UNICO I+D Project
6G-SORUS-RIS

SORUS-RIS-A1.1-E2 (E5)

Final version of the architecture

Abstract

This Deliverable presents an integrated architecture for Reconfigurable Intelligent Surfaces (RIS) in Beyond 5G (B5G) systems, detailing its controller design and interaction with real-time (RT) controllers for coordinated operation with Unmanned Aerial Vehicles (UAVs) and virtualized Radio Access Networks (vRAN). We first conduct a comprehensive review of related work on RIS-enabled networks, UAV-assisted communications, and vRAN integration, identifying the gaps in existing control and coordination mechanisms. Building on this analysis, we propose an architecture where the RIS controller interfaces seamlessly with RT controllers to dynamically manage RIS configurations, enable UAV-assisted coverage enhancement, and optimize communication with vRAN controllers. This design facilitates flexible, low-latency control and efficient orchestration of RIS and UAV resources, contributing to improved adaptability and performance in B5G networks.

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List of Acronyms

Beyond 5G: B5G

Virtualized Radio Access Networks: vRAN

Reconfigurable Intelligent Surfaces: RIS

Unnamed Aerial Vehicles: UAVs

Central Units: CUs

Distributed Units: DUs

Radio Units: RUs

Radio Network Controller: RNC

New Radio: NR

Cloud RAN: CRAN

Self-Organizing Networks: SON

Automated Neighbor Relation: ANR

Machine Learning: ML

Artificial Intelligence: AI

Real-Time RAN: RTRAN

RAN Intelligent Controller: RIC

Network Data Analytics Function: NWDAF

Electromagnetic: EM

Base Station: BS

Access Point: AP

Non Line of Sight: NLoS

Multiple-input Multiple-output: MIMO

Reinforcement Learning: RL

Key Performance Indicators: KPI

non-terrestrial network: NTN

Integrated Sensing and Communications: ISAC

signal-to-noise ratio: SNR

Quality of Service: QoS

Open RAN: ORAN

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Resumen Ejecutivo

Este documento presenta una arquitectura integrada para Superficies Inteligentes Reconfigurables (RIS) en sistemas más allá de 5G (B5G), con un enfoque en el control coordinado con Vehículos Aéreos no Tripulados (UAV) y Redes de Acceso de Radio Virtualizadas (vRAN). El objetivo de la arquitectura es abordar el desafío de coordinar estas tecnologías para mejorar la adaptabilidad y el rendimiento de la red.

La arquitectura es un sistema de capas con cuatro capas conceptuales principales que separan la manipulación electromagnética de la inteligencia de la red. Las capas incluyen una Capa de Metasuperficie para la manipulación de ondas , una Capa de Control Embebido para la actuación local en tiempo real , una Capa de Inteligencia que contiene el controlador RIS , y una Capa de Interfaz para la interoperabilidad de la red. Este diseño facilita un control flexible y de baja latencia, y una orquestación eficiente de los recursos de RIS y UAV.

El marco de control del sistema utiliza bucles de varios niveles para conectar la optimización global con la capacidad de respuesta local a través de diferentes escalas de tiempo. El Controlador RIS en Tiempo Real es el componente central que recibe datos del Controlador vRAN en Tiempo Real y del Controlador UAV en Tiempo Real para calcular la configuración óptima de fase y potencia para el RIS. Esto permite que el RIS adapte dinámicamente sus patrones de reflexión en el rango de 1 a 10 ms a los cambios en el movimiento del usuario y la posición del UAV. El documento señala que la arquitectura cumple con los estándares emergentes de ETSI y O-RAN Alliance, y satisface los requisitos de las redes no terrestres de 3GPP

Executive Summary

This document presents an integrated architecture for Reconfigurable Intelligent Surfaces (RIS) in Beyond 5G (B5G) systems, with a focus on coordinated control with Unmanned Aerial Vehicles (UAVs) and Virtualized Radio Access Networks (vRAN). The architecture's goal is to address the challenge of coordinating these technologies to improve network adaptability and performance.

The architecture is a layered system with four main conceptual layers that separate electromagnetic manipulation from network intelligence. The layers include a Metasurface Layer for wave manipulation, an Embedded Control Layer for local real-time actuation, an Intelligence Layer containing the RIS controller, and an Interface Layer for network interoperability. This design facilitates flexible, low-latency control and efficient orchestration of RIS and UAV resources.

The system's control framework uses multi-tiered loops to connect global optimization with local responsiveness across different timescales. The Real-Time RIS Controller is the central component that receives data from the Real-Time vRAN Controller and Real-Time UAV Controller to compute optimal phase and power settings for the RIS. This allows the RIS to dynamically adapt its reflection patterns in the 1-10 ms range to changes in user movement and UAV position. The document notes that the architecture complies with emerging standards from ETSI and the O-RAN Alliance, and meets requirements for non-terrestrial networks from 3GPP.

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1. Introduction

Reconfigurable Intelligent Surfaces (RIS) represent a groundbreaking technology in wireless communications, enabling the dynamic control of electromagnetic (EM) waves to optimize signal transmission and enhance communication efficiency. RIS are composed of programmable elements that can adjust their reflection, refraction, or absorption characteristics, allowing for the shaping and reconfiguration of wireless environments to meet specific communication objectives. This revolutionary concept has garnered significant interest in the context of 5G and beyond-5G networks due to its potential to transform traditional passive environments into intelligent, programmable spaces.

1.1. RIS

RIS, also known as Intelligent Reflecting Surfaces, consist of arrays of sub-wavelength passive elements, often referred to as "meta-atoms." These elements are equipped with tunable phase shifters that can reconfigure the incident EM waves. Unlike conventional communication systems that rely solely on base stations and user devices, RIS introduces a third element in the communication chain that can manipulate signal propagation, thereby enhancing network performance without the need for additional transmit power [1] [2].

A typical representative scenario is illustrated in Figure 1, where the access point (AP) transmits a signal that can reach the user through multiple paths: directly (**yellow**), via a conventional reflecting surface (**green**), or via a reconfigurable intelligent surface (RIS) (**orange**). A physical blockage obstructs some of the direct or reflected paths (**red**), highlighting the RIS's role in preserving connectivity by enabling alternative signal routes.

The architecture of an RIS typically includes the following key components:

- Passive Reflecting Elements: These elements can control the phase, amplitude, and polarization of incoming signals. By adjusting the phase shifts of these elements, the RIS can steer, focus, or scatter the signals in desired directions.
- Controller Unit: The RIS controller is responsible for configuring the reflecting elements based on network requirements and environmental conditions. This unit communicates with the base station (BS) or access point (AP) to optimize the RIS configuration for maximum performance.

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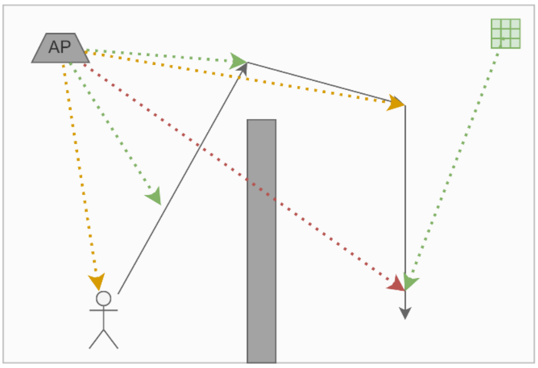

FIGURE 1 ILLUSTRATION OF RIS-ASSISTED WIRELESS COMMUNICATION.

- Communication Interface: RIS relies on wireless links to receive commands from the BS or AP, ensuring that the surface can adapt dynamically to changing network needs.

The integration of RIS into wireless networks [3] is expected to revolutionize several aspects of communication, particularly in the following areas:

Enhanced Coverage and Capacity: One of the primary applications of RIS is to enhance network coverage by intelligently reflecting signals to areas that are typically hard to reach due to blockages, such as dense urban environments or indoor spaces. RIS can also improve network capacity by focusing signals on specific users or regions, thus reducing interference and enhancing the signal-to-noise ratio (SNR).

Energy Efficiency: Unlike traditional relays or active antenna systems, RIS are passive devices that do not require significant energy to operate. This makes them highly energy-efficient solutions for extending coverage and improving connectivity without the need for additional power-hungry components. Their ability to focus and steer signals also reduces the overall energy consumption in wireless networks by minimizing the need for retransmissions and excessive signal amplification [4].

Beamforming and MIMO Optimization: RIS can play a crucial role in multi-antenna (MIMO) systems by aiding in the design of optimized beamforming strategies. By controlling the reflection of signals, RIS can assist in creating more focused beams, improving spatial diversity, and enhancing signal quality for multiple users simultaneously. This makes RIS particularly valuable in dense user environments and for high-frequency communications, such as millimeter-wave (mmWave) bands.

Interference Management and Security: In environments with multiple users or devices, managing interference becomes a critical challenge. RIS can help mitigate interference by dynamically adjusting the propagation of signals, ensuring that transmissions between different users or devices do not interfere with each other. Moreover, RIS can be used to enhance the physical layer security of wireless communications by manipulating the EM waves to obscure the signal paths or create jamming effects for unauthorized eavesdroppers.

Integration with UAV Networks: The combination of Reconfigurable Intelligent Surfaces (RIS) and Unmanned Aerial Vehicles (UAVs) opens up new possibilities for enhancing wireless communication

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networks, particularly in scenarios requiring rapid deployment or temporary infrastructure. UAVs can carry and position RIS panels in hard-to-reach or obstructed environments, leveraging their mobility to dynamically adjust the RIS location and orientation for optimal coverage. This approach is especially valuable in emergency response, rural areas, and disaster recovery situations, where traditional infrastructure is unavailable or damaged. By intelligently manipulating reflected signals, UAV-mounted RIS can establish reliable non-line-of-sight (NLoS) links and improve signal quality in challenging environments [5, 6].

In addition to coverage extension, this synergy enables enhanced capacity and energy efficiency. Studies have shown that RIS-equipped UAVs significantly improve coverage probability, reduce outage rates, and support adaptive beamforming based on real-time user distribution and channel conditions [7]. Optimization frameworks have been proposed to jointly design UAV trajectories and RIS configurations, maximizing network performance metrics such as throughput and spectral efficiency [8]. These advancements position UAV-RIS integration as a key enabler of flexible, intelligent, and reconfigurable 6G network architectures [4].

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2. Specific Architecture of Reconfigurable Intelligent Surface (RIS) System

Reconfigurable Intelligent Surfaces extend the classic node-centric view of wireless networks by inserting a programmable electromagnetic layer between radios and the environment. A modern RIS architecture therefore must orchestrate three tightly coupled subsystems, a metasurface, an embedded control fabric and a network-facing intelligence stack, while remaining scalable, low-power and standard-compliant. Below we synthesise the key architectural concepts defined in ETSI GR RIS 002 [9] with the latest findings from the research literature.

2.1. Conceptual Layering

The design and operation of Reconfigurable Intelligent Surfaces (RIS) in next-generation networks require a modular and layered approach that separates electromagnetic manipulation from network intelligence and control. A four-layer conceptual architecture mirroring recent 6G visions and implicitly assumed in standards such as ETSI clause 5.2 [9] has emerged to address this need. This layered decomposition not only clarifies the separation of concerns across physical and digital domains but also aligns with the broader paradigm of a Software-Defined Propagation Environment (SDPE), where the wireless channel itself becomes programmable and adaptive.

2.2. Metasurface Layer

At the foundation lies the Metasurface Layer**,** responsible for the instantaneous manipulation of electromagnetic wavefronts. This layer is composed of passive, active, or hybrid unit cells, which can control wave parameters such as phase, amplitude, polarization, and frequency. Depending on the implementation, this layer may incorporate impedance networks or tunable components (e.g., varactors or MEMS switches) to enable reconfigurability. The key function of this layer is to provide the physical actuation needed to alter the radio environment, operating at timescales compatible with fast channel variations and transmission dynamics.

2.3. Embedded Control Layer

Above the metasurface lies the Embedded Control Layer, which facilitates real-time or near-real-time actuation based on local sensing and low-latency control. Typical components include microcontrollers, embedded processors, and on-board sensors capable of measuring environmental metrics (e.g., signal strength, direction-of-arrival, or mobility indicators). This layer may also support low rate backhaul connectivity for minimal command or telemetry exchange. The embedded control layer is essential for enabling autonomy at the edge of the network, supporting functionalities such as self-configuration, calibration, and real-time adaptation without the need for full network coordination.

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2.4. Intelligence Layer

The Intelligence Layer provides high-level decision-making capabilities such as optimization, learning, and policy enforcement. It encompasses local or remote RIS controllers, often designed hierarchically to scale across large deployments. This layer may integrate Reinforcement Learning (RL) agents, meta-heuristic optimizers, or model-driven control schemes to adapt the surface configuration in response to network-level objectives, user behavior, or traffic patterns. The intelligence layer decouples slow-timescale decisions (e.g., power-efficient policy learning) from fast-timescale actuation, allowing RIS to contribute meaningfully to RAN Key Performance Indicators (KPIs) such as spectral efficiency, energy consumption, and user experience [10, 11].

2.5. Interface Layer

At the top, the Interface Layer ensures interoperability with the rest of the network, including terrestrial and non-terrestrial network (NTN) cores. This layer supports standardization efforts such as the O-RAN Alliance's R-RIS interfaces and the 3GPP Reconfigurable Intelligent Surface API (ReAPI) proposals. It also integrates with broader SDN/NFV frameworks to expose programmable RIS functionality to network orchestrators and applications. The interface layer is crucial for enabling seamless integration of RIS within virtualized and disaggregated network architectures, allowing for unified orchestration, monitoring, and lifecycle management [12].

By delineating the RIS system into these four distinct layers, this architectural framework allows for scalable, flexible, and standards-compliant deployment of intelligent surfaces. It enables a clear path from physical-layer reconfiguration to network-layer integration, supporting both centralized and distributed intelligence. This model is foundational to the vision of RIS as a native component of future 6G networks, where electromagnetic environments are as programmable and service-aware as the network itself.

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3. Unified Architectures and Control Strategies for Next-Generation RIS

As RIS transition from theoretical constructs to deployable technologies in 6G networks, their effectiveness increasingly depends on the co-design of physical hardware and control architectures. Advances in hardware, ranging from passive and hybrid tiles to beyond-diagonal topologies and frequency-selective surfaces, are expanding the functional capabilities of RIS, allowing for more efficient beamforming, sensing, and spectral coexistence. However, without complementary innovations in control, these capabilities cannot be fully harnessed. To this end, emerging control-plane strategies, including hierarchical architectures and intelligent reinforcement learning algorithms, are being developed to dynamically manage RIS behavior across different timescales and deployment contexts. Together, these developments represent a unified approach to RIS system design, where intelligent control and reconfigurable hardware jointly enable scalable, autonomous, and high-performance wireless environments.

3.1. Hardware Configurations: From Diagonal to Beyond-Diagonal RIS

The evolution of RIS hardware has moved far beyond the original concept of purely passive, independently tunable unit cells. Recent research and prototyping efforts reflect a growing shift toward more sophisticated and versatile configurations that enhance performance while maintaining energy efficiency. These innovations aim to unlock RIS's full potential for integration in both terrestrial and non-terrestrial 6G infrastructures.

A fundamental distinction lies between passive, active, and hybrid RIS architectures. Passive RIS panels, composed entirely of tunable but unpowered elements, offer extremely low energy consumption and simple design, making them ideal for dense, large-scale deployments. However, their performance is constrained by the well-known double-hop path loss, as they can only reflect incoming signals without amplifying them. To address this limitation, active RISs integrate amplifiers—often low-noise amplifiers (LNAs)—into each unit cell, enabling the panel to boost signal strength and overcome propagation losses. This comes at the cost of increased energy consumption and circuit complexity. Hybrid RIS architectures provide a middle ground by embedding a sparse set of active elements within an otherwise passive metasurface. This configuration allows for local sensing and signal amplification where needed, while keeping the overall energy footprint low. Recent experimental results at mmWave and sub-terahertz frequencies confirm that hybrid layouts offer an excellent trade-off between signal gain, power consumption, and integration complexity [13].

Beyond the active/passive dimension, the internal connectivity of RIS panels has become a major focus of innovation. Traditional "diagonal" RIS designs operate with the assumption that each element acts independently. While this simplifies control, it limits the surface's ability to create

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complex wavefronts, especially in the near field. Emerging "beyond-diagonal" (BD-RIS) designs address this by incorporating reconfigurable scattering matrix topologies. These architectures use impedance networks to interconnect elements fully, in groups, or hierarchically (e.g., in tree or forest structures), allowing for much richer spatial control. BD-RIS panels have demonstrated significant advantages in experimental Integrated Sensing and Communications (ISAC) scenarios, offering multi-order-of-magnitude improvements in signal-to-noise ratio (SNR) and enabling novel applications such as near-field beam shaping and joint communication-sensing operations [14].

Another notable direction is the integration of frequency-selective filtering within RIS hardware to address spectrum coexistence and electromagnetic compatibility (EMC) requirements. This configuration can achieved more than 20 dB of out-of-band signal rejection while preserving two-bit phase control. Such advancements are essential for complying with EMC obligations outlined in standards like ETSI, particularly in environments where RISs must operate alongside densely packed frequency allocations [15].

3.2. Control-Plane Architectures

The control plane of RIS-equipped networks plays a central role in enabling intelligent, adaptive, and efficient operation. As RIS hardware evolves in complexity and capability, so too must the architectures that manage their configuration. ETSI [9] has proposed a high-level classification that distinguishes among five modes of control: network-controlled, network-assisted, standalone, user equipment (UE)-controlled, and hybrid-controlled. These categories reflect varying degrees of autonomy and centralization in RIS decision-making. However, current research pushes this framework further, advocating for a hierarchical control structure to better support large-scale and dynamic deployments.

This emerging hierarchical architecture separates RIS control into two primary roles. The first is the **meta-controller**, typically located on the RAN or edge-cloud side, which performs global optimization tasks. It is responsible for high-level decisions such as which RISs to activate, when to place them in sleep mode to save energy, and how to allocate RIS resources in response to network-wide Quality of Service (QoS) constraints. The second is the **sub-controller**, often located on-board the RIS or at a nearby edge node, which handles rapid local actuation. This includes real-time tuning of phase shifts and reflection amplitudes based on locally estimated channel state information (CSI). This two-level structure allows the network to combine strategic oversight with fast, context-aware adjustments, ensuring responsiveness and scalability.

Recent implementations of hierarchical reinforcement learning (HRL) in RIS systems have shown promising results. In particular, experiments in dense heterogeneous RAN environments demonstrated that HRL-based control architectures achieved more than double the energy efficiency of flat reinforcement learning baselines, without sacrificing throughput or reliability. These results are significant in the context of “green-6G” objectives, which prioritize energy-aware design without compromising performance [16]. By distributing intelligence across layers and balancing global objectives with local adaptation, hierarchical control enables RIS to function as agile, efficient, and cooperative network components.

3.3. Network-Controlled RIS

In network-controlled configurations, Reconfigurable Intelligent Surfaces (RIS) operate under centralized decision-making entities within the mobile network infrastructure. Control logic may be co-located with the base station (gNB), embedded in an Open RAN (O-RAN) near-real-time RAN Intelligent Controller (RIC), or outsourced to a third-party RIS service provider. This centralization enables coordinated optimization of multiple RIS panels across the network, allowing for global Quality-of-Service (QoS) enforcement, coordinated handovers, and efficient spectrum utilization. By integrating RIS into the same control plane as the rest of the RAN, network operators can dynamically adapt surface configurations in response to user mobility, traffic demand, or environmental changes [17].

4. Standardisation Outlook

As RIS technology matures toward wide-scale deployment, standardisation efforts become critical to ensure interoperability, scalability, and adoption. The ETSI Industry Specification Group on RIS (ISG RIS), established in September 2021, provides foundational reference architecture, deployment use cases, and technical requirements [18]. However, emerging research has identified three key gaps that must be addressed to enable RIS to transition from isolated prototypes to first-class programmable entities within 6G networks.

The first gap lies in the **accurate modeling of Beyond-Diagonal (BD) RIS architectures** in standard link-level simulators. ETSI currently relies on models that assume diagonal operation—each RIS element independently configured [19]. However, BD-RIS panels utilize reconfigurable impedance networks that introduce inter-element coupling, significantly influencing beamforming patterns, near-field shaping, and Integrated Sensing and Communications (ISAC). Without explicit support for cross-RIS coupling, existing simulation tools risk misestimating performance. Therefore, a standardised inclusion of coupling models is needed to ensure consistent and realistic evaluation across the industry.

Second, the proliferation of RIS in non-terrestrial networks (NTNs), such as satellites, high-altitude platforms, and **drones**, requires extending current standards. ETSI and 3GPP have begun addressing NTN requirements (e.g., timing, Doppler compensation, radiation patterns) [20], yet none formally support RIS-specific adaptations. A dedicated NTN-RIS profile must define constraints on reflection timing, mobility compensation, and radiation regulations for spaceborne deployments. This will enable safe and effective use of RIS as passive repeaters in NTN architectures.

By addressing these three specification gaps: cross-RIS coupling models, hierarchical RIC service models, and dedicated NTN-RIS profiles, standardisation can accelerate the integration of RIS into 6G networks. Closing these gaps will transform RIS from lab-based novelties into critical programmable infrastructure, enabling intelligent, efficient, and ubiquitous wireless systems that treat the propagation environment as a network-native, software-defined asset.

4.1. Quasi-Autonomous (Hybrid) RIS

Quasi-autonomous, or hybrid-controlled RIS, strike a promising balance between standalone and fully network-controlled operation. These systems embed limited intelligence, typically microcontrollers and power detectors, directly on the RIS panel to enable local decision-making. By measuring the incident signal through sequential probing-beam sweeps, the RIS constructs a local power map and estimates angle-of-arrival (AoA) information from the base station (BS) or user equipment (UE). Based on this data, the RIS autonomously selects and applies an optimal phase configuration without constant network input [21].

A key advantage of this approach is the near-zero fronthaul overhead, as control is performed locally without requiring high-bandwidth backhaul. This is especially valuable in dense deployments or remote installations where network connectivity may be limited or costly. Moreover, working prototypes operating at 28 GHz have demonstrated retargeting latency under 2 ms, enabling rapid beam adjustment suitable for highly dynamic environments such as mobile users or vehicle-to-infrastructure scenarios. These demonstrations indicate that hybrid RIS can meet strict latency demands without sacrificing deployment flexibility.

Despite their autonomy, hybrid RIS architectures remain receptive to external contextual cues. Simple "hints" such as UE mobility vectors or rough location estimates can be provided by the BS or UE to assist local adaptation, enabling joint global and per-user optimization. In essence, the RIS carries out fast, local tuning, while the network supplies coarse guidance to align with broader system objectives. Trials combining computer-vision assistance or hybrid sensing modes further illustrate how such systems can benefit from multi-modal feedback (e.g., visual, CSI, or location data) to enhance performance while maintaining control-plane simplicity [22].

Overall, quasi-autonomous RIS systems provide a compelling middle ground: they are highly responsive and low-overhead, yet remain extensible to broader network orchestration. As 6G architectures increasingly emphasize distributed intelligence and responsiveness, hybrid RIS offers a scalable, practical approach capable of supporting sophisticated use cases—from mmWave communications to ultra-low-latency vehicular links—while minimizing infrastructure and signaling requirements.

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5. Integrated Roles and Control Mechanisms in RIS-Assisted vRAN with UAVs

As next-generation mobile networks evolve to incorporate programmable environments and mobile infrastructure components, the orchestration of Reconfigurable Intelligent Surfaces (RIS), Unmanned Aerial Vehicles (UAVs), and virtualized Radio Access Networks (vRAN) becomes increasingly complex. This section outlines the key actors, their runtime responsibilities, and the associated control loops that enable real-time coordination across heterogeneous network elements. Together, these components enable dynamic, low-latency, and performance-optimized end-to-end control for aerial RIS-assisted communication systems.

5.1. Actors and Responsibilities

The integrated system architecture relies on a layered set of controllers and hardware elements, each with distinct roles and timescales. At the heart of the network-side intelligence is the Real-Time vRAN Controller, typically implemented as a near-real-time RAN Intelligent Controller (RIC) hosting xApps responsible for radio slice optimization, beamforming weights, scheduling, and handover decisions within the disaggregated Central Unit–Distributed Unit–Radio Unit (CU-DU-RU) stack. Operating within a control interval of 10 milliseconds to 1 second, this controller ensures that vRAN performance objectives are met while adapting to load and mobility fluctuations.

Complementing the vRAN control logic is the Real-Time UAV Controller, a microservice operating at the edge (e.g., on an edge server or embedded platform) responsible for piloting the drone-mounted BS or RIS relay node. It provides telemetry such as 3D position, velocity, battery status, and payload constraints. Operating at runtimes of 50 to 100 milliseconds, this controller also exposes APIs for trajectory planning and stability monitoring, enabling higher-layer optimization components to account for UAV kinematics and energy constraints.

A key enabler of this architecture is the Real-Time RIS Controller, which can be implemented as either a RIS-focused xApp within the near-RT RIC or as a standalone microservice. This controller could ingest data from both the vRAN and UAV subsystems, such as slice-level KPIs, E2 telemetry, and UAV telemetry, computing optimal phase- and power-control matrices for the RIS. Using efficient algorithms, we could arrive at near-millisecond control loops (operating in the 1–10 ms range), where the controller adapts the RIS's reflection pattern in real time to compensate for user movement, UAV drift, and link-quality fluctuations. For instance, in [24] the authors developed a 20×20 RIS prototype with a high-speed control board that enables real-time updates of the reflection coefficients, demonstrating the feasibility of dynamic beam tracking in response to environmental changes.

Beneath this software-defined control plane lies the Micro-Controller, an on-board embedded unit responsible for element-level operations at the RIS panel. It applies the bias voltages to configure the tunable unit cells and performs low-rate sensing (e.g., power, temperature), while ensuring regulatory compliance such as Equivalent Isotropically Radiated Power (EIRP) limits and Listen-

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Before-Talk (LBT) policies. Operating at microsecond granularity (10–100 μs), this component is essential for implementing ultra-fast local adjustments that bypass higher-latency network layers.

Finally, the RIS Panel acts as the physical layer interface, a hybrid passive/active metasurface capable of shaping electromagnetic wavefronts toward target UEs. It operates continuously in the background, reflecting or modulating incident signals according to the phase configuration received from the controllers. In essence, the RIS panel serves as the execution layer for the abstract beamforming logic generated by the higher control stack.

5.2. End-to-End Control Loops

To enable efficient operation across diverse timescales and functionalities, the system leverages **multi-tiered control loops** that connect global optimization objectives with local responsiveness.

1. **Global Optimization (Non-/Near-RT):** Recent advances in UAV–RIS–vRAN integration have demonstrated how O-RAN's E2 interface and emerging service models (such as E2SM-KPM and E2SM-RC) can enable closed-loop orchestration of RIS configurations, UAV trajectories, and gNB beamforming in real time [] show that jointly optimizing UAV trajectory and RIS phase shifts significantly enhances the average achievable rate in RIS-assisted UAV communications, using successive convex approximation techniques to adapt to dynamic environment [7]. Extensions of this idea leverage Near-RT RIC xApps consuming channel-state and KPI metrics to drive coordinated control, with O-RAN service models enabling slice-aware and CSI-aware commands. Experimental prototypes at mmWave frequencies (around 28 GHz) validate that deploying UAV-carried or ground-mounted RIS with adaptive control can yield robust coverage and throughput improvements, supporting gains in high-mobility scenarios [26].
2. **Fast Local Adaptation (Micro-RT):** To reduce latency and fronthaul demands, the RIS Micro-Controller autonomously conducts periodic power-sensing sweeps using a preloaded codebook of phase configurations. Based on observed signal strength, it estimates the AoA/AoD between the BS and UE, then selects a refined phase vector to maintain optimal beam alignment. These operations occur between global updates, keeping latency under 2 milliseconds and reducing control signaling by several orders of magnitude compared to element-wise instructions. This ensures seamless responsiveness to local changes, such as user movement or UAV vibrations.
3. **UAV Trajectory Feedback Loop:** The UAV Controller continuously streams waypoints and flight dynamics updates, including gust alarms and attitude shifts. The RIS Controller uses this real-time telemetry to proactively recompute phase configurations, maintaining beam alignment and user connectivity despite rapid UAV motion. This control loop is essential for ensuring coverage continuity in aerial RIS deployments, particularly when operating in environments with wind disturbances or path variability.

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5.3. System Architecture

Figure 2 encapsulates the core control-plane relationships that bind the reconfigurable intelligent surface to its neighbouring actors in a RIS-assisted, UAV-enabled virtualised RAN. Although deceptively simple, the diagram touches all four conceptual layers introduced in Section 6.2 (metasurface, embedded control, intelligence, interface) and mirrors the orchestration principles advocated by the most recent specifications from ETSI ISG RIS, the O-RAN Alliance and 3GPP's Rel-19/Rel-20 study items on RIS and non-terrestrial networks (NTN).

As illustrated in the Figure below, the real-time (RT) RIS Controller interfaces with both the RT virtualized radio access network (vRAN) Controller and the RT unmanned aerial vehicle (UAV) Controller to coordinate RIS behavior in dynamic environments.

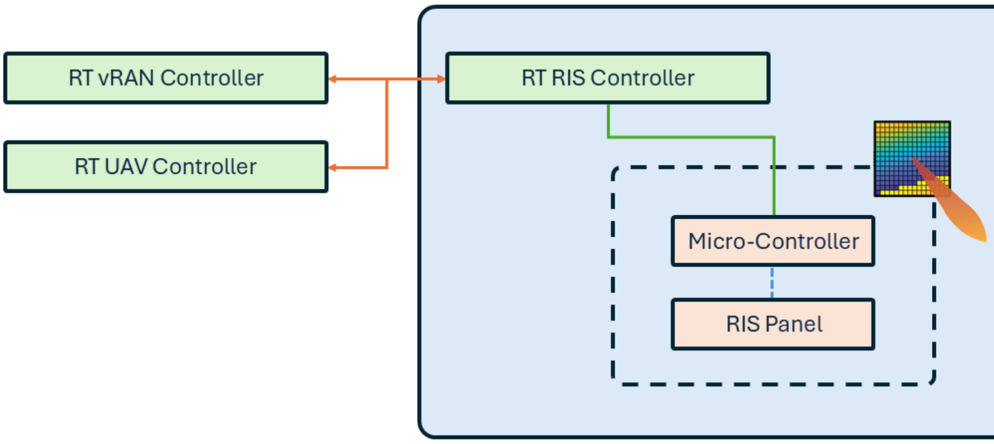

FIGURE 2 ARCHITECTURE OF THE RIS CONTROL SYSTEM

1. Placement in the Layered RIS Stack

At the physical edge, the RIS panel represents the *Metasurface Layer*. It is assumed to be a hybrid passive/active structure containing sparse low-noise-amplified tiles for sensing and gain while the majority of elements remain passive, in line with the energy-aware layouts reported in ETSI GR RIS-003. Directly beneath the dashed outline sits the on-board micro-controller, charged with applying bias voltages, sampling on-board sensors and enforcing spectrum-access constraints such as EIRP caps or Listen-Before-Talk timers demanded by regional EMC regulation. Operating in the 10–100 µs domain, this unit realises the *Embedded Control Layer*.

The RT RIS Controller itself occupies the *Intelligence Layer*. It fuses network information arriving from the RT vRAN Controller (slice KPIs, CSI snapshots, scheduling maps) and mobile-platform cues from the RT UAV Controller (attitude, way-points, battery state) to compute a phase-power matrix that maximises a composite objective: cell-edge throughput, UAV endurance and interference containment. Empirical studies at 28 GHz report reaction times as low as 1–10 ms when the controller is co-located at an edge node with GPU acceleration—well inside the near-real-time budget defined by O-RAN WG3 for xApps.

Finally, the orange and green arrows external to the RIS box symbolise the *Interface Layer*. To the north, they correspond to an extended O-RAN E2-terminating Surface Management function: ETSI's draft RCI (RIS-Controller Interface)".

2. Compliance with Emerging Standards

ETSI ISG RIS. Clause 5.2 of ETSI GR RIS-001 mandates a logical separation between the "RIS Control Function" and the "RIS Function". The figure complies by situating the RIS Control Function (RT RIS Controller) outside the dashed hardware enclosure, while the RIS Function (micro-controller + panel) remains inside. It further honours the self-configuration aspirations of ETSI GR RIS-002 by allowing the micro-controller to execute autonomous codebook sweeps when back-haul latency spikes.

O-RAN Alliance. The orange bidirectional link to the RT vRAN Controller maps to an E2 interface running an evolving E2SM-RIS service model. This placement satisfies WG9's requirement that RIS optimisation logic reside in the near-RT RIC for closed-loop control with xApp granularity (10 ms–1 s). At the same time, the green dashed path from the RT RIS Controller to the micro-controller anticipates WG4's fronthaul specification for "surface management units", including clock synchronisation borrowed from the Open Fronthaul Initiative.

3GPP NTN Work-Items. When the RIS is air-borne (e.g., mounted on a UAV), 3GPP TR 38.811 and TR 38.821 impose Doppler-resilient timing budgets. The depicted architecture meets these by inserting trajectory feedback from the RT UAV Controller directly into the RIS control loop, ensuring pre-emptive phase-table rotation as attitude changes are forecast.

5.4. Inter-Layer Data Flow and Timing Harmonisation

The arrow colours convey latency tiers. Orange (10 ms–1 s) signals *near-RT* coordination between network slices and the programmable environment—ample time for the RT vRAN Controller to push updated KPIs or receive telemetry. Green (1–10 ms) carries *sub-RT* reconfigurations: phase-table revisions, codebook indices and null-steering directives destined for the micro-controller. Blue (≤100 µs) is reserved for *µ-RT* actuation within the RIS hardware itself—fine-grain DAC updates, power-detector reads and safety policing.

Crucially, this stratification prevents feedback storms. Dense RIS deployments that employ BD-RIS coupling (§ 6.2) would overwhelm back-haul if raw 10-kb phase vectors were pushed every millisecond; the compressed index method reduces traffic by ≈90 %, satisfying both fronthaul capacity limits and O-RAN security posture SP-009.

5.5. Gaps and Forward-Looking Enhancements

Although compliant, several extensions would future-proof the design:

Northbound Exposure. Publishing open, REST-style northbound APIs from the RT RIS Controller allows RAN Intelligent Controllers to request "what-if" evaluations, facilitating cross-slice optimisations and SON frameworks anticipated in ITU-T FG NET-2030.

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Cross-RIS Coordination Plane. For dense deployments, east-west links among RT RIS Controllers (dotted in future revisions) could negotiate mutual nulls to suppress inter-RIS interference—an aspect ETSI's coupling model work item (RIS-WI-008) is expected to cover.

Integrated Sensing Data Path. Where the RIS serves an ISAC role, sensed micro-Doppler or localization data should flow upstream via a secure telemetry channel, re-entering the ML pipeline for adaptive beamforming. Current O-RAN drafts do not yet define this, though WG6 has opened a study item.

5.6. Real-Time RIS Controller Architecture

The Real-Time RIS (RT-RIS) Controller is the functional and computational core responsible for managing the behavior of a reconfigurable intelligent surface in a dynamic wireless environment. Unlike purely passive metasurfaces or standalone panels with embedded microcontrollers, the RT-RIS Controller operates within a broader system context, interfacing with the virtualized RAN (vRAN), UAV controllers, and the RIS panel itself. As illustrated in Figure X, the controller is organized into modular components that support event-driven control, machine learning-based adaptation, and real-time decision-making within strict latency constraints.

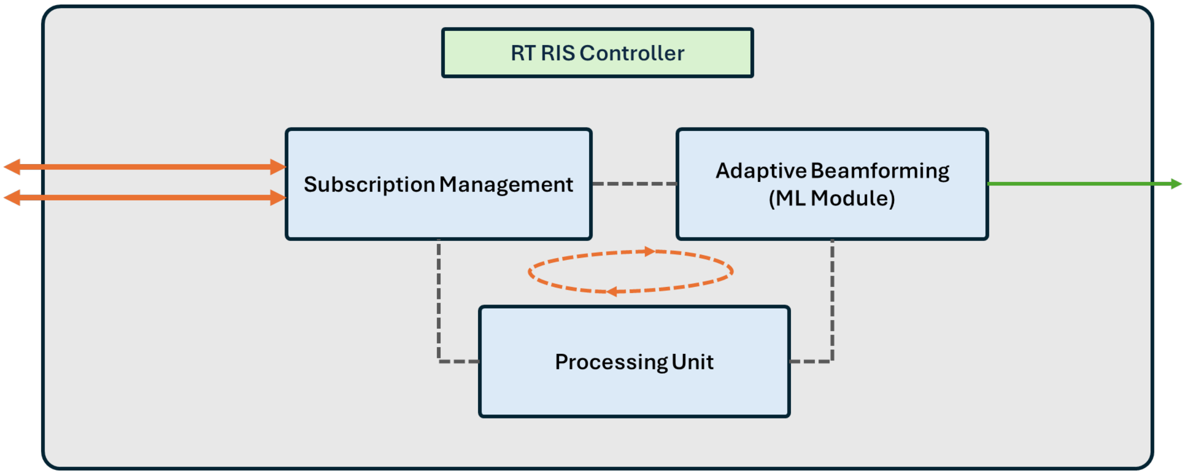

FIGURE 3. INTERNAL ARCHITECTURE OF THE RT RIS CONTROLLER.

At the interface layer, the Subscription Management module handles bidirectional communication between the RIS controller and external entities. This includes receiving configuration intents, CSI snapshots, and telemetry from the vRAN controller (typically via an extended O-RAN E2 interface or a proposed R-RIS interface), as well as receiving predictive updates from the UAV controller, such as mobility vectors and gust alarms. The subscription manager also manages the publication of RIS telemetry and status reports back to the RIC or service orchestration layer. This ensures that the RIS remains an active, reportable node in the network fabric, capable of responding to high-level control policies while preserving local autonomy.

Adjacent to the subscription interface is the Adaptive Beamforming module, which serves as the controller's learning and optimization engine. This module is typically driven by machine learning algorithms, such as reinforcement learning agents trained to map real-time inputs (e.g., CSI, UAV telemetry, power maps) to RIS phase configurations. Its function is to continuously compute or update the optimal phase and power matrices for the RIS, based on either real-time feedback or long-term policy goals set by the network. The beamforming module not only enables high-throughput, directional signal reflection but also supports advanced features like user-specific optimization, joint UAV-RIS coordination, and Integrated Sensing and Communications (ISAC).

Both the subscription and ML-driven beamforming modules rely on a centralized Processing Unit**,** which acts as the data fusion and execution engine. The processing unit aggregates inputs from external systems and internal sensors—including those originating from the RIS's embedded Microcontroller—which was previously described as responsible for fine-grained, element-level biasing and environmental sensing. It is within this unit that incoming data streams are processed into actionable control updates, scheduled into command queues, and forwarded downstream to the microcontroller via low-latency wired or wireless links. This pipeline ensures tight coordination between system-level intelligence and hardware-level execution.

Crucially, the RIS panel itself—the physical substrate of electromagnetic control—executes the beamforming instructions received from the RT-RIS controller. The RIS Panel, previously described as a hybrid active/passive metasurface, applies these instructions in real time, adjusting reflection coefficients element-wise to shape the wireless channel in accordance with the controller's objectives. The microcontroller ensures these commands conform to physical and regulatory constraints (e.g., EIRP, LBT), thus enforcing safety and standards compliance.

The interplay between the RT-RIS Controller and the underlying panel infrastructure is essential to meeting the latency, adaptability, and scalability goals of RIS-native 6G deployments. The controller bridges high-level intent from the network with low-level control of the radio environment. It also supports integration with the O-RAN architecture through proposed enhancements to the E2 interface and ongoing efforts within ETSI to define RIS-specific telemetry and control profiles.

In sum, the Real-Time RIS Controller functions as the nervous system of the programmable surface, aligning inputs from UAVs, vRAN controllers, and environmental sensors to execute real-time, learning-enhanced beamforming. This architecture marks a critical step in the transformation of the wireless medium from a static channel into an intelligent, programmable resource—realizing the vision of a software-defined propagation environment at the heart of future 6G networks.

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6. Summary and Conclusions

In this work, we introduced an architecture for Reconfigurable Intelligent Surfaces (RIS) in Beyond 5G (B5G) systems, emphasizing its integration with real-time (RT) control frameworks and its interaction with UAV and vRAN controllers. After reviewing existing literature on RIS-enabled communications, UAV-assisted networking, and vRAN control, we identified the lack of coordinated control mechanisms across these components as a critical challenge. To address this, our proposed architecture integrates an RT RIS controller responsible for managing RIS panels via embedded micro-controllers, while maintaining bidirectional communication with RT UAV and RT vRAN controllers. This setup enables a streamlined control flow, where the RIS configuration dynamically adapts to UAV-assisted deployments and vRAN requirements, supporting efficient coverage enhancement and resource allocation. By aligning RIS control with real-time UAV positioning and vRAN orchestration, the system establishes a unified control plane capable of reacting promptly to network dynamics.

The proposed RIS architecture demonstrates a practical pathway to integrating intelligent surfaces within B5G networks by coupling RIS control with UAV and vRAN operations under a unified RT control framework. This design improves network flexibility by enabling RIS panels to be reconfigured in real time based on UAV mobility and vRAN coordination, thus enhancing coverage, capacity, and adaptability in dynamic environments. Moreover, the modular design of the architecture supports future extensions, such as incorporating AI-driven optimization for RIS configuration and UAV trajectory planning. Overall, this work establishes a foundational step toward the practical deployment of RIS-assisted UAV and vRAN systems, addressing existing control and orchestration gaps and paving the way for more intelligent and adaptive B5G network infrastructures.

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