Adaptive Network Management in 6G O-RAN
A Framework for Dynamic User Demands

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Abstract. *6G networks demand unparalleled adaptability and energy efficiency. This work presents a dynamic O-RAN-based framework integrating the SMO, Near-RT RIC, and Non-RT RIC for real-time analytics, intelligent policy application, and adaptive energy management. By deploying rApps (e.g., Energy Savings) and xApps, the framework dynamically clusters and manages radio nodes, optimizing resource allocation while reducing power consumption. A prototype implementation shows substantial improvements over traditional static approaches, notably conserving energy during low-demand periods while sustaining high performance at peak times. Key components enable seamless integration across the network, demonstrating the framework's capability to adapt to varying demands and establishing a new benchmark for 6G network management.*

1. Introduction

The emergence of Sixth Generation (6G) drives mobile networks to offer higher data rates, lower latency, and stronger connections [Tataria et al. 2021, Tomkos et al. 2020]. Base Stationss (BSs) split into Central Units (CU), Distributed Units (DU), and Radio Units (RU), fostering efficient resource allocation. Virtualization (Virtualized Radio Access Network (vRAN)) and Virtual Network Functions (VNFs) deployed over Network Function Virtualization Infrastructure (NFVI) reduce hardware dependence [Jaafari and Chuberre 2023]. At the same time, novel Open Radio Access Network (O-RAN) features such as the Near Real-Time RAN Intelligent Controller (Near-RT RIC) and Non Real-Time RAN Intelligent Controller (Non-RT RIC) enable adaptable network policies. Their synergy sustains performance targets like throughput, reliability, and energy efficiency [Alavirad et al. 2023].

The transition to 6G and virtualized Next Generation Radio Access Network (vNG-RAN) highlights sustainability, prompting advanced schemes for containerized deployments and Radio Access Network (RAN) RAN Intelligent Controllers (RICs). Dynamic network management arises as a key priority, using open O-RAN standards to optimize resource usage, while addressing sporadic capacity demands. Energy-saving methods (e.g., cell deactivation) are a principal focus [Beshley et al. 2022, O-RAN Alliance 2023d]. Amid fluctuating user demands, a central question emerges: *How can RAN be orchestrated for agile infrastructure and minimal energy use?*

Studies underline the need for adaptive resource management, real-time data traffic control, and integrated orchestration frameworks [Mungari 2021, Vila et al. 2022, Kasuluru et al. 2023]. Furthermore, insights into advanced O-RAN strategies, such as Massive MIMO and network slicing, underscore the importance of dynamic adjustment for application performance and energy goals [O-RAN Alliance 2023c, O-RAN Alliance 2023e].

Key research questions focus on (i) effectively integrating O-RAN components, (ii) pinpointing representative scenarios of demand fluctuation, (iii) disaggregating Near-RT RIC functions, and (iv) evaluating orchestration strategies [Almeida et al. 2023]. Proposed answers emphasize adaptive techniques in resource assignment, traffic steering, and flexible RIC placement. Evaluation involves monitoring latency, throughput, and consumption metrics with real-time insights [O-RAN Alliance 2023b]. In "Adaptive Network Management in 6G O-RAN: A Framework for Dynamic User Demands", we detail an O-RAN-based orchestrator for real-time resource and energy optimization, a mathematical engine to adapt and reduce power usage under shifting conditions, RIC-based platforms for scalable and sustainable operation, and open-source materials to advance 6G research.

To validate these strategies, simulations and prototype emulations test performance during high- and low-load intervals, revealing how the Near-RT RIC and Non-RT RIC cooperate to maintain service continuity. This work culminates in a flexible architectural framework, bridging energy efficiency with user-centric demand management. The final Sections detail fundamental concepts (Section 2), related literature (Section 3), the proposed system (Section 4), evaluation plans (Section 5), and results leading to conclusions and future directions (Sections 6 and 7).

2. Background

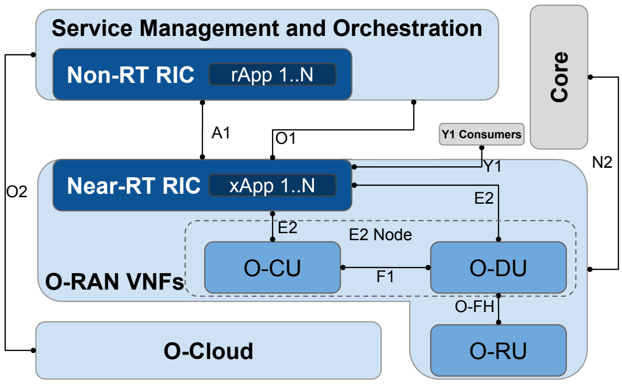
Virtualizing the RAN (vRAN) enables critical disaggregation of hardware and software, allowing for flexible function placement among CUs, DUs, and RUs. This flexibility improves adaptability, reduces costs, and supports higher data rates and lower latency. Conventional RAN designs began with Distributed Radio Access Network (D-RAN), co-locating Baseband Units (BBUs) and Remote Radio Heads (RRHs), moved to Cloud Radio Access Network (C-RAN), which centralizes BBUs in the cloud. Eventually, vNG-RAN introduced up to two split points, creating CU, DU, and RU units to meet various latency, bandwidth, and traffic scenarios [3GPP 2017].

The Crosshaul network comprises Fronthaul (FH), Midhaul (MH), and Backhaul (BH), handling segmented traffic flows among disaggregated nodes. Each split option (O1–O8) tackles different capacity and latency requirements. These Network Function Virtualization (NFV)-driven RAN functions run on software-over-general-purpose servers, following European Telecommunications Standards Institute (ETSI) guidelines. Lower splits can simplify the RU but demand more from the transport, while higher splits centralize processing for tighter Quality of Service (QoS) control [Bernardos et al. 2019].

The O-RAN initiative promotes openness, enabling multi-vendor RANs via standard control loops and interfaces. A Service Management and Orchestration (SMO) manages Fault, Configuration, Accounting, Performance, and Security (FCAPS) and orchestrates cloud resources, aided by a Non-RT RIC (for policy-based controls) and a

Near-RT RIC (for near-real-time decisions) [O-RAN Alliance 2023a]. Figure 1 provides a high-level depiction of O-RAN, showing the Non-RT RIC in the SMO domain and the Near-RT RIC controlling user-plane and lower-layer functions. The SMO uses A1 for policy exchange; O1, O2, and the M-plane for configuration, resource management, and RU commands [O-RAN Alliance 2023a].

Figura 1. High-Level View of the O-RAN Architecture



Moving RAN functionality onto commercial servers increases energy usage in CU/DU, amplified by radio power amplification at RUs and transport-network overhead [Azariah et al. 2022]. Balancing splits, centralization, and transport demands is crucial for efficient energy usage [Larsen et al. 2019]. Approaches include dynamically activating/deactivating DUs, selectively centralizing processing, and indirectly reducing routing load to trim power while maintaining QoS.

3. Related Work

This section provides a concise overview of core O-RAN research efforts since 2021, highlighting strategies to meet dynamic user demands on the path toward 6G networks. Three main aspects are addressed: (i) efficient O-RAN integration for managing fluctuating traffic and resource needs, (ii) representative use cases focusing on energy-saving approaches, and (iii) a concluding perspective.

3.1. Efficient O-RAN Integration for Adaptive Resource Demands

Studies emphasize resource allocation and data traffic management approaches to handle varied service requirements. Table 1 summarizes selected works exploring O-RAN components to adaptively meet user needs in near-real time. Multiple authors propose Application on Near-Real-Time RAN Intelligent Controller (xApp)-based solutions for dynamic resource provisioning [Mungari 2021, Yoo et al. 2022], while others address load balancing via advanced scheduling [Orhan et al. 2021, Kouchaki et al. 2022]. Recent research also integrates energy-aware principles, suggesting that agile spectrum and power allocation can significantly optimize performance under varying user densities [Sohaib et al. 2024].

3.2. Energy-Saving Use Case in O-RAN

Among various O-RAN applications, energy efficiency stands out as a vital use case for addressing irregular user activity. Table 2 highlights studies focusing on energy optimiza-

Tabela 1. Sample of Works Addressing Resource Adaptation in O-RAN

Reference	Focus	Experimentation	Key Aspect
[Yoo et al. 2022]	Load balancing	Emulation (SD-RAN)	xApp for dynamic allocation
[Kouchaki et al. 2022]	QoE maximization	Emulation (OSC)	Adaptive scheduling
[Sohaib et al. 2024]	Green resource allocation	Emulation/Simulation	DRL-based energy efficiency
This Work	Dynamic resource management	Emulation/Simulation	xApp/rApp synergy

tion in O-RAN, showing how advanced orchestration and intelligent switching off/on of resources maintain performance while reducing power consumption.

Tabela 2. Selected Energy-Saving Efforts in O-RAN

Reference	Objective	Method	Key Feature
[Abedin et al. 2022]	Elastic slicing for IIoT	Simulation	Reinforcement learning
[Hammami and Nguyen 2022]	Off/On-policy Deep Reinforced Learning (DRL) for resource allocation	Simulation	Energy-aware scheduling
[Kalntis and Iosifidis 2022]	vBS optimization for better energy performance	Testbed	Online learning
[Schiavo et al. 2024]	Shared pool of heterogeneous processors	Testbed	Efficiency in vRANs
This Work	Dynamic resource management	Emulation/Simulation	xApp/rApp synergy

Collectively, these works demonstrate that advanced switching, selective radio usage, and intelligent orchestration (often powered by Machine Learning (ML)/Artificial Intelligence (AI)) help tailor O-RAN to fluctuating demands with lower energy footprints. Recent O-RAN research underscores the importance of adaptive resource control, energy-efficient solutions, and flexible design strategies. By integrating advanced xApp/rApp intelligence, scalable control functions, and data-driven optimization, O-RAN can balance performance and sustainability in evolving 6G contexts. The subsequent sections of this work provide details on an overarching framework that uses these strategies for robust, energy-aware network management.

4. Framework Architecture and Use Case

This section presents an adaptive network management framework for 6G O-RAN, emphasizing dynamic user demand and energy efficiency. We outline key project decisions, highlight major architectural components (SMO, Near-RT RIC, Non-RT RIC), and present specialized Application on Non-Real-Time RAN Intelligent Controllers (rApps) and xApps that optimize resource usage while maintaining satisfactory user experiences.

Key Decisions and Modified Components. Our framework deploys rApps (e.g., rApp Energy Savings) in tandem with architectural blocks such as the SMO and Near-RT RIC, exploiting O1 and A1 interfaces to manage radio power and handover strategies. A synergy among these components ensures that energy-saving policies are data-driven and rapidly enforced. We introduced custom adjustments, e.g., enhanced *VespaMgr* configurations in the Near-RT RIC, orchestrated local storage with the Rancher Local Path Provisioner for Kubernetes (K8s), and updated the Policy Management Service to align with partial A1 Interface (A1) Application Programming Interface (API) support. For broader integration, we adapted SMO components from the Open Radio Access Network Software Community (OSC) to manage VNF Event Streaming (VES) messages, store them using InfluxDB, and deliver real-time monitoring insights via Kafka.

Architectural Overview. Figure 2 depicts the three main components forming our adaptive RAN management: (1) SMO, including data ingestion (Data Lake and Data River) and A1 policy handling; (2) Near-RT RIC, deployed on Open Cloud (O-Cloud), conducting near-real-time tasks and hosting xApps for monitoring and control; (3) Non-RT RIC, which uses rApps to analyze historical data and issue long-term policies. Deployed E2 Node (E2N) nodes can be powered or paused to match user demand, supporting scalable and energy-efficient operation.

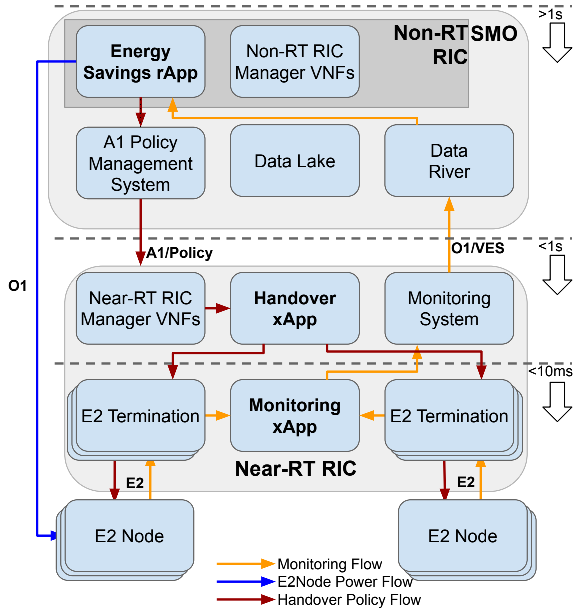


Figura 2. Adaptive network management framework architecture.

Use Case: Energy Savings. We designed the *rApp Energy Savings* in the Non-RT RIC to minimize power consumption across E2Ns based on current load, coverage overlap, and dynamic triggers. The xApp Monitoring collects real-time User Equipment (UE) and radio parameters (e.g., Reference Signal Received Power (RSRP), Signal-to-Interference-plus-Noise Ratio (SINR), throughput), supplying them to the rApp through the SMO. When feasible, specific E2Ns are deactivated, and UEs are handed over elsewhere. This policy is computed as an optimization problem seeking to reduce an Open Radio Unit (O-RU)'s transmit power and static consumption while meeting user demands. A shortened objective:

$$\text{minimize} \quad \sum_{t} \sum_{r_j} \left(\frac{\mathrm{w}_{r_j}^{t}}{\eta} + \theta_{r_j}^{\mathrm{RF}} \right), \tag{1}$$

subject to capacity, association, and coverage constraints. Triggers include at least 20% changes in UE connections or timer-driven updates, ensuring timely adaptation for load spikes or idle conditions.

xApp Handover. On the Near-RT RIC, a xApp Handover enacts directives from the rApp Energy Savings, toggling E2Ns on/off and shifting UEs accordingly. It applies real-time decisions via E2 protocols to manage activation, ensuring smooth mobility for end users while lowering energy overhead.

5. Evaluation Methodology

This section outlines our systematic approach to assess optimization strategies within the O-RAN ecosystem, emphasizing real-world scalability and efficiency. Our methodology is grounded in a multifaceted experimental environment that integrates the Non-RT RIC, Near-RT RIC, and SMO, supplemented by enhancements in E2N simulation and a dedicated UE Manager. These elements jointly enable the replication of challenging network scenarios, such as high-density events.

Experimental Setup: Deployed on a Kubernetes (v1.21) cluster with four worker nodes (each 4 vCentral Processing Units (CPUs), 8 GB RAM, 50 GB disk) plus a master node (8 vCPUs, 16 GB RAM), our environment accommodates representative RAN conditions. We host the cluster via VMware ESXi 6.7 on a DELL PowerEdge M610 server (Intel Xeon X5660, 192 GB RAM).

Core Framework Components: The Non-RT RIC utilizes rApps for policies, data aggregation, and decision-making through the A1 interface, enabling real-time coordination. The Near-RT RIC leverages xApps (e.g., handover, monitoring) for fine-grained control and incorporates E2sim [Almeida et al. 2023, Bruno et al. 2023b] to simulate UE metrics and handovers. The SMO orchestrates and manages RAN operations; its minimal implementation comprises a VES Collector, InfluxDB support, and Kafka-based messaging to consolidate data flows and monitoring.

Scenario and Metrics: A soccer stadium use case is modeled, positioning antennas and thousands of UEs under complex channel conditions; Crucial metrics include Energy Efficiency (EE), evaluated by total consumption under dynamic load and comparing a baseline (all nodes at full power) versus adaptive power; Resource Utilization, encompassing CPU, memory, and response times for rApps and xApps; and Handover Performance, considering success rates, latencies, and QoS impact.

Procedures: The network is initialized by deploying antennas (cells) and UEs to reflect realistic crowd density. Each UE simulates data, voice, and video traffic, scaling to 1.024 UEs. The rApp optimizes energy usage, while xApp handles real-time monitoring and expedites edge handovers. Performance logging collects key indicators (CPU, memory, Energy Efficiency (EE), connection metrics) via Prometheus, Kafka, and InfluxDB.

We repeat experiments to ensure statistical reliability, averaging results and capturing standard deviations. The resulting data illustrate the benefits and trade-offs of deploying optimized energy policy and control within O-RAN, indicating how adaptive strategies can boost efficiency, particularly during surges in user density.

6. Use Case Energy Saving Results

This section presents the energy-saving performance of our adaptive network management framework in a 6G O-RAN environment. By dynamically activating or deactivating E2Ns depending on user load, the system aims to reduce power consumption while maintaining acceptable performance.

Figure 3 shows how energy usage changes with the number of UEs. At lower loads (e.g., 16–64 UEs), only one E2N is active. As more UEs join (e.g., 128–512), additional E2Ns are turned on incrementally. For 1024 UEs, all 17 E2Ns become active to support the increased demand. Although total power draw grows with more UEs, the energy consumed per UE declines, reflecting efficient resource utilization when distributed over a larger user base.

Figure 4 highlights how CPU and memory usage scale with rising UE counts for

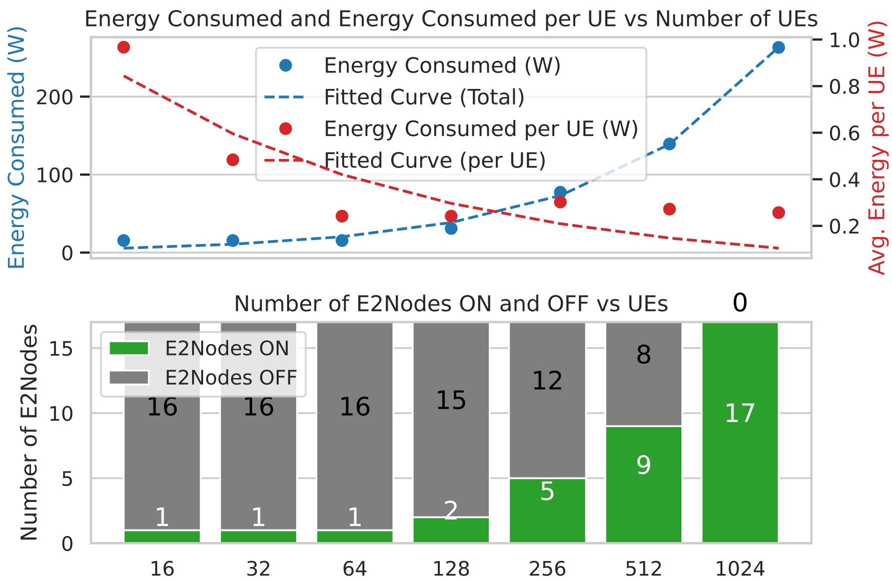


Figura 3. Energy consumption as the number of UEs increases (top) and corresponding active/inactive E2Ns (bottom).

the rApp Energy Savings. As the system processes more connections, average CPU usage increases from about 0.09 to 8 millicores, while mean memory consumption grows from 45 MB to roughly 1070 MB. Larger user volumes also lead to longer processing times, though the framework can still manage the expanded load without excessive overhead.

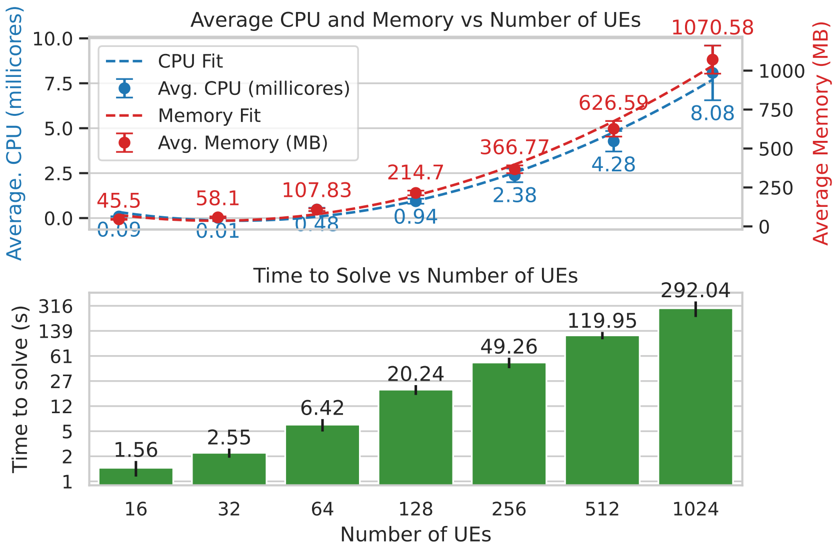


Figura 4. Resource usage (top) and time to solve demands (bottom) for increasing UEs under rApp Energy Savings.

These results demonstrate an effective approach to balancing capacity and energy efficiency in 6G O-RAN scenarios. The rApp-based energy policies dynamically adjust the number of active E2Ns, lowering power drain at low loads and efficiently allocating resources under heavier traffic. Such adaptable strategies can help operators minimize operational costs while sustaining adequate performance for various user densities.

7. Conclusion

We introduced an adaptive network management framework for 6G O-RAN, emphasizing dynamic user demand and EE. By integrating rApps, xApps, and the Near-RT RIC/SMO infrastructure, the system supports energy-saving primitives (e.g., Carrier and Cell Switch Off/On), ensures resource adaptability, and optimizes network responsiveness. Extensive simulations confirmed enhanced EE and service quality in dense-coverage scenarios, although limited antenna availability, dependency on OSC, and reliance on simulated RU remain key constraints. Furthermore, we are investigating optimization approaches to enhance rApp scalability by integrating a genetic algorithm-based method alongside heuristic strategies for efficient resource allocation. Additionally, we are developing scalable solutions for the Near-RT RIC's VESPA module to ensure robust near-real-time decision-making as network demands increase.

Building on complementary works [Rodrigues et al. 2022, de Lima et al. 2022, Macedo et al. 2022, Morais et al. 2023, Bruno et al. 2023b, Almeida et al. 2023, Bruno et al. 2023a, Bruno et al. 2024a, Bruno et al. 2024b], the findings underscore the relevance of adaptive orchestration, data analytics, and optimization techniques integration for next-generation networks. By exploring advanced placement strategies, refining observability tools, and conducting field experiments, forthcoming research can deliver more robust RAN solutions, ultimately shaping greener, more efficient 6G systems with more excellent coverage, scalability, and user-centric configuration.

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