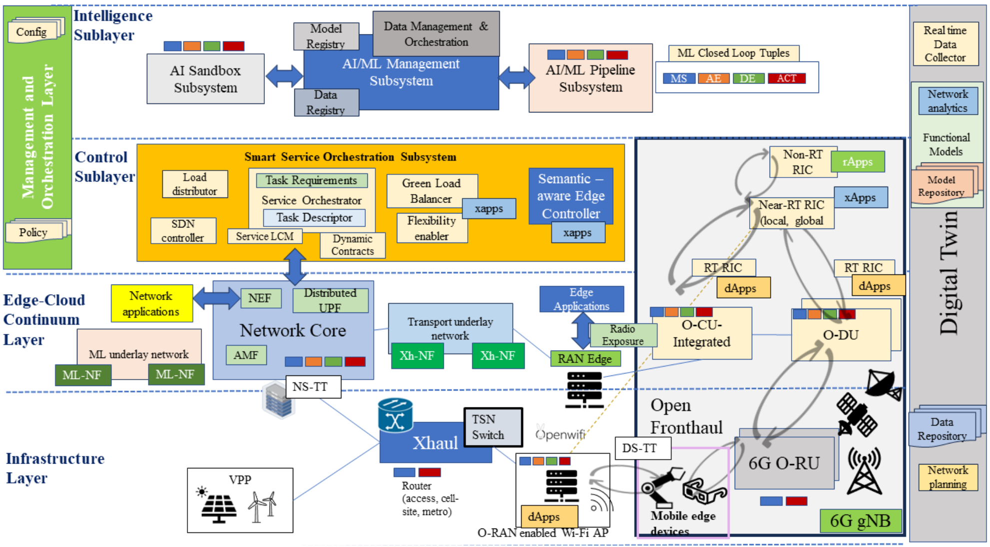

Figure 1: Proposed Unified Architecture of UNITY-6G

management and integrates Digital Twin (DT) technology to simulate, optimize, and predict network behavior. This contrasts with projects like DAEMON [4] and MONB5G [5], which primarily focus on centralized or partially distributed network intelligence. While projects like 6GREEN emphasize energy efficiency, UNITY-6G extends this by incorporating renewable energy sources, microgrids, and AI-based sustainability metrics. It prioritizes reducing the carbon footprint of integrated networks while supporting scalable and eco-friendly solutions.

UNITY-6G pioneers semantic communication, which transmits only the context or meaning of data, reducing redundant transmissions and energy use [9]. It also enhances Open RAN with real-time reaction capabilities, enabling seamless integration of Non-Terrestrial Networks (NTNs) and Terrestrial Networks (TNs), by extending the architecture views provided in 5G-STARDUST [10] and 6G-NTN [11] projects. Unlike projects such as AI4GREEN [6] and REINDEER [7], UNITY-6G emphasizes multi-tenant resource sharing, conflict resolution mechanisms using Distributed Ledger Technologies (DLTs), and unified management across heterogeneous domains (e.g., edge-cloud, satellite, and terrestrial). UNITY-6G goes beyond frameworks like 6G-CLOUD by not only conceptualizing but also implementing and validating AI-native architectures in real-world use cases, such as disaster handling and immersive XR communications, ensuring proactive and adaptive network management. Through these innovations, UNITY-6G aims to establish a scalable, sustainable, and trustworthy 6G network architecture that addresses diverse application needs, energy efficiency goals, and evolving technological requirements.

B. Paper Contributions

The proposed approach addresses these challenges by focusing on energy-efficient, integrated network infrastructures that converge heterogeneous domains like Non-NTNs, Non-Public Networks (NPNs), and TNs. Key goals include: (i) Developing AI-native, scalable network architectures with new green metrics for energy efficiency. (ii) Transitioning to distributed management systems to handle dynamic, multi-tenant environments. (iii) Ensuring interoperability across diverse domains through standardized protocols. (iv) Integrating distributed applications (dApps) for real-time data-driven network management. (v) Deploying distributed AI for automated decision-making, conflict resolution, and reduced data processing overhead.

This approach prioritizes trust-building mechanisms using Distributed Ledger Technologies (DLTs) and secure AI models to enhance reliability in multi-tenant networks. The initiative also focuses on scalable solutions for managing strict Service Level Agreements (SLAs) and resilient networks for remote and disaster-affected areas. By leveraging renewable energy, efficient resource allocation, and innovative disaster response strategies, UNITY-6G aims to ensure sustainability and energy efficiency in future networks. The proposed hierarchical management framework supports automated, fault-tolerant, and adaptive network operations. We also explore use cases like sustainable networks for disaster recovery, semantic-aware real-time XR/holographic communications, and digital twinning-based 6G network evaluation. These initiatives are crucial to achieving the ambitious goals of energy-efficient and sustainable 6G networks.

II. UNIFIED ARCHITECTURE AND USE CASES

A. Proposed Unified Architecture

The proposed architecture is given in Figure 1 and is built on *seven main pillars*. Each pillar focuses on achieving sustainable, scalable, and efficient 6G network solutions:

1. Integrated Network Architecture: The proposed architecture aims to design interoperable, AI-native architecture to support various 6G applications. Its multi-layered structure includes: (i) Management and orchestration layer, which includes AI/ML-driven decision-making systems (Monitoring System, Decision

Engine, Analytics Engine and Actuator) for real-time resource optimization. (ii) Edge Cloud Continuum, which combines core network functions with edge computing to reduce latency and increase efficiency. The infrastructure layer includes IoT devices, Open RAN components and renewable energy sources for scalability and sustainability. Finally, the DT Layer is a digital representation of the network that monitors and optimizes operations and improves predictive control and energy efficiency.

2. Energy-Efficient Networks: The proposed architecture focuses on minimizing energy consumption across equipment, protocols, and applications. Key strategies include: (i) Implementing power-saving modes for underutilized resources. (ii) Designing new energy-efficient protocols and traffic optimization techniques. (iii) Integrating renewable energy sources and local microgrids for environmentally aware service load balancing.

3. Dynamic Resource Orchestrator: A unified system dynamically manages resources across heterogeneous domains, such as Open RAN, edge-cloud infrastructure, and satellite networks. It employs distributed AI and Distributed Ledger Technologies (DLTs) to enhance security, flexibility, and efficiency.

4. Digital Twin for Network Evaluation: The proposed architecture leverages DT technology for proactive decision-making and predictive control. DTs simulate the network's performance to optimize energy use, identify resource savings, and facilitate AI model training, enhancing sustainability and operational efficiency.

5. Semantic-Empowered Communications: By transmitting only the context or meaning of data, semantic communication reduces redundant transmissions, improving latency and resource utilization. The proposed architecture focuses on real-time, high-quality applications like XR and video communication to meet latency and accuracy requirements.

6. Service-Based Architecture (SBA): The proposed architecture integrates services across heterogeneous domains (e.g., Open RAN, satellite, X-haul) using SBA. The architecture supports resource sharing and service lifecycle management, enabling seamless discovery, registration, and consumption of network services.

7. Time-Sensitive Non-Public Networks (NPNs): UNITY-6G supports time-sensitive applications through multi-Radio Access Technologies (RATs), combining cellular and Wi-Fi networks. It enables real-time monitoring and control, achieving determinism across wired and wireless networks.

Overall, the proposed integrated architecture seeks to revolutionize 6G networks by integrating AI, edge-cloud computing, DLTs, and renewable energy sources to ensure sustainability, scalability, and adaptability for future technologies and applications.

B. Use Cases

1. Sustainable Networks for Disaster Handling: UNITY-6G addresses network disruptions caused by disasters by developing resilient and sustainable network infrastructures. These networks will leverage renewable energy sources (e.g., solar and wind) and smart microgrids for efficient operations. Key innovations include AI-enabled energy-saving mechanisms, multi-tenant resource sharing, and trust-based mechanisms using DLTs. UNITY-6G will integrate edge computing, semantic communications, and distributed AI to ensure reliable communication during emergencies. The focus is on enabling rapid recovery to normal operations while maintaining sustainability and reducing environmental impact.

2. Immersive Experiences with Real-time XR/Holographic Communications: UNITY-6G aims to support next-generation XR and holographic applications by developing a semantic-aware 6G network capable of transmitting high-quality, low-latency 3D video. By leveraging edge computing, multi-RAT interfaces, distributed AI, and flexible resource allocation, UNITY-6G will optimize performance, reduce energy consumption, and ensure seamless user experiences. Semantic-aware AI techniques will enable efficient resource utilization, while real-time video coding and task allocation will support immersive applications with stringent latency and accuracy requirements.

3. Digital Twin for Integrated 6G Network Evaluation: UNITY-6G will create a digital twin (DT) of the network infrastructure to simulate and optimize performance. DT enables proactive decision-making, predictive maintenance, and AI-driven closed-loop management. By analyzing real-time and historical data, it can identify opportunities for energy savings, optimize resource allocation, and test new services before deployment. The DT also supports network resiliency and helps prevent equipment failures by providing insights for efficient orchestration and management.

4. Multi-RAT O-RAN Enabled NPN for Industry 4.0: This use case focuses on creating unified management and control for multi-Radio Access Technologies (RATs), combining cellular and Wi-Fi networks. UNITY-6G will enable time-sensitive, low-latency communication essential for industrial automation in Industry 4.0. Utilizing the O-RAN framework, the solution integrates novel TSN features in both wireless and wired domains, enabling seamless optimization across technologies. Real-time and near-real-time applications will monitor and control resource allocation, ensuring high reliability and precision for industrial applications.

III. OPEN RAN, TRANSPORT, EDGE, RIC FUNCTIONS, NETWORK EXPOSING AND DIGITAL TWIN

Having an integrated network infrastructure that supports flexibility and interoperability between different radio access technologies (RAT) as well as terrestrial and non-terrestrial networks requires a unified framework for RAN control and management. To achieve this, UNITY-6G aims to incorporate Open RAN components that will enable unified management and control of multi-RAT networks.

O-RAN components will be incorporated in the edge cloud and an integrated Central Unit (CU) will be integrated in regional cloud for seamless integration between satellite and terrestrial networks. The Radio intelligence controllers (RICs) will be responsible for managing and orchestrating radio, transport and satellite resources, ensuring efficient and optimized use of the integrated network (for both non-real time (non-RT RIC) and near-real time (Near-RT RIC) operations and the real time (RT-RIC) thanks to dApps). In addition to this, O-RAN interfaces will be extended to support the Wi-Fi RAT segment. As such Wi-Fi APs will become O-RAN compatible terminating O1 and E2 interface in southern bound. In this regard, UNITY-6G has foreseen local (per technology) RICs and global RICs (across different RATs). The aim is also to support an O-RAN E2 interface for transport, looking at differences between wireless, fiber and satellite. UNITY-6G will enable a common interface to support load balancing, mobility and multi-homing using various transport technologies. In addition, it will focus on wireless and transport technologies to enhance the transport layer capabilities to enable AI based routing algorithm for load balancing and energy saving.

For efficient network control and management, rich network exposing function should be enabled by exposing not only monitoring information but also controlling knobs from each network part (i.e., RAN, transport, core). UNITY-6G aims to use standardized exposing functions (when possible) and that (i) for core network it will utilize 3GPP CAPIF, NEF and NWDAF functions, (ii) for transport network it will utilize SDN-based information sharing while (iii) for multi-RAT O-RAN exposing functions will be used. Monitoring and controlling knobs will include an exhaustive per-flow and per-device information list. The exposed information is expected to be exploited both by the UNITY-6G vertical applications, as well as by the digital twining of the integrated architecture.

The complexity of an integrated network will increase and will pose certain challenges in its network control and management. To reduce such challenges, UNITY-6G targets to establish a digital twin (DT) replica of the integrated network architecture modeling different heterogeneous technological domains, as well as their interactions, environment, and configuration parameters. UNITY-6G foresees DT playing several roles in the network during planning, training, and operation times. The Planning Twin will focus on network design optimization for the integrated sustainable UNITY-6G architecture, while the Training Twin will provide a platform for AI model training, moving computational overhead from the physical environment to the digital network twin. Finally, the Operational Twin will act as a network brain, generating data and enabling on-demand decisions based on real and virtual data.

IV. ADVANCING AI-DRIVEN 6G NETWORKS

A. AI-Driven Edge-Cloud Computing for Sustainable Networks

UNITY-6G aims to revolutionize 6G networks through distributed AI techniques for managing energy resources, computing infrastructure, and integrated communication systems [12]. Leveraging federated edge learning, the project tackles challenges such as device heterogeneity, data privacy, energy efficiency, and scalability. A fully distributed AI-native approach across multi-RAT, edge, transport, core, and non-terrestrial domains enhances capacity planning, optimizes resource utilization, and enables predictive maintenance. Distributed AI will also facilitate self-healing networks, reducing the need for human intervention while ensuring network reliability and sustainability. To enhance performance, UNITY-6G integrates AI model optimization techniques such as pruning, quantization, knowledge distillation, and low-rank factorization. Hardware acceleration and continuous learning further improve inference speed and resource efficiency. These efforts position UNITY-6G as a next-generation framework for managing dynamic, multi-tenant 6G networks with minimized costs and environmental impact.

B. Semantic Communication for Intelligent Network Optimization

A key innovation in UNITY-6G is semantic communication, which shifts focus from transmitting raw data to transmitting meaning and context. This reduces bandwidth requirements, improves efficiency, and supports high-quality, low-latency applications such as XR, holographic communications, and digital twins. Using deep neural networks (DNNs), reinforcement learning (RL), and federated learning (FL), UNITY-6G optimizes network performance by understanding tenant requirements and dynamically allocating resources. Semantic-aware AI enables context-based transmission, ensuring that only relevant data is shared, thereby reducing network congestion. Techniques like knowledge graph-based reasoning and semantic compression will further optimize communication, leading to significant improvements in latency, energy efficiency, and resource utilization.

C. Conflict Resolution and Secure Resource Sharing

With increasing complexity in 6G networks, secure and fair resource allocation is crucial. UNITY-6G leverages Distributed Ledger Technologies (DLTs) for transparent and decentralized conflict resolution in the Edge-Cloud continuum. Using trust-based policies, automated AI-driven resolution mechanisms, and Explainable AI (XAI), UNITY-6G ensures fair and unbiased network resource distribution. An innovative aspect of UNITY-6G is real-time conflict mitigation in Open RAN environments, where multiple xApps/dApps compete for shared computational, radio, and storage resources [13]. Novel distributed AI algorithms will enable real-time monitoring and intelligent arbitration, preventing network performance degradation.

V. SERVICES AND APPLICATIONS

In the SBA, defining a precise service development lifecycle (SDLC) is crucial. The implementation or activation of new products or services in integrated, heterogeneous networks demands clear rules for their activation, operation, pausing, suspension, or closure. By adopting microservices, CI/CD pipelines, and agile methodologies, SDLC management will encompass careful planning for software implementation, testing, validation, and deployment. UNITY-6G aims to develop a reliable and scalable SBA capable of integrating diverse components, including Open RAN, transport, and satellite systems, to deliver end-to-end networking solutions. This architecture will address the dynamic and diverse requirements of integrated networks by enabling communication between consumer pools and specific service instances via a dedicated service bus as given in Figure 2. UNITY-6G will analyze the use of a service registry and discovery database to ensure seamless service integration and define messaging exchanges and communication flows between SBA elements for smooth operation and efficient management. In this matter, UNITY-6G will also explore comprehensive product and service management within integrated environments, focusing on features required for remote application rendering.

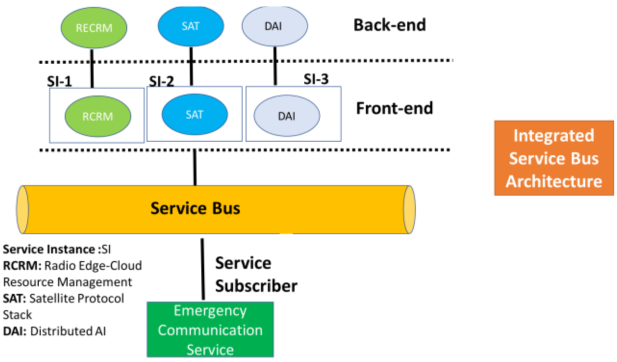

Figure 2: UNITY-6G SBA example design to provide an emergency communication service in network disaster use case

Within SDLC framework, integrated services such as Open RAN, transport, NPN, and satellite-oriented systems will serve as a foundation for implementing dedicated applications as exemplified in Figure 3. In this context, UNITY-6G will investigate xApps, rApps, and potentially dApps to optimize network resources and support advanced concepts such as semantic communication and DTs as services. These efforts aim to create a more efficient, sustainable network infrastructure capable of supporting diverse applications while maximizing resource utilization. Unified services leveraging the integrated network will enhance flexibility and agility for mobile service providers. The development of new services and applications within SDLC will require integration into the overall SBA network and running DT environments. Thus, UNITY-6G aims to target component integration and testing, defining and implementing automated tests to verify the correctness of new services and applications. Through these measures, UNITY-6G seeks to ensure seamless integration, robust performance, and the evolution of next-generation network services.

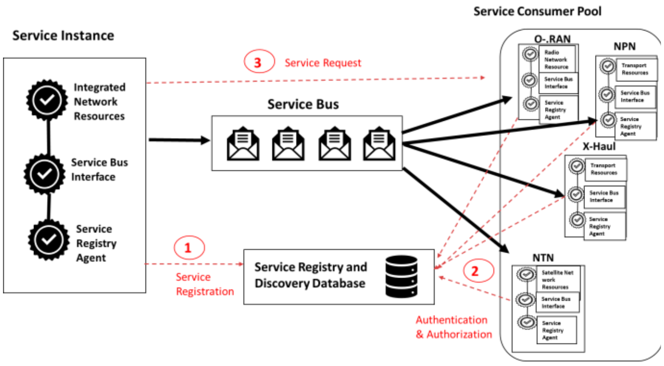

Figure 3: Providing UNITY-6G integrated services (belonging to different domains)

VI. INTEGRATION AND PoC

UNITY-6G aims to develop and demonstrate an integrated distributed network infrastructure that supports the convergence and interoperability of heterogeneous networks, where federated AI-powered algorithms will enable proactive, energy-efficient and secure resource management for the evolution of future 6G mobile networks. The integrated network architecture, which will support a wide range of 6G services and applications but will also consider shared resource utilization (e.g., for sustainable and scalable networks) as one of its design parameters. The specific architecture of the UNITY-6G is focused on the integration of various technologies, sustainable resource management, and efficient network performance. The overall design will build a functional, more comprehensive and interoperable network architecture that can support 6G use cases and their requirements by developing an AI-native architecture that can scale and sustainably support innovative business models.

Multiple vectors along which networks can be made "greener" will be considered at the equipment, application, protocol, and network. In terms of equipment, power consumption can be categorized into the energy used by the core device (CPU) and the additional energy consumed per port and line card. The goal of UNITY-6G is to research innovative solutions and controller applications that can optimize energy usage across the network, considering differences in power consumption between idle and loaded network resources, and the incremental cost of additional transmission versus the initial cost of transmission. Dynamic resource orchestrator for 6G integrated networks involves the development of a unified and intelligent resource orchestration system. This system will be capable of dynamically managing and allocating network resources across multiple heterogeneous network domains and resources, including X-haul, Open RAN and NTN networks, edge-cloud continuum computing infrastructure and edge computing resources. The goal is to create an efficient and flexible integrated network architecture that can meet the diverse requirements of different tenants and 6G extreme use cases, while also providing high levels of security and trust.

Digital twinning enables the efficient deployment and monitoring of an integrated 6G zero-touch network. UNITY-6G will create a digital replica of the integrated network to simulate the network's components and the different heterogeneous technological domains, as well as their interactions, environment, and configuration parameters. DT will be a valuable tool for designing, optimizing, managing, and recovering networks, especially when combined with the widespread adoption of distributed AI/ML across different levels of the network. Semantic-empowered communications, that has emerged as an alternative to conventional communication, is particularly important in complex integrated 6G where there is a large volume of data being generated and transmitted, as semantic communication will allow for more intelligent decision-making and automation. UNITY-6G will develop semantic-aware AI techniques to achieve flexible resource allocation and VNF/CNF/task placement or offloading. In addition, in UNITY-6G we will enable native support for time-sensitive applications in the network by providing new time-sensitive features at the radio level of both RATs. Integrated multi-RAT NPN design will utilize the O-RAN concept for a seamless across-technologies network optimization utilizing unified control and management architecture for radio network.

VII. RECOMMENDATIONS AND FUTURE ROADMAP

The UNITY 6G project represents a visionary approach for the further development of 6G technology. The recommendations and future roadmap can focus on ensuring the seamless evolution of telecommunications infrastructures to meet future needs while addressing current challenges. Key recommendations include prioritizing sustainable network practices that incorporate energy-efficient technologies and renewable energy sources to significantly reduce the environmental impact of network operations. In addition, the project advocates the integration of advanced AI and machine learning techniques to automate network management, improve service delivery and increase security measures to support the development of intelligent and self-optimizing networks.

Looking to the future, the UNITY-6G roadmap emphasizes continued innovation in network architecture to support the growing data volumes and demanding services expected in the 6G era. This includes expanding edge computing capabilities to reduce latency and bandwidth issues and improving the use of digital twins to enable accurate real-time simulations for network planning and management. In addition, UNITY-6G emphasizes the importance of robust security frameworks to manage the complexity created by more open and interconnected network environments.

VIII. CONCLUSIONS

UNITY-6G is pioneering the development of a sustainable, scalable, intelligent and integrated 6G network infrastructure that integrates cutting-edge technologies such as artificial intelligence, distributed ledger technology, semantic communication and digital network twinning. UNITY-6G EU-funded project aims to develop a scalable AI-native network architecture that not only improves network efficiency and responsiveness but also focuses on environmental sustainability by incorporating renewable energy sources and advanced management techniques. The architecture is designed to support diverse and stringent network requirements in integrated and complementing non-terrestrial and terrestrial networks, non-public networks, Open RAN and edge/cloud systems, evolving into a real-time, state-aware network that integrates decentralized applications to meet stringent timing requirements. AI-driven automation, semantic-aware communication, and conflict-resilient resource sharing are integrated to create a sustainable, efficient, and self-optimizing 6G network architecture. By prioritizing distributed intelligence, renewable energy integration, and scalable resource orchestration, the proposed UNITY-6G architecture sets a new benchmark for future 6G networks, ensuring high performance, reduced environmental impact, and improved service reliability. Finally, with a strong commitment to global standardization and practical deployment, UNITY-6G targets critical use cases such as disaster management, immersive real-time XR/holographic communications, digital twin evaluation of integrated networks, and multi-RAT O-RAN-enabled non-public networks for time-sensitive Industry 4.0 applications, setting an important milestone for the next generation of global communication networks

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