Open RAN Handbook 2nd Edition: a Guide for Sustainable Networks

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Authors:
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Version:
1.0

Document Status:
Released

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Document Control

Revision History

Version	Date	Authors	Change Summary
1.0	Feb. 2025	Akash Dumbre (Vodafone) Eng Wei Koo (Keysight) Christian Nunez-Alvarez (Keysight) Jasper Li (Keysight)	First release

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1 Executive Summary

Network energy efficiency is a key sustainability goal for mobile network operators (MNOs) around the world aiming to reduce environmental impacts and achieve operational cost savings, as energy consumption is a major component of their operational expense (OpEx). European energy costs have risen by more than 400 percent, on average, over a two-year period. While many MNOs' individual OpEx cost components have dropped over a similar period, energy costs have risen by 2 percent of overall OpEx cost and are expected to continue to increase.

Against this context, Vodafone has set ambitious targets to reduce its carbon footprint. It aims for net-zero emissions across its entire value chain by 2040 and, in the near term, powering all operations with renewable energy by 2025.

The radio access network (RAN) consumes most of the network energy (~70%) and is therefore the focus of optimization for monolithic base stations in terms of energy consumption, efficiency, and artificial intelligence (AI) / machine learning-enabled (ML) savings techniques.

While the Open Radio Access Network (Open RAN) is an attractive option for operators with key benefits such as supplier diversification and liberating AI / ML innovation, it remains necessary to demonstrate that its energy efficiency and savings aspects are at least on par with or better than those of monolithic RANs.

Vodafone has been a leader in advancing Open RAN deployments across its markets, with live sites currently operating in countries, including the UK and Romania, with the potential to deploy in other partner markets. These deployments demonstrate Vodafone's commitment to diversifying the vendor ecosystem and achieving greater network flexibility and efficiency. In addition, the key performance indicators (KPIs) of these sites now demonstrate that the performance of Open RAN exceeds that of the legacy equipment in most areas, including 4G and 5G call success rates, as well as download and upload speeds across multiple spectrum frequencies.

Since 2022, Vodafone has taken a pivotal step to evaluate and test the energy efficiency of Open RAN solutions by hosting a series of focused PlugFests. These events gathered multiple vendors and fostered collaboration to identify and develop innovative energy optimization techniques for Open RAN deployments.

In this handbook, Vodafone and Keysight will share:

- Progress on the state of the 3GPP and O-RAN ALLIANCE standards with respect to Open RAN energy savings features development.
- Open RAN energy consumption, efficiency, and savings benchmarking considerations, test scenarios, methodologies, and test setups for the Open Radio Unit (O-RU), Open Distributed Unit / Central Unit / Cloud (O-DU / O-CU / O-Cloud), RAN Intelligent Controller (RIC), and the associated xApps / rApps.
- Test results and key observations for the testing conducted with Vodafone's technology partners in the Vodafone labs, which started in 2022 up until the end of 2024.
- Recommendations for improving standards and product implementations.

2 Motivation and Challenges

Energy efficiency is a critical consideration in the evolution of Open RAN technology due to its significant impact on sustainability, operational costs, and overall network performance. The drive for greater energy efficiency stems from the increasing demand for data services, the deployment of higher-capacity networks like 5G, and the pressing need for environmentally sustainable solutions. Open RAN introduces a modular and disaggregated architecture that fosters supplier diversity and innovation, enabling collaboration across a diverse ecosystem of hardware and software providers. This diversity creates an exciting opportunity to pioneer advanced energy-saving techniques and establish benchmarks that can surpass traditional monolithic RAN systems.

Testing and validating energy efficiency in Open RAN components such as the O-RU, O-DU, O-CU, and the RIC involve addressing varying operational scenarios, traffic patterns, and deployment configurations that reflect real-world conditions. While promising in terms of enhancing efficiency, the inclusion of AI / ML-driven features adds layers of complexity to validation, requiring robust frameworks to assess the real-world effectiveness of such features. Furthermore, the dynamic nature of Open RAN networks, where components must adapt to changing workloads and environmental conditions, requires advanced testing methodologies that go beyond traditional lab environments to include real-world operational contexts. These advancements align with the industry’s broader shift toward automation and intelligent systems, creating a robust foundation for energy-efficient, future-ready networks.

Another challenge is aligning vendor-specific implementations with global standards. While organizations such as the 3GPP and O-RAN ALLIANCE are actively developing energy-saving features, the varying pace of adoption and differences in implementation across vendors create discrepancies in energy performance. These discrepancies highlight the need for clear, standardized benchmarks and collaborative efforts among stakeholders to harmonize approaches.

The collaborative efforts of global standards bodies like 3GPP and the O-RAN ALLIANCE should further increase the potential for unified approaches to energy efficiency. While vendor-specific implementations vary, the diversity presents an opportunity to drive alignment and innovation through collective efforts, ensuring Open RAN solutions deliver consistent and measurable energy savings.

The continued focus on energy efficiency testing, benchmarking, and real-world validation is not only a technical imperative but also an opportunity to set new industry standards. By embracing these opportunities, Open RAN can confidently demonstrate its ability to meet and exceed operators' energy efficiency expectations, paving the way for a more sustainable and economically efficient future for mobile networks.

3 Standardization and Industry Forums

The 3GPP and O-RAN ALLIANCE are actively developing specifications for radio access network energy savings.

The 3GPP focuses on the air interface and NG-RAN aspects of the network energy savings studies and normative specifications. Refer to Figure 1.

The O-RAN ALLIANCE focuses on specifying the requirements, architecture, procedures, protocols, and test specifications required to support interoperable, multi-vendor Open RAN functions for energy savings features and capabilities.

3.1 3GPP

3GPP Rel 17	3GPP Rel 18	3GPP Rel 19 - planned	6G - proposed
• AI/ML-based network energy saving o cell activation/deactivation o Handover strategy o Predicted energy efficiency/state • Load Balancing • Mobility Optimization	• SSB-less SCell operation • Spatial/power domain enhancements and on cell DTX/DRX • Low-Power Wake-up Signal/Receiver • efficient adaptation of power offset values between PDSCH and CSI-RS • cell handovers procedure enhancement(s) • Inter-node beam activation and enhancements	• On-demand SSB transmission • Adaptation of common signal/channel transmission • Ambient power/enabled IoT (energy harvesting, battery-less/storage) • Low-Power Wake-up Signal/Receiver (WUS/WUR)	• Zero Energy Devices • Reconfigurable Intelligent Surfaces (RIS) • Net Zero Networks

Figure 1. 3GPP release 17 - 19 energy-saving features

In Release 17, the 3GPP initiated a study item (3GPP RP-201304) on AI / ML for NG-RAN with network energy savings, one of the three use cases described in 3GPP TR 37.817 [1] which summarizes the output of this study.

Cell activation / deactivation is an energy-saving scheme in the spatial domain that exploits traffic offloading in a layered structure to reduce the energy consumption of the entire RAN. When the expected traffic volume is lower than a fixed threshold, the cells may be switched off, and the served user equipment (UEs) may be offloaded to a new target cell.

It is also possible to achieve efficient energy consumption by other means, such as reducing load, coverage modification, or making other RAN configuration adjustments. The optimal energy-saving decision depends on many factors, including the load situation at different RAN nodes, RAN nodes' capabilities, KPI / Quality of Service (QoS) requirements, number of active UEs and UE mobility, cell utilization, and more.

However, identifying actions aimed at energy efficiency improvements is not trivial. The wrong switch-off of the cells may seriously deteriorate the network performance since the remaining active cells need to serve the additional traffic. Incorrect traffic offload actions may lead to a deterioration of energy efficiency instead of an improvement.

The conventional network energy-saving techniques are vulnerable to potential issues such as:

1. Inaccurate cell load prediction: Energy-saving decisions currently rely on the current traffic load without considering future traffic load.

2. Conflicting targets between system performance and energy efficiency: Maximizing the system's KPIs is usually done at the expense of energy efficiency. Similarly, the most energy-efficient solution may impact system performance. Thus, there is a need to balance and manage the trade-off between the two.

3. Conventional energy-saving-related parameters adjustment: Energy-saving-related parameters configuration is set by traditional operation. This is based on different thresholds of cell load for cell switch on / off, which is somewhat rigid since it is difficult to set a reasonable threshold.

4. Conflicting goals in optimizing both local and overall energy efficiency: Actions that may produce a local (for example, limited to a single RAN node) improvement in energy efficiency, could simultaneously result in an overall (for example, involving multiple RAN nodes) deterioration of energy efficiency. As a result, it is important to find a balance between the two.

To confront the issues listed above, it is possible to use AI / ML techniques to optimize energy-saving decisions by leveraging the data from the RAN network. AI / ML algorithms may predict the energy efficiency and load state of the next period, providing useful information to make better decisions on cell activation / deactivation for energy savings. Based on the predicted load, the system may dynamically configure the energy-saving strategy; for example, the switch-off timing, granularity, and offloading actions, to maintain a balance between system performance and energy efficiency and reduce energy consumption.

The normative work based on the conclusion of this Release 17 study item was undertaken in Release 18 (3GPP RP-233441), with specifications of data collection enhancements and signaling support within existing NG-RAN interfaces and architecture (including non-split architecture and split architecture) for AI / ML-based network energy savings, load balancing, and mobility optimization.

The 3GPP has approved a study item in Release 19 to study enhancements for AI / ML for NG-RAN, which include energy-saving enhancements, such as energy cost prediction.

In Release 18, the 3GPP completed a study (3GPP RP-220297) on network energy savings for NR. It has studied, identified, and evaluated techniques on the gNB and UEs to improve energy savings of the networks for both FDD and TDD, FR1 and FR2. The output of this study is summarized in 3GPP TR 38.864 [2]. These techniques were evaluated based on the base station (BS) energy consumption model, evaluation methodology, and KPIs from multiple domains which were used to assess and optimize energy consumption and savings gain. At the same time, these techniques aim to find the optimal balance on the impacts to network and user performances (such as spectral efficiency, capacity, UPT, latency, handover performance, call drop rate, initial access performance, SLA assurance related KPIs), energy efficiency, UE power consumption, and complexity.

The study prioritizes idle / empty and low / medium load scenarios, allows different loads among carriers and neighbor cells, and permits legacy UEs to continue accessing a network implementing Rel-18 network energy savings techniques, except for techniques developed specifically for greenfield deployments.

The evaluation of energy savings techniques explored time, frequency, spatial, and power optimizations.

- The techniques in time and frequency domains mainly aim to reduce the power consumption for the dynamic power part, by trying to shut down more symbols on one or more carriers to achieve BS micro sleep, and even for the static power part, by enlarging the interval between the contiguous active transmission / reception occasions to achieve BS light / deep sleep.
- The techniques in spatial and power domains mainly aim to reduce the power consumption of the transceiver (TRX) chains and power amplifiers (PAs) by trying to shut down more spatial elements and / or reduce transmission power / power spectrum density or increase PA efficiency.

Based on the study's findings, the 3GPP approved a work item on network energy savings for NR in Release 18 (3GPP RP-230566) and has developed normative specifications in Release 18 for a set of network energy savings techniques. The specified techniques include:

- serving-cell without synchronization signal block (SSB-less SCell) operation
- enhancement of the cell DTX / DRX mechanism
- methods for the spatial and power domains to enable efficient adaptation of:
  - spatial elements (such as antenna ports, active transceiver chains)
  - power offset values between physical downlink shared channel (PDSCH) and channel state information reference signal (CSI-RS)
- cell handovers procedure enhancement(s)
- inter-node beam activation and enhancements among others.

In Release 19, the 3GPP has approved a work item for enhancements of network energy savings for NR (3GPP RP-240170) to specify further network energy savings targeting the beneficial techniques studied in Rel-18, but unspecified. These techniques include on-demand SSB and on-demand system information block type 1 (SIB1) transmissions, as well as adaptation of common signal / channel transmissions

3.2 O-RAN ALLIANCE

The O-RAN ALLIANCE recently completed its specifications for Release 004 features (see Figure 2), including RIC AI / ML-enabled network energy savings features and capabilities. The features listed below are fully compatible with 3GPP specifications:

- The RF cell/carrier on / off complements the 3GPP Release 18-specified NG-RAN feature for cell / carrier on / off.
- The RF channel reconfiguration enables selective on / off switching of antenna elements on the massive multiple-input / multiple-output (MIMO) antenna array.
- The RF advanced sleep mode enables on / off switching for slots and symbols.

Release 005 candidates (see Figure 2) include:

- O-Cloud energy savings, which involve switching on / off computing resources (cores) and adjusting their sleep modes / levels, such as a CPU's C-States / P-States.
- Alignment with the 3GPP Release 18-specified network energy savings features
- Test specifications.

Release 004 Completed	**(1) RF Cell/Carrier Switch On/Off** • Phase 1. Completed in March 2023 • Switch on/off cells and carriers	**(2) RF Channel Reconfiguration** • Phase 2. Completed in July 2024 • Switch on/off cells antenna elements on the massive MIMO antenna array	**(3) RF Advanced Sleep Mode Selection** • Phase 2. Completed in July 2024 • Switch on/off slots/symbols
Release 005 Candidates	**(4) O-Cloud Energy Savings Mode** • Phase 3. In Progress • Switch on/off computing resources (cores). • Adjustment of various sleep modes of computing resources (cores) such as the C/P states.	**(5) 3GPP Rel'18 and additional O-RU ES** • Phase 3. Feature definition in Progress. • SSB-less SCell operation for Inter-band CA • Power Amplifier Dynamic Voltage Bias Adaptation, ..	**(6) Test Specifications for (1, 2, 3,..)** • Phase 3. Feature definition in Progress • RIC-enabled Use cases Testing

Figure 2. O-RAN ALLIANCE network energy savings feature planning overview

4 Open RAN Architecture and Components

The O-RAN ALLIANCE specifies the Open RAN architecture [3] (refer to Figure 3), as consisting of components that implement O-RAN standards-compliant interfaces.

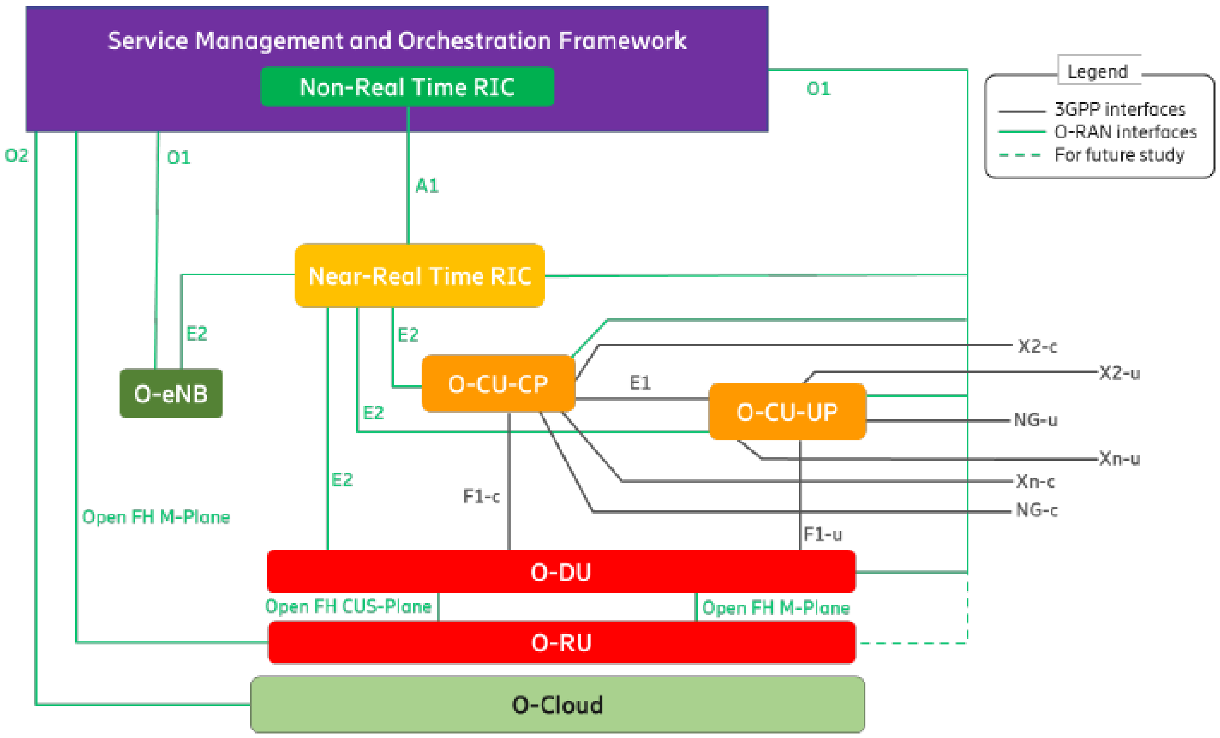

Figure 3. O-RAN architecture (source O-RAN ALLIANCE)

O-RAN-compliant components (refer to Figure 4) include:

- O-RU: Different categories of radio A, B, and ULPI Class A / B.
- O-DU / CU: RAN workloads that operate on the Cloud infrastructure.
- RIC and RIC applications: AI-enabled xApps / rApps, and service management and orchestration (SMO).
- O-Cloud: Chipsets / GPUs, accelerators, Cloud as a Service (CaaS) sub-components, and server infrastructure.

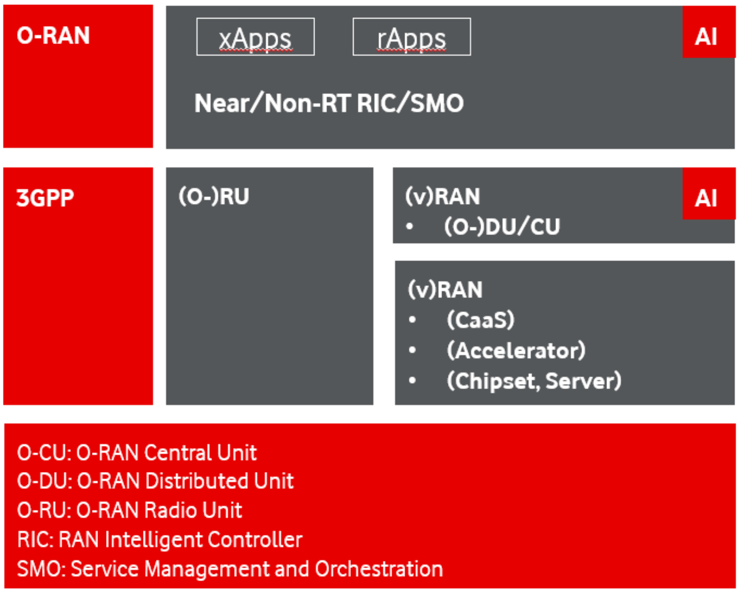

Figure 4. O-RAN components

Various suppliers can implement each of these O-RAN components using different options. For example, choose from several options to implement the O-Cloud. This requires evaluating performance gains versus CapEx, OpEx, and complexity without compromising customers' experiences and service level agreements (SLAs).

Here is an example of a listing of computing platform options and considerations:

- Different processing architectures (x86 and/or GPUs)
- Different acceleration options (inline versus look aside)
- Different chipsets (Intel x86, NVIDIA, AMD, ARM / Marvell, and more)
- Different vendors and virtualization stacks versus bare metal
- Different vDU / vCU energy savings interoperability with O-Cloud
- Different disaggregation strategies.
- Use the same vendor with different configurations, software / firmware / hardware.

Each component and the entire Open RAN solution as a system under test must be performance-tested and benchmarked using a well-defined, consistent, and repeatable testing methodology. This is to ensure proper evaluation and optimization of the Open RAN solution for multi-vendor interoperability with high performance, which is either on par with or better than traditional RAN solutions in commercial networks today.

5 Open RAN Energy / Performance Benchmarking Considerations

Open RAN energy tests and benchmarking must consider energy consumption, energy efficiency, and energy savings.

- **Energy consumption (EC)** is the measured energy used by the DUT / SUT; unit is in Joules (J) or Kilowatt-hour (kWh).
- **Energy efficiency (EE)** is the measured effectiveness of energy consumed based on certain factors such as data volume (DV), coverage, and network slices. For example, compute EE (DV) for bi-directional data volume delivered per unit of energy consumed (bits/J).
- **Energy savings (ES)** refers to dynamic closed-loop optimization of energy consumption and efficiency leveraging AI / ML-assisted methods and AI / ML models. The AI / ML models require training and testing and must be monitored throughout their life cycle.

It is possible to measure and evaluate energy savings using a set of multidimensional KPIs that seek to maximize energy savings (or minimize losses). This is accomplished while considering material costs and complexity, and ensuring no compromise (or acceptable planned impacts) to the user experience (user QoS), service level agreements, and network performances (network KPIs).

Table 1 is a sample list of measurements applicable for energy savings performance evaluation.

Table 1. Energy savings measurements

Measurements Category	Measurements	Comments
1) Energy	a) Energy consumption b) Energy efficiency (data volume / energy consumed) c) Energy savings gain / loss	Network energy saving gain is computed based on the energy consumption for a technique and the baseline over the same duration.
2) User experiences	a) User perceived throughput (UPT) gain / loss b) Packet losses, jitter, and latency	
3) Network performance	a) Initial access performance (success rate, and latency) b) Call drop rate c) Cell block error rate (BLER) d) Cell throughput e) Cell retransmissions f) Handover performance (success rate) g) Spectral efficiency	

4) Computing	a) CPU utilization (number of cores and % utilization) b) Memory utilization (%)	Computing efficiency is less straightforward in relation to differences in computing platforms (differences in accelerators, chipsets, and more). Material costs may also require consideration.

6 Open RAN Energy Benchmarking Test Scenarios, Methodology and Setups

Vodafone has set challenging targets for energy-saving goals and reducing its carbon footprint. The company aims to achieve net-zero emissions across its entire value chain by 2040, with a near-term goal of cutting its environmental impact in half by 2030. In line with this vision, energy efficiency in Open RAN networks is critical to ensuring a sustainable and scalable telecommunications infrastructure.

Open RAN offers a unique opportunity to integrate innovative energy-saving mechanisms across disaggregated components, such as O-RUs and cloud-based O-DU / CU systems, through rigorous testing and optimization. Vodafone is exploring groundbreaking methods to automate energy efficiency, dynamically adjusting network parameters based on traffic patterns and environmental conditions by leveraging advanced xApps and rApps deployed via the RIC platform. These efforts align with Vodafone's sustainability goals and also set a benchmark for the telecommunications industry by demonstrating how technology can address the twin imperatives of operational excellence and environmental responsibility.

In the following sections, we will delve into the specifics of various testing activities conducted in Vodafone's labs, showcasing our innovative approach to enhancing energy efficiency in Open RAN networks. Additionally, we will highlight a key initiative to which Vodafone actively contributed by providing its dataset to demonstrate tangible energy savings, further solidifying its commitment to driving sustainability in telecommunications.

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6.1 O-RU

6.1.1 Vodafone perspective

As the most power-hungry component in the RAN, O-RUs are central to energy transformation due to the high demands of the PA. The energy O-RUs consume not only exceeds that of other network elements but also directly impacts both operational costs and environmental sustainability. As the O-RAN ALLIANCE standardizes energy-saving features and vendors work to implement these innovations, assessing the energy efficiency of O-RUs is now paramount for MNOs.

When evaluating O-RU energy performance, Vodafone focuses on two key areas:

- First, we assess pure hardware consumption — measuring the O-RU's power draw without any active energy-saving features to establish a baseline.
- Second, we evaluate performance with energy-saving features (ESFs) activated, such as PA shutdown during idle PDSCH symbols, which can significantly lower power demands without compromising service quality.

Rigorous benchmarking in these areas enables Vodafone to compare vendor solutions, ensuring alignment with energy efficiency standards while optimizing network sustainability. Through these efforts, Vodafone is a leader in sustainable connectivity, exemplifying responsible innovation and building a greener, more efficient future for telecommunications.

6.1.2 O-RAN specifications

The O-RAN ALLIANCE established several working groups (WGs) to define the various interfaces between diverse elements in the disaggregated radio access network. One of them, WG4, focuses on the definition of the fronthaul interface between O-RU and O-DU [4].

- The O-RU includes most of the low-level 3GPP physical layer (L1) operations, such as FFT / IFFT, filtering, up / down conversion, beamforming, and other radio frequency processes. It is the element that interfaces with mobile users over the air.
- The O-DU includes most of the high-level physical layer or most of the baseband processing of the communications.

The O-RAN WG4 conformance test specification [5] defines the testing required for certification of the O-RU and O-DU as WG4 fronthaul-compliant. The test specification includes different chapters:

1. Device under test classification:
   a. Standalone testing for O-RU
   b. Standalone testing for O-DU
2. WG4 fronthaul planes:
   a. M-Plane tests
   b. CU-Plane tests
   c. S-Plane tests

To validate the energy-saving capabilities declared by an O-RU, the O-RAN WG4 conformance test specification provides several test cases in the M-Plane and CU-Plane chapters dedicated to energy-saving features that the M-Plane and CU-Plane control. The main objective of these tests is to validate that the O-RU applies the energy-saving features that it declares rather than its efficiency in energy-saving. This means the WG4 O-RAN conformance test specification does not target the energy consumption characterization of the O-RU but rather functional testing.

Also the ETSI 202 706 [6] test specification attempts to test for actual energy consumption and characterization. This test specification originally defines a set of tests that aims to characterize the power consumption of a BS under static conditions (refer to Figure 5), rather than an O-RU in isolation. Although this test specification targets the BS, it allows for distributed BS models. In a distributed BS the main metrics are measured at the RF interface (antennas), and at the direct current (DC) or alternate current (AC) feed entry of the distributed BS (power feed). The O-RU (refer to Figure 6) includes both interfaces so the ETSI test specification can be reused to test the O-RU.

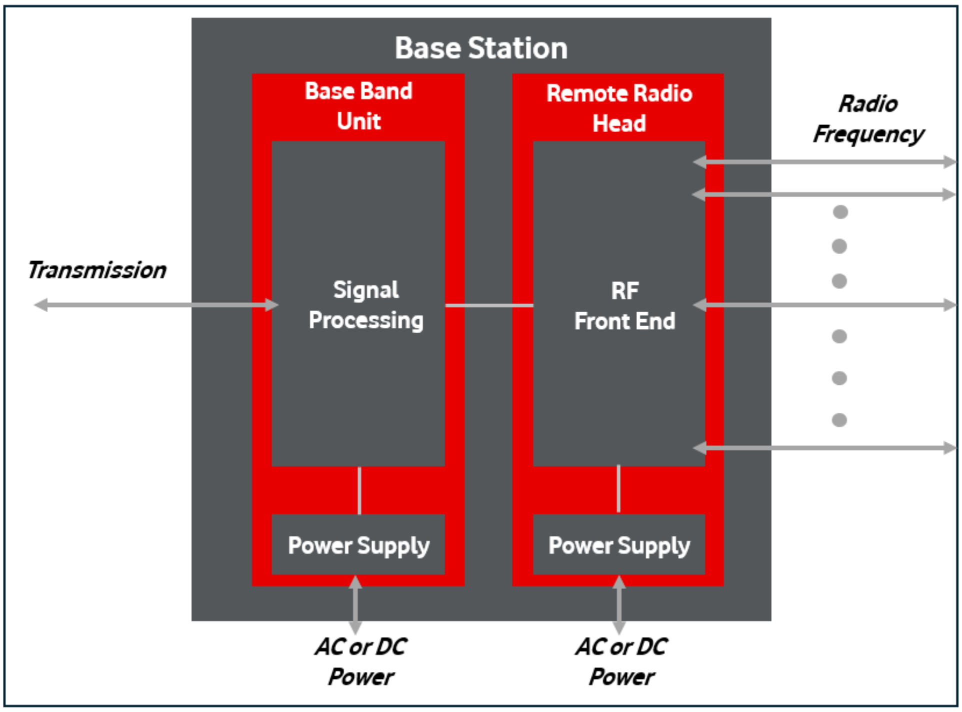

Figure 5. Interfaces available for the base station

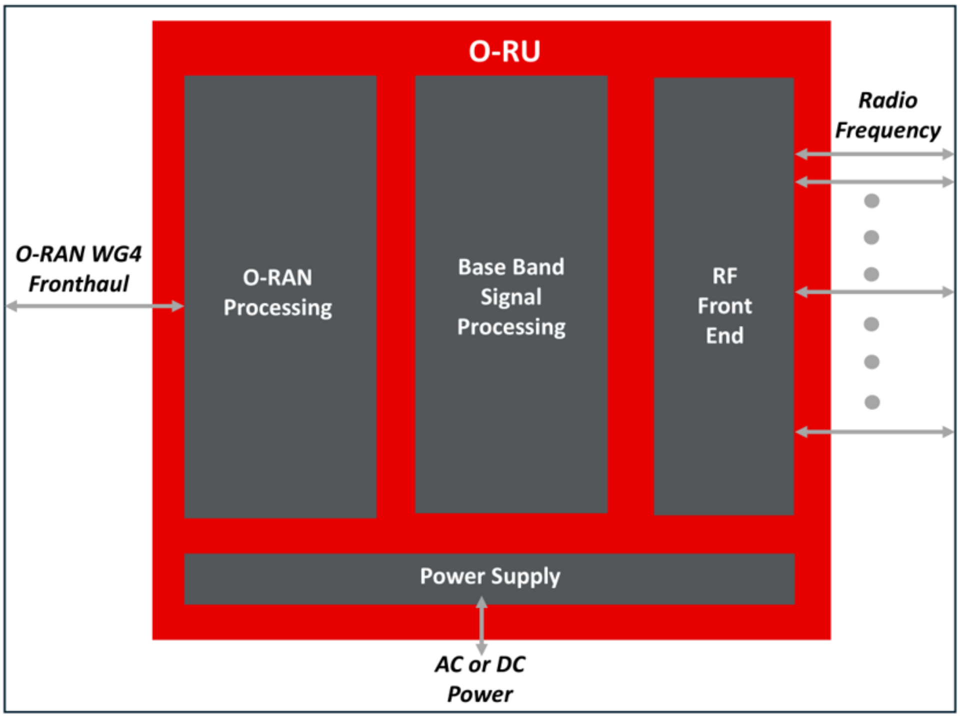

Figure 6. Available interfaces for the O-RAN radio unit

The ETSI test specification describes several loads that define the amount of resource allocation in the grid to which the BS, or the O-RU, schedules and transmits during the test. Therefore, these are purely downlink tests. These loads are:

1. Low load: This load uses a small set of resource allocations for SSB and remaining minimum system information (RMSI) (refer to Figure 7).

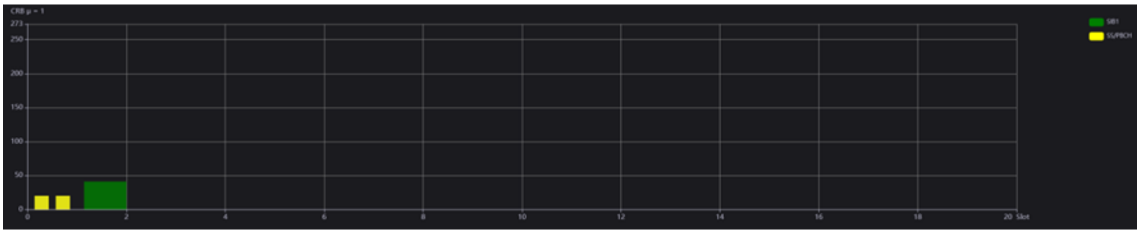

Figure 7. Low load resource allocation

2. Medium load: This load uses an increased set of resource allocations for SSB and 30 percent of the allocation available for PDSCH in the radio frame (refer to Figure 8).

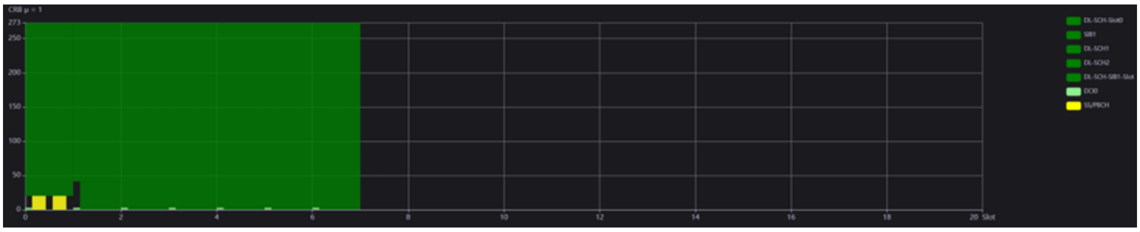

Figure 8. Medium load resource allocation

3. Busy load: This load also uses SSB allocation, and 50 percent of the allocation is available for PDSCH in the radio frame (refer to Figure 9).

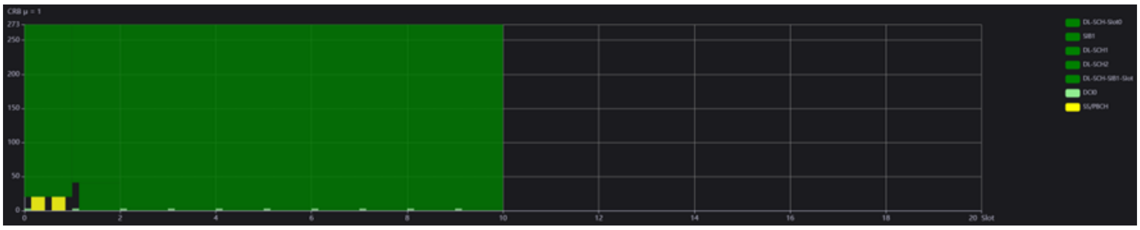

Figure 9. Busy load resource allocation

4. Full Load: This load uses the full grid such as the NR-TM1.1 test vector. There is no SSB allocation for this load (refer to Figure 10).

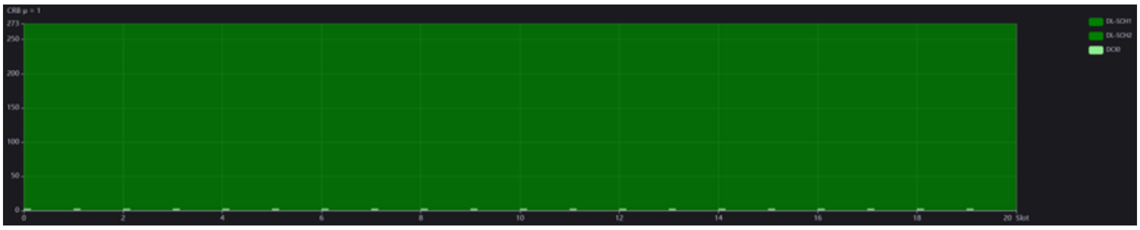

Figure 10. Full load resource allocation

The goal is to identify the energy consumption of the O-RU under these different loads for comparison purposes. This test assumes constant data transmission over the load interval. The test durations defined in the specifications target two types of power consumption measurements:

1. **Average power consumption**: The target characterizes the average power consumed by the BS, or O-RU in this case, over an equal period for each load.
2. **Daily consumption**: The target characterizes the BS's, or O-RU's daily power consumption over a 24-hour period. During this 24-hour period, three different load conditions — low load, medium load, and busy load — are tested with different time durations to mimic different traffic demands during the day.

The test results are published in test reports, which provide network vendors and operators with key metrics such as RF power output and DC / AC power consumption under different conditions.

6.1.3 Different options

There are several options for implementing energy-saving features for O-RUs. Some are proprietary to the vendor, meaning that the algorithms are vendor-dependent and not defined in any standard, and some are standard as defined by the O-RAN WG4 fronthaul specification:

1. Proprietary algorithms are a suitable path for the early implementation of energy-saving features in radios. This is because the standard might take some time to reach the desired level of maturity. Proprietary implementations might also help shape the specification's future and provide excellent insight into what works best.

   As the vendor implementation does not necessarily follow a standard or an industrial agreement, the algorithms used are based on autonomous operation. This means the O-RU vendor must implement energy-saving mechanisms that operate without requiring any signalling or external input — for example, from an O-DU or other device in the network. Some examples of autonomous vendor implementations are the temporary switching on and off of unused antennas and RF front elements such as power amplifiers (PAs) when there is no temporary allocation of traffic that requires these resources. In addition, radios might independently decide to go into deep sleep for an undetermined amount of time if no traffic is detected and wake up when necessary.

2. The O-RAN WG4 fronthaul specification defines non-real-time operations (M-Plane) [7] and real-time operations (CU-Plane) [1]. Both allocate capabilities to manage energy consumption and savings in the O-RU.

   M-Plane energy-saving operations target macro changes in the O-RU to substantially decrease energy consumption. In this case, the O-DU actively sets some radio settings in energy-saving mode. Examples include switching off entire antenna panels, some antenna elements, carriers, bands, and sectors. Another example is when the O-DU might decide to put parts of or the entire O-RU to sleep if no traffic is expected to be sent to the radio. These operations take a long time to execute and more importantly, take a long time to turn back on the parts of the O-RU that were set off or that went to sleep.

CU-Plane energy-saving operations target micro changes in the O-RU operation and typically for a shorter time period. Like M-Plane-based energy savings, the O-DU actively signals the radio what actions the radio needs to perform with the intention of lowering energy consumption. The only difference here is timing restrictions. The changes are signaled in real time and can be applied as briefly as an orthogonal frequency division multiplexing (OFDM) single symbol. For example, the O-RU might dynamically switch off power amplifiers or antenna elements if it detects no fronthaul traffic is scheduled for the radio in those antennas. Likewise, the O-DU might decide that fewer antenna elements are needed to serve users but consider that the situation might change and does not commit to putting parts or the entire O-RU to sleep.

As an initial attempt to cover energy-saving features for O-RU, the C-Plane section type 0 (ST0) messaging was defined in the O-RAN WG4 control plane, user plane, and synchronization plane (CUS-Plane) specification to enable an O-DU to explicitly signal to an O-RU that certain resource allocations for a determined period must not be allocated, or in other words, silenced. This could be used to allow an O-RU to run internal calibrations or to execute energy consumption algorithms, such as switching off radio elements. Although this ST0 could be useful for energy saving, it is not very flexible and is limited in scope. For this reason, newer versions of the specification have added new section types to expand this. Section Type 4 and Section Type 8 messages were introduced as a new method for the O-DU to explicitly signal to the O-RU which energy-saving methods the radio must apply. For example, Section Type 4 messages with the transceiver control (TRX_Control) command type allow the O-DU to enable and disable a specific number of antenna elements when using a set of resource allocations with a determined or undetermined duration. Another example is Section Type 4 messages with advanced sleep mode; the ASM command type allows the O-DU to place the O-RU in certain degrees of sleep according to a specific or unspecific amount of time, as needed.

Although the goal tends to standardize as many features as possible, it also leaves room for network equipment vendors to innovate and implement autonomous, proprietary implementations. These incentives push radio vendors to bring differential features into a competitive environment and are especially appealing to network operators. At the same time, the standardization bodies continue to define requirements for a minimal set of operations.

6.1.4 Collaboration test setup

The device under test, the O-RU, provides three important probe locations:

1. RF antenna ports: The deployment of the radio units includes antenna panels. To test them, there are two options:
    a. OTA: The radio signals travel from and into the radio; the testing requires environmentally and electromagnetically-controlled chambers and test probe antennas.
    b. Conducted: The radio signals travel over a conductor, such as cabling. In this case, testing is simplified, as only cables connecting the radio to the test equipment are necessary.
2. Optical fronthaul interface: This interface connects the radio to one or multiple O-DUs, either as a point-to-point connection or via a network. Typically, this connection is made via optical cabling. For testing, the O-RU connects to an O-DU emulator that provides O-RAN traffic.
3. DC power feed: Voltage and current feed into the radio's power supply unit to power it up. The testing equipment provides the demanded voltage and current and can report these values.

All three of these interfaces connect to the test equipment, and measurements can be taken to characterize the power transmitted by the O-RU and to monitor the DC power consumption simultaneously.

In the tests run between Vodafone and Keysight, the solution used is a combination of radio equipment, network emulation, and power and energy test equipment, all integrated under Keysight's unique test automation umbrella (refer to Figure 11).

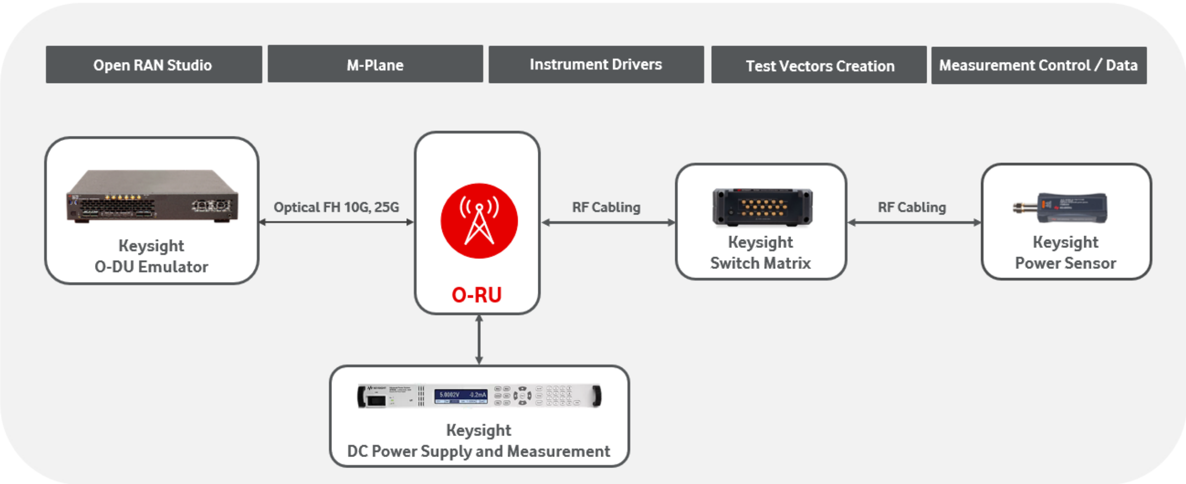

Figure 11. Keysight O-RU automated energy test and reporting solution

The test solution consists of the following components:

- Power sensor: Measures the RF power detected at the output of the radio.
- Switch matrix: Enables the connection of multiple antenna ports to single or multiple power sensors.
- O-DU emulator: Generates and captures O-RAN traffic to and from the radio over the fronthaul.
- DC power supply: Feeds the voltage and current into the radio to power it up and reports consumption of the voltage and current.
- Test automation execution software: Coordinates the full execution of the energy consumption tests by integrating the control of all the hardware and software involved in the solution.
- Test report and analytics: Provides the final report and insights on the measurements taken during the test.

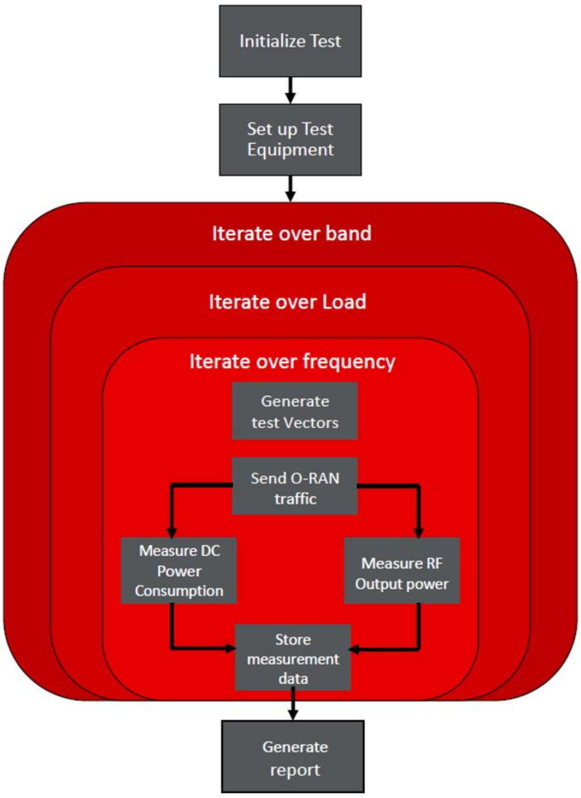

Figure 12. Keysight O-RU automated energy test flow

Here are the steps in the test flow that appear in Figure 12:

1. Initialize the test case: Run pretest operations such as establishing connections and selecting test parameters.
2. Set up test equipment: Configure the test equipment including the power supply, power sensors, and O-DU emulator.
3. Test each radio band: If the radio supports multiband, iterate the test for each band, one at a time.
4. Test each load: The test covers the different load configurations needed for each band. Depending on the test, not all the loads are used.
5. Test each frequency: For each band and load, the test goes over the different frequencies within the band such as the low, middle and high frequency parts within each band. Depending on the load, not all the frequencies are tested. For example, low load does test all three frequencies. For all other loads, only the middle frequency in the band is tested.
6. Generate test vectors: This occurs according to the load distribution under test.
7. Send O-RAN traffic: The O-RU processes the O-RAN traffic and transmits the RF signal accordingly.
8. Make measurements: Measure both DC power and RF output power while the radio transmits the signals. If there are multiple antennas, measure the RF power output for each antenna.
9. Data collection and storing: The test gathers data for each iteration.
10. Test report: After completing all the iterations, the test case generates a test report per the ETSI specification.

6.1.5 Findings and results

The main tests executed on the Fujitsu O-RU[1] are the average power consumption (APC) and the daily energy consumption (DEC) described in [6]. Both tests comply with the following conditions and requirements:

1. For APC the measurement unit is in watts (W).
2. For DEC, the measurement unit is measured in watts per hour (Wh).
3. The following loads run in these two tests:
    a. Low load with a 2-hour duration for each frequency within a band, for a total duration of 6 hours.
    b. Medium load with only a single frequency, the middle frequency, for a duration of 10 hours.
    c. Busy hour load with only a single frequency, the middle frequency, for a duration of 8 hours.
    d. Full load with only a single frequency, the middle frequency, for a duration of 2 hours.
4. For each antenna port, the measurement unit for radio frequency output power is in watts (W).
    a. This measurement is run for all four loads — low, medium, busy hour, and full load.
    b. Full load is set to 2 hours of test duration.
    c. The output power that appears in the test report is the average RF output across all antenna ports.
5. If an O-RU supports multiple bands, the test is repeated for each band, one at a time. A test report is generated individually for each band.

The Fujitsu O-RU provides the following test reports for the three bands it supports (refer to Table 2 to 10).

Band 1 - NR:

Table 2. Band 1 – static power consumption and RF output power

4	**Static power consumption (measured)**		
4.1	Full load, middle-frequency channel	453.51	W
4.2	Busy hour load, middle-frequency channel	335.8	W
4.3	Medium load, middle-frequency channel	277.86	W
4.4	**Low load**		
4.4.1	Low-end frequency channel	209.61	W
4.4.2	Middle-frequency channel	209.64	W
4.4.3	High-end frequency channel	209.23	W
4.4.4	Average consumption with low load	209.49	W
5	**RF output power**		
5.1	Full load, middle-frequency channel	16.99	W
5.2	Busy hour load, middle-frequency channel	9.13	W

[1] A model provided for proof-of-concept testing in Vodafone's Open RAN central lab

5.3	Medium load, middle-frequency channel	5.39	W
5.4	**Low load**		
5.4.1	RF output power at low-end channel	0.76	W
5.4.2	RF output power at middle-end channel	0.73	W
5.4.3	RF output power at high-end channel	0.77	W
5.4.4	Average RF output power with low load	0.75	W

Table 3. Band 1 – average power consumption reporting

Average power consumption reporting			
S.No	**Parameter**	**Value**	**Unit**
1	*$P_{equipment}$ of integrated RU power consumption*		*W*
3	**$P_{equipment}$ of distributed RU power consumption**		
3.1	*$P_{equipment}$ of distributed RU power consumption for the central part*		*W*
3.2	$P_{equipment}$ of distributed RU power consumption for remote parts	289.58	W

Table 4. Band 1 – daily energy consumption reporting

Daily energy consumption reporting			
S.No	**Parameter**	**Value**	**Unit**
1	*$E_{equipment}$ of integrated RU energy consumption*		*Wh*
3	**$E_{equipment}$ of distributed RU energy consumption**		
3.1	*$E_{equipment}$ of distributed RU energy consumption for the central part*		*Wh*
3.2	$E_{equipment}$ of distributed RU energy consumption for remote parts	5212.24	Wh

Band 3 - NR:

Table 5. Band 3 – static power consumption and RF output power

4	**Static power consumption (measured)**		
4.1	Full load, middle-frequency channel	531.43	W
4.2	Busy hour load, middle-frequency channel	383.88	W
4.3	Medium load, middle-frequency channel	305.53	W
4.4	**Low load**		
4.4.1	Low-end frequency channel	213.61	W
4.4.2	Middle-frequency channel	213.6	W

4.4.3	High-end frequency channel	213.55	W
4.4.4	Average consumption with low load	213.59	W
5	**RF output power**		
5.1	Full load, middle-frequency channel	26.82	W
5.2	Busy hour load, middle-frequency channel	15.17	W
5.3	Medium load, middle-frequency channel	8.94	W
5.4	**Low load**		
5.4.1	RF output power at low-end channel	1.22	W
5.4.2	RF output power at the middle-end channel	1.22	W
5.4.3	RF output power at high-end channel	1.22	W
5.4.4	Average RF output power with low load	1.22	W

Table 6. Band 3 – average power consumption reporting

Average power consumption reporting			
S.No	**Parameter**	**Value**	**Unit**
1	*$P_{equipment}$ of integrated RU power consumption*		*W*
3	**$P_{equipment}$ of distributed RU power consumption**		
3.1	*$P_{equipment}$ of distributed RU power consumption for the central part*		*W*
3.2	$P_{equipment}$ of distributed RU power consumption for remote parts	321.43	W

Table 7. Band 3 – daily energy consumption reporting

Daily energy consumption reporting			
S.No	**Parameter**	**Value**	**Unit**
1	*$E_{equipment}$ of integrated RU energy consumption*		*Wh*
3	**$E_{equipment}$ of distributed RU energy consumption**		
3.1	*$E_{equipment}$ of distributed RU energy consumption for the central part*		*Wh*
3.2	$E_{equipment}$ of distributed RU energy consumption for remote parts	5785.69	Wh

Band 75 - NR:

Table 8. Band 75 – static power consumption and RF output power

4	**Static power consumption (measured)**		
4.1	Full load, middle-frequency channel	553.98	W

4.2	Busy hour load, middle-frequency channel	396.65	W
4.3	Medium load, middle-frequency channel	312.51	W
4.4	**Low load**		
4.4.1	Low-end frequency channel	211.83	W
4.4.2	Middle-frequency channel	211.68	W
4.4.3	High-end frequency channel	211.6	W
4.4.4	Average consumption with low load	211.7	W
5	**RF output power**		
5.1	Full load, middle-frequency channel	25.28	W
5.2	Busy hour load, middle-frequency channel	14.16	W
5.3	Medium load, middle-frequency channel	8.35	W
5.4	**Low load**		
5.4.1	RF output power at low-end channel	1.12	W
5.4.2	RF output power at the middle-end channel	1.12	W
5.4.3	RF output power at high-end channel	1.13	W
5.4.4	Average RF output power with low load	1.12	W

Table 9. Band 75 – average power consumption reporting

Average power consumption reporting			
S.No	**Parameter**	**Value**	**Unit**
1	*$P_{equipment}$ of integrated RU power consumption*		*W*
3	**$P_{equipment}$ of distributed RU power consumption**		
3.1	*$P_{equipment}$ of distributed RU power consumption for the central part*		*W*
3.2	$P_{equipment}$ of distributed RU power consumption for remote parts	329.35	W

Table 10. Band 75 – daily energy consumption reporting

Daily energy consumption reporting			
S.No	**Parameter**	**Value**	**Unit**
1	*$E_{equipment}$ of integrated RU energy consumption*		*Wh*
3	**$E_{equipment}$ of distributed RU energy consumption**		
3.1	*$E_{equipment}$ of distributed RU energy consumption for the central part*		*Wh*
3.2	$E_{equipment}$ of distributed RU energy consumption for remote parts	5928.23	Wh

Testing energy efficiency across Open RAN systems is critical to advancing industry-wide efforts to optimize power usage while maintaining performance. Vodafone's current findings on the Fujitsu radio are achieved with the activation of the Micro DTX energy-saving feature, underscoring the potential of such innovations to reduce power consumption without compromising signal quality. To further these insights, we will conduct comparative tests by deactivating the energy-saving feature to measure the differences in power consumption. Additionally, we plan to simulate real network conditions in the lab by transmitting on all three bands simultaneously, with and without Micro DTX, to evaluate its impact on power consumption and signal integrity. Vodafone will also analyze the feature's performance under full load conditions, using symbol-level transmission control to validate power consumption patterns. These tests highlight Open RAN's pivotal role in driving energy efficiency through adaptable and innovative solutions.

Vodafone is committed to driving advancements in energy efficiency by rigorously testing all radio products entering our lab under similar conditions. This standardized approach ensures a consistent evaluation of energy-saving features across different vendors and configurations. By benchmarking power consumption and performance, we aim to identify the most energy-efficient solutions, further promoting sustainability and innovation in Open RAN networks.

6.2 O-DU / CU / Cloud (chipsets / GPUs, accelerators, CaaS)

6.2.1 Vodafone perspective

In the rapidly evolving landscape of telecommunications, energy efficiency has become a strategic priority, especially in Open RAN networks where minimizing OpEx and supporting global sustainability are key goals. For MNOs, optimizing energy usage within O-DU / O-CU / O-Cloud components offers the opportunity to significantly reduce power consumption, directly impacting cost efficiency and environmental sustainability. Open RAN modular, vendor-agnostic architecture provides an ideal foundation for implementing advanced power-saving technologies, enabling dynamic adjustments based on real-time traffic and operational conditions.

6.2.2 O-RAN specifications

O-RAN ALLIANCE WG6 is undertaking a technical report [8] to study several key advancements and strategies for energy savings within the O-Cloud infrastructure. It describes O-Cloud mainstream energy management techniques including:

- CPU energy management: Adjusts CPU frequency and voltage to reduce energy consumption.
- Clock gating: Disables parts of the CPU circuit to save power.
- Adaptive link rate: Adjusts network link data rates during low traffic periods.
- Idle and performance states: Uses different states to manage power based on usage.

The technical report also provides the following energy-saving use cases for O-Cloud:

- Node shutdown in idle mode: Shuts down idle nodes to save energy, based on predictive models of resource usage.

- CPU core frequency and pinning configuration: Adjusts CPU configurations for virtualized network functions (VNFs) / Cloud-native functions (CNFs) during low usage periods to save energy.
- C-State usage for NF deployment: Configures CPU states to reduce power consumption during NF deployments.
- Node cluster mode selection: Selects specific modes for node clusters to achieve energy savings.

6.2.3 Different options

Several options exist for implementing energy-saving features for the O-DU / O-CU / O-Cloud through dynamic adjustments of the processors' C-States, P-States, and Uncore Frequency. These dynamic adjustments need to interoperate seamlessly with O-DU / O-CU workloads to ensure that customer experiences, service level agreements, and network performance stay optimal at all times.

C-States mainly impact application-level power savings. It is possible to use dynamic adjustments of C-State to control the sleep mode per CPU core. C-States (refer to Figure 13) usually start in C0, which is the normal CPU operating mode. With increasing Cx, the CPU sleep mode becomes deeper, and more circuits are turned off. However, more time is required to bring the CPU back to C0 or to wake it up.

P-States mainly impact server-level power savings. Dynamic adjustments to P-States allow each CPU core to run at a different frequency or voltage (execution power).

Uncore Frequency refers to the clock speed of a CPU's non-core components, such as the memory controller, cache, and other integrated peripherals. This frequency is separate from the core frequency, which is the speed at which the CPU cores operate.

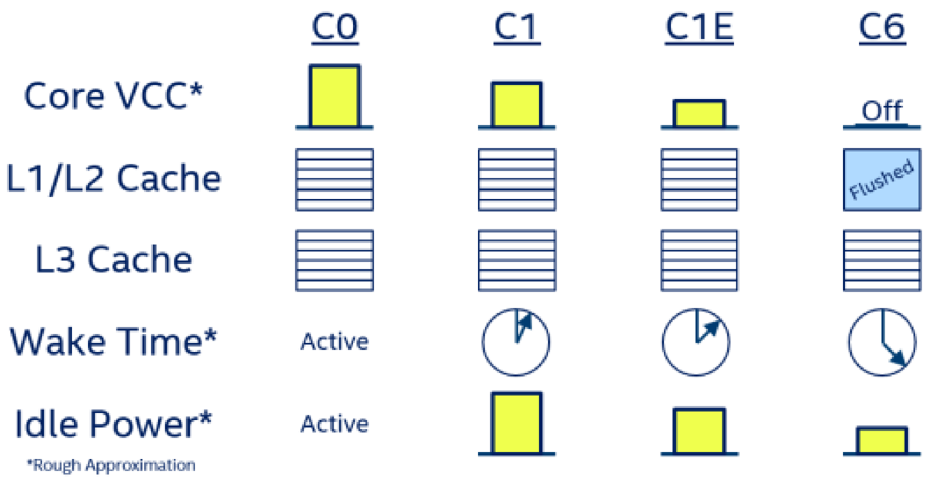

Figure 13. C-States (image provided by Intel)

6.2.4 Collaboration test setup

Through various Open RAN PlugFest demonstrations and live network validations, Vodafone has partnered with leading vendors to explore the potential of energy usage optimization in O-DU / O-CU / O-Cloud to achieve breakthroughs in energy savings.

These energy-saving initiatives with traffic profiles defined in ETSI TS 103-786 [9] and Vodafone's live traffic profile simulated, including up to 20% energy reduction at key events like Mobile World Congress (MWC) 2023 and O-RAN PlugFest Fall 2023. This result underscores the importance of innovations such as dynamic C-State and P-State optimizations, real-time KPI-driven power management, and the integration of hardware accelerators. By validating these multi-vendor solutions, Vodafone is not only advancing industry standards for energy-efficient Open RAN deployments but also demonstrating a practical path to sustainable network growth.

6.2.5 Gains and achievements in energy savings optimization research

The various PlugFest and MWC demonstrations reveal significant gains in energy efficiency across multiple dimensions of O-RAN systems. We summarize the key gains and tactics in Table 11.

Table 11. Energy Savings Optimization Table

Demo Milestone	PlugFest Spring 2022	PlugFest Fall 2022	MWC Barcelona 2023	PlugFest Fall 2023
Energy Savings (percentage)	9-12 percent (up to 15 percent)	Dynamic savings (no exact percentage)	≤20 percent	20 percent
Main Needle Mover	C1 + P-States combination	Closed loop P-State control	C-State, P-State, Uncore Frequency	HW Accelerator + AAL Interface
Test Setup Changes	Cloud-based multi-vendor O-RAN	Closed-loop control based on KPIs	Closed-loop dynamic control with Near-RT-RIC and SMO	New hardware (Intel 4th Gen)
Optimization Techniques	C1 state on by default, dynamic P-States	CPU management via P-State, Uncore Frequency	Telemetry, dynamic power control	Core reduction, P-State tuning
Key Observations	Best results with C1 & P-States combined	PRB, CPU Utilization as thresholds	A closed loop ensures optimal RAN performance	HW and SW abstraction for FEC Acceleration
Validation Method	Keysight PA, Redfish	KPI-based thresholds	Live traffic + telemetry	HW accelerators, DPDK BBDEV
Additional Energy-Saving Methods	Fine-tuning C and P-States	Uncore Frequency management	AI / ML potential	Core reduction, FEC integration

Table 11 provides a clear overview of the progression of energy savings techniques from early C and P-State optimizations to more advanced closed-loop controls and hardware acceleration in later demos. Each stage has progressively leveraged both hardware and software innovations to push energy efficiency in O-RAN systems.

Intel, Keysight, Radisys, Vodafone, Wind River Studio, and the University of Utah collaborated in O-RAN Global PlugFest Spring 2022, demonstrating O-RAN energy efficiency (EE) and energy savings (ES) PoC. Figure 14 illustrates the topology of the collaboration test setup.

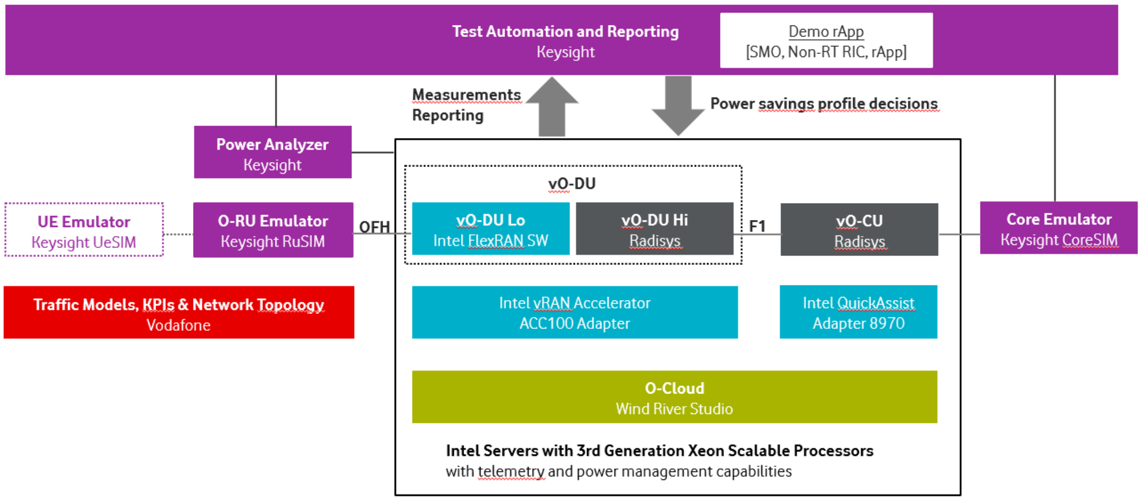

Figure 14. Topology of the collaboration test setup for O-RAN PlugFest Spring 2022

Table 12 provides details on the components collaborators used at the O-RAN Global PlugFests Spring and Fall 2022 and at MWC Barcelona in 2023.

Table 12. components collaborators at the O-RAN PlugFests Spring / Fall 2022 and at MWC 2023

Collaborators	Components	2022 Spring / Fall PlugFest + MWC 2023	2023 Fall PlugFest
Intel	•**O-DU and O-CU hardware** including servers based on **3rd Generation Intel® Xeon® Scalable Processors** with telemetry and power management capabilities •**Intel® vRAN Accelerator** ACC100 Adapter (DU)	Yes	
	O-DU and O-CU hardware including servers based on **4th Generation Intel® Xeon® Scalable Processor with Intel vRAN Boost**, telemetry and power management capabilities		Yes
	•**Intel® QuickAssist Adapter** 8970 (CU) •**Intel® FlexRAN™ software** implements the **O-DU Lo** and **O-RAN Fronthaul** functionality, executing as NFs in containers in the Wind River CaaS platform	Yes	Yes

Collaborators	Components	2022 Spring / Fall PlugFest + MWC 2023	2023 Fall PlugFest
Keysight	•**O-RU**(RuSIM) and **UE Emulator** (UeSIM) •**Core Emulator** (CoreSIM) •**Power Analyzer** (PA2203A IntegraVision) •**Demo rApp** for energy savings policy decisions •**Test Automation** (Pathwave Test Automation)	Yes	Yes
	•**Reporting and Analytics** (Atlas TMC-Analytics) •**Test cases** (E-Plane Design Test Suite for O-DU/O-CU)		Yes
Radisys	•**Containerized O-DU and O-CU software** automatically allocates vCPU and VF resources from a resource pool provided by Wind River CaaS Platform running on a server with Intel Xeon processor and hardware acceleration	Yes	Yes
Dell	•Two **Dell Hook (XR8620)**		Yes
Vodafone	•**Live network traffic models**, KPIs and Network topology	Yes	Yes
Wind River	•**O-Cloud** using Wind River Studio	Yes	Yes
University of Utah	•Lab and Lab-as-a-Service	Yes	

6.2.6 Measurement techniques

We used a common measurement methodology across all three PlugFests (2022, 2023 and 2024).

The Keysight Energy Plane Test Suite topology, depicted in Figure 15, traverses multiple aspects with a test automation and reporting framework following the methodology described in ETSI TS 103 786 [9]. Keysight UE / O-RU Emulator (RuSIM) and Core Emulator (CoreSIM) generate a dynamic traffic load and channel emulation by expecting a lower traffic level to result in lower energy consumption.

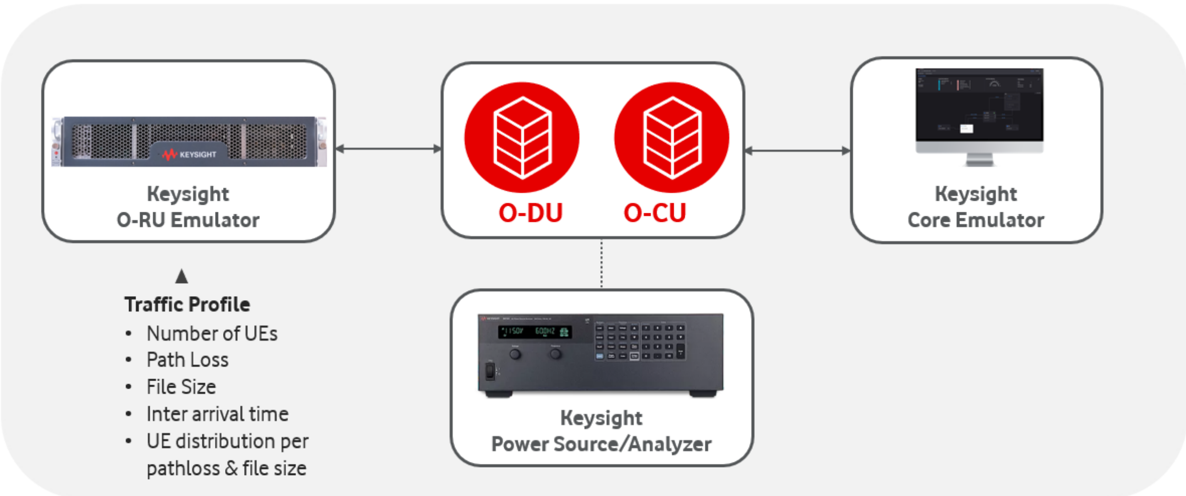

Figure 15. Keysight energy plane test suite topology

The traffic load is modelled after Vodafone commercial network clusters. At each test iteration, DMTF Redfish or the Keysight Power Source / Analyzer automatically evaluate the DUT's energy consumption. The Keysight UE / O-RU emulation (RuSIM) also emulates groups of UEs with high / medium / low path loss and different file sizes (small / medium / large) for data transfer as pictured in Figure 16 and per ETSI TS 103 768 [9].

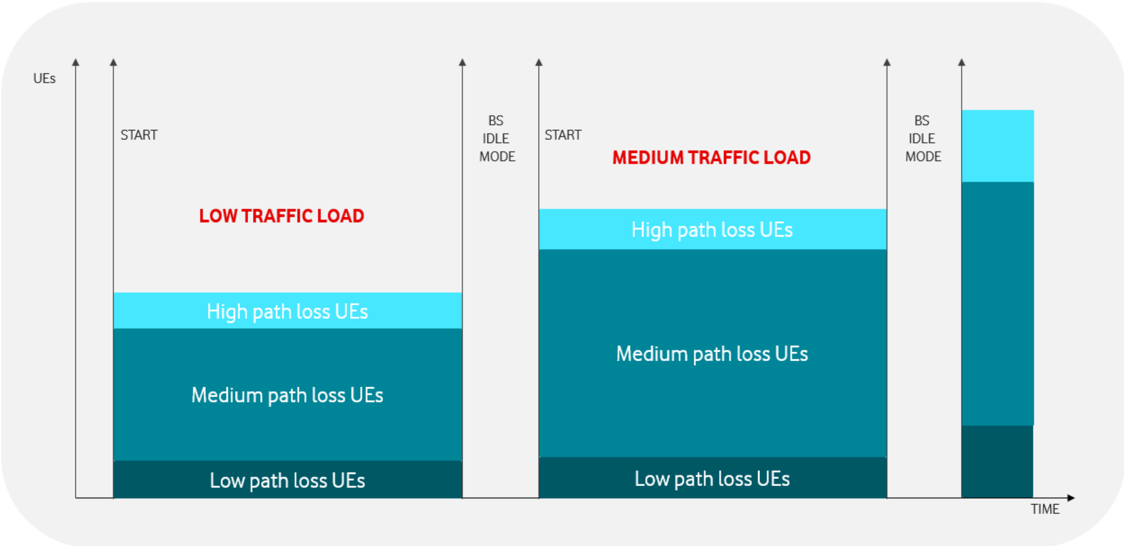

Figure 16. UE groups with different path loss and traffic load

In such cases, there are around 2,000 automated test iterations (refer to Figure 17) to execute to ensure a fully comprehensive coverage:

- All protocol layers: vO-DU Lo (High-PHY), vO-DU Hi, vO-CU
- Traffic load levels (low, medium, busy hours)
- Voltage-frequency control states (P-States)
- Power consumption control states (C-States)
- Uncore Frequency scaling (UFS) technique.

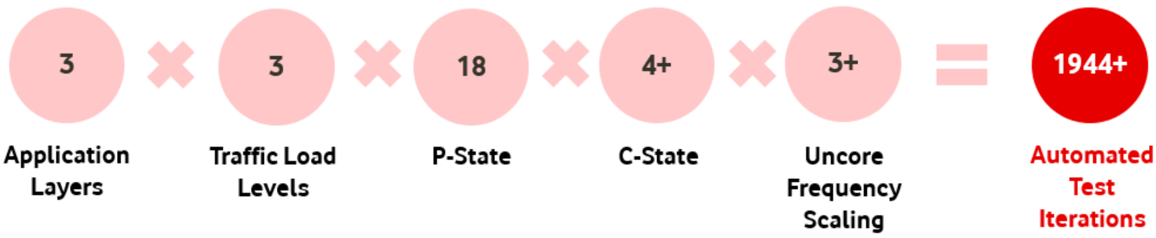

Figure 17. Automated test iterations

The test suite can measure not only power consumption but also the subscriber's quality of experience (QoE). We cannot sacrifice the subscriber's QoE to save energy consumption and need to assure subscriber QoE in a service level agreement (SLA).

The test suite executes repeatably and consistently and is fully automated. Finally, it can generate detailed test reports for every test iteration and the corresponding intuitive chart, as shown in Figure 18 below. A sample of the detailed test report appears in Table 13.

Table 13. Sample of the Test Report

Measurements conditions and results to be reported for gNB/eNB Energy Performance				
S.No.	**Parameter**	**Test case 25 °C**		**Unit**
4	**Weighting Factors**			
4.1	Wlow	6		hour
4.2	Wmedium	10		hour
4.3	Wbusy-hour	8		hour
5	**Dynamic energy consumption (measured)**	**Power Analyzer**	**Redfish**	
5.1	Low traffic level	1704.6	1680.12	Wh
5.2	Medium traffic level	2851	2819.1	Wh
5.3	Busy-hour traffic level	2296.64	2259.52	Wh
6	**Accumulated measured data volume**			
6.1	Low traffic level	1.09837E+14		bits
6.2	Medium traffic level	2.44205E+14		bits
6.3	Busy-hour traffic level	3.25558E+14		bits
Calculated results to be reported for gNB/eNB Energy Performance				
S.No.	**Parameter**	**Value**		**Unit**
1	Total delivered data in bits during the test	6.79601E+14		bits
		Power Analyzer	**Redfish**	
2	Total energy consumption	6852.24	6758.74	Wh
		Power Analyzer	**Redfish**	
4	gNB/eNB Energy Performance (BSEP)	9.91794E+10	1.00551E+11	bits/Wh

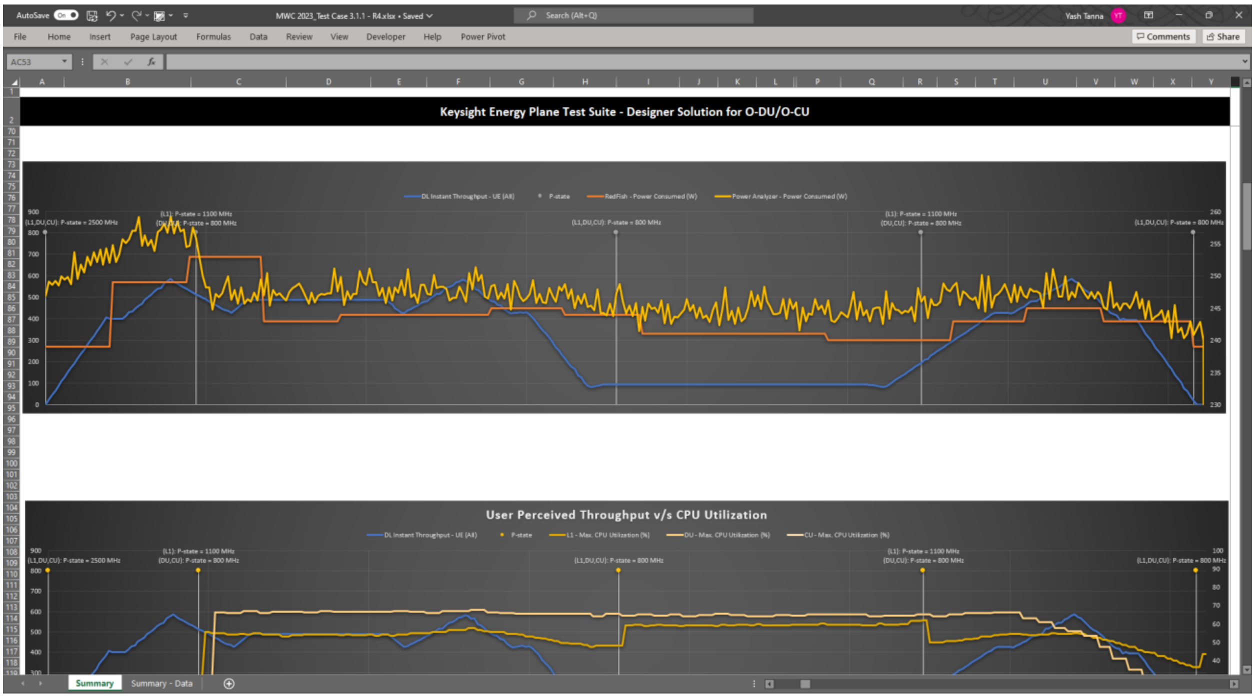

Figure 18. Test report and chart

Most importantly, the test report (refer to Table 14) shows the energy-saving gains of different technologies (C / P-State and Uncore Frequency).

Table 14. Test report with energy-saving gain

Traffic:	High		Avg		Low	
Uncore:	1700 MHz	2400 MHz	1700 MHz	2400 MHz	1700 MHz	2400 MHz
C-state:	C1	C1	C1	C1	C1	C1
P-state:	2500 MHz	2500 MHz	1500 MHz	1100 MHz	1200 MHz	800 MHz
Max (Avg DL PRB)	191	186	172	153	149.5	52
Max (CPU Utilization)	39.0%	32.0%	51.2%	58.0%	59.4%	68.0%
Energy Savings	**13.7%**	**6.9%**	**15.1%**	**14.4%**	**19.7%**	**16.5%**

6.2.7 Findings and results

At the O-RAN Global PlugFest **Spring 2022**, we conducted experiments to evaluate the best approaches to configure C and P-States to achieve the best possible energy savings gains without impacting customers' experiences and network performances. We observed that:

1. Combining C1 and P-States (2.1GHz) power savings optimization resulted in the highest energy savings compared to enabling them separately.
2. An additional percent energy savings can be achieved when the C1 state is enabled by default for all load levels, as opposed to only being enabled for low-load scenarios. Switching between C0 and C1 states seems to consume additional energy, which can be saved when the CPUs are maintained in the C1 state across all load levels.

At the O-RAN Global PlugFest **Fall 2022**, we conducted experiments to evaluate the energy savings profile of the system under test from the closed loop automation perspective with dynamic control of the P-States and explore additional methods to achieve greater energy savings gain.

1. Identify the KPIs for closed-loop automation of energy savings by the O-RAN xApps / rApps through dynamic control of the P-States. We observed that the physical resource blocks (PRBs) and CPU utilization can be used as thresholds to control the P-States for closed-loop automation.

2. Characterize the detailed timing of the closed-loop automation for each of the processing stages, starting with the identification of the triggering event at the O-RAN xApps / rApps, the decision of the P-State changes by the O-RAN xApps / rApps, and when the P-State change has been implemented in the O-Cloud. We observed that the amount of energy savings gain is directly correlated to the precision of the timing control of the P-State changes.

3. Evaluate additional energy savings gain using the Uncore Frequency adjustments after configuring the optimal P-States. We observed that lower Uncore Frequency can lead to additional energy savings gains (between 6.9 and 19.7 percent) on top of the energy savings gain achieved through the optimal C and P-States settings.

At **MWC Barcelona 2023**, the focus was on fine-tuning the energy savings controls (C / P States and Uncore Frequency), leveraging learnings from prior work seeking to maximize the energy savings gain without impacting customers' experiences and network performance. We applied Vodafone's traffic model gathered from a live network cluster and emulated the models in the lab test environment to simulate close-to-real-world traffic scenarios throughout the closed-loop optimization process. We achieved an additional up to 20 percent energy savings gain, which was showcased at the MWC Barcelona 2023 event in the Vodafone booth.

In O-RAN Global PlugFest **Fall 2023**, we focus on characterizing the additional energy savings that can be achieved by leveraging the state-of-the-art computing resources available at that time. Intel launched its fourth-generation processors with integrated acceleration vRAN Boost, and no external accelerator is required at this time. With Intel's Gen 4 processors, all other conditions being equal, we observed:

- A system power reduction of 19.7 percent with integrated acceleration.
- A 13 percent energy savings was achieved from C1-State-enabled and uncore, as well as a P-State frequency change to match traffic load. The O-DU / O-CU workloads have also been optimized for energy savings.

At the O-RAN Global PlugFest **Fall 2024**, the focus was on estimating the energy consumption of the individual points of delivery (PODs) within which the containerized O-DU / O-CU workloads will operate. This will give us a more accurate characterization of the energy usage when more than one POD is operating on a common computing infrastructure, which is highly likely in cloud deployment scenarios.

Vodafone has collaborated with its partners to explore energy consumption estimations in two Cloud as a Service (CaaS) operating environments:

- **Red Hat** in collaboration with Dell, Keysight and OAI.
- **Wind River Studio** in collaboration with Dell and Intel.

The outcomes of the PlugFest Fall 2024 work provide insights into the energy consumption instrumentation and estimations in an Open RAN environment using Red Hat Kepler (Kubernetes-based Efficient Power Level Exporter) and Wind River Analytics (WRA) when operating in Red Hat and Wind River Studio operating environments respectively.

It was successfully demonstrated that both methods can be used to collect energy consumption measurements at the granularity of the POD and application resource level in run-time without degrading application performance.

This has demonstrated to the industry that it is possible to assess power consumption across different components and conditions within a cloud-native Open RAN deployment and ultimately help guide strategies for power optimization in cloud-native Open RAN networks.

6.2.8 Future work and next steps

We would like to further explore the energy usage of hardware accelerators and compare the power consumption of specialized hardware accelerators (GPUs and DPUs) versus standard CPUs when processing RAN workloads. The goal is to determine which processing units offer the best performance per watt in the Open RAN cloud environment, as RAN energy efficiency and savings need to be optimized for specific deployment scenarios and real-world applications.

Furthermore, energy profile comparisons across RAN vendors and cloud providers need more work in deployment scenarios where the Open RAN platform is deployed across multiple cloud environments. Therefore, measurements of the energy consumption profiles across providers are needed. This can inform decision-making about RAN software and cloud platform efficiency.

These will require continuing to refine power consumption characterization across different components and conditions within the network and showcasing these refinements at future PlugFest events.

6.2.9 Recommendations

1. **Standardization**: O-RAN ALLIANCE should leverage these outcomes from the 3GPP effort to help mobile operators save energy costs while improving subscriber QoS. With these outcomes from the 3GPP, the O-RAN ALLIANCE should continue to develop more use cases on energy efficiency and energy savings, which will lead to evolving O-RAN specifications in various working groups. The 3GPP R18/R19 has multiple study items working on the network energy-saving feature.
2. **Operators and Adoption of AI-driven Energy Management:** Operators should apply AI-based technology to dynamically manage energy consumption, especially in multi-carrier setups where traffic demand varies significantly.

6.3 RIC applications (xApps/rApps), SMO

6.3.1 Operator perspective

MNOs face an ongoing challenge to balance the growing demand for wireless services with operational cost efficiency and environmental responsibility. Traditionally, networks are designed to operate at maximum capacity, leading to high energy consumption, particularly during periods of low traffic demand. With the advent of Open RAN and 5G technologies, operators can now access innovative tools such as RAN Intelligent Controllers (RICs) and energy-saving applications that dynamically adjust network resources, significantly improving energy efficiency without compromising the QoS.

Implementing RIC-based energy efficiency solutions in Open RAN networks represents a pivotal shift toward smarter, more sustainable, and cost-effective network operations for operators. By dynamically managing network resources, reducing energy consumption, and maintaining high levels of service quality, operators can significantly reduce their OpEx while enhancing the user experience. As the telecommunications industry continues to prioritize sustainability and cost efficiency, the adoption of RIC-driven energy-saving use cases will become an essential strategy for operators to remain competitive and profitable over the long term.

6.3.2 O-RAN specifications: architecture and procedure flow for cell on / off use case

The Open RAN architecture, as defined by the O-RAN ALLIANCE, enables real-time control and automation of RAN elements through the RIC. In the context of energy efficiency, the non-real-time (Non-RT) RIC hosts rApps that execute long-term optimization tasks such as energy-saving algorithms, while the near-real-time (Near-RT) RIC hosts xApps that execute time-sensitive functions, including traffic steering. This setup is essential for the dynamic management of cells, enabling MNOs to power down underutilized cells through the energy savings (ES) mode and redistribute traffic through active neighboring cells.

The architecture and procedure flow for carrier / cell on / off in the context of improving the energy efficiency of mobile networks through dynamic cell switching, with coordination between traffic steering (TS) xApps and ES rApps, can be described as follows.

Architecture Overview

The architecture is based on the O-RAN framework, where different components communicate over defined interfaces to perform the required functions. Figure 3 depicts the key elements involved.

The elements of the O-RAN framework include:

- **Entities (or components)**
  - **Non-RT RIC**: Manages the rApps, including the Energy Saving (ES) rApp. It operates in a non-real-time control loop, with a typical response time of one second or more, and interacts with the Near-RT RIC through the A1 interface.

- **Near-RT RIC**: Hosts the xApps, including the Traffic Steering (TS) xApp. It operates in a near-real-time control loop, typically ranging from 10 milliseconds to 1 second, and communicates with the RAN via the E2 interface.
- **ES-rApp**: This rApp is responsible for identifying candidate cells for switch-off/switch-on based on network traffic conditions and energy efficiency goals. It runs in the Non-RT RIC.
- **TS-xApp**: This xApp is responsible for offloading or onboarding users to neighboring cells when a candidate cell is to be switched off/on. It runs in the Near-RT RIC.
- **O-CU / O-DU**: The components of the RAN, also known as E2 nodes that handle the radio resources, connect to the Near-RT RIC over the E2 interface.

- **Interfaces**
  - **A1 Interface**: Used for sending policy-based instructions from the Non-RT RIC to the Near-RT RIC (such as ES-rApp instructing the TS-xApp about cell switch-off candidates).
  - **E2 Interface**: Provides real-time control and monitoring between the Near-RT RIC and the RAN (such as TS-xApp interacting with the O-CU/O-DU).
  - **O1 Interface:** Plays a crucial role in the architecture by enabling the Non-RT RIC, where the ES rApp resides, to manage and configure the RAN elements, including switching cells on or off based on AI-driven decisions, ensuring efficient network operations and energy optimization.
  - **R1 Interface**: It is an open logical interface within the O-RAN architecture between the rApps and the Non-RT RIC framework. The R1 interface supports the exchange of control signaling information and the collection and delivery of data between endpoints. The R1 interface is not utilized in the current energy-saving use case test.

High-level Procedure Flow for Dynamic Cell Switching

The procedure flow begins with the ES-rApp detecting low traffic conditions, prompting it to prepare specific cells for deactivation. The TS-xApp receives an alert to reroute user traffic to adjacent cells before powering down these cells. Once the migration is complete and the target cells are empty, they can be switched to an energy-saving mode.

6.3.3 Two options for notification from ES-rApp to TS-xApp

There are two options for notifying the TS-xApp about energy-saving actions from the ES-rApp:

- **Option 1: A1 Interface (Policy-based Notification)**
  - The ES-rApp uses the A1 interface to send policies to the Near-RT RIC, including a “FORBID” clause for cells that are candidates for switch-off.
  - The TS-xApp receives this policy and starts the user offloading process.
- **Option 2: E2 Interface (E2 Service Model, Cell Configuration and Control- E2SM-CCC)**

- The TS-xApp uses the E2 interface to interact directly with the Near-RT RIC and the RAN, utilizing the cell configuration and control service model (E2SM-CCC).
- This approach allows for more direct and real-time control over the cells, enabling faster response times for cell switch-on/off actions.

6.3.4 Collaboration test setup

The test setup demonstrates a multi-vendor environment where the ES rApp and traffic steering xApp collaborate via Juniper Networks' RIC platform, simulated with Keysight's RICtest emulation tool. The following partners provided key components:

- **Juniper Networks:** Non-RT RIC and Near-RT RIC platforms
- **AirHop Communications:** Energy Saving rApp (ES-rApp)
- **Rimedo Labs:** Traffic Steering xApp (TS-xApp)
- **Keysight:** RICtest for RAN emulation.

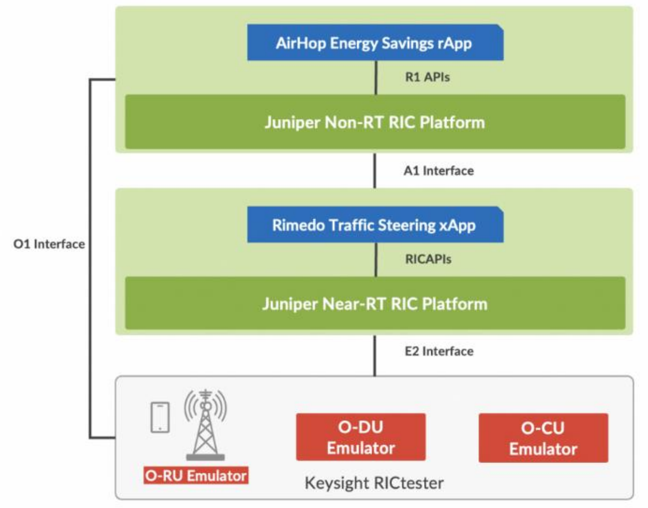

Figure 19. Multi-vendor rApp-xApp coordination topology (image provided by Juniper Networks)

This logical architecture shown in Figure 19 illustrates how each component interacts through the O-RAN interfaces, marking the specific responsibilities of each vendor. The energy-saving actions initiated by the ES-rApp trigger procedural flows across both inner and outer loops. Although the TS-xApp can be driven using both A1 policy-assisted and E2SM-CCC-based notifications, this particular setup demonstrates the second option.

6.3.5 Keysight RICtest configuration and statistics

Keysight RICtest is a comprehensive solution for testing RIC / xApp / rApp via E2. A1 and O1 interfaces to address customer requirements for conformance, performance, interoperability, and use case validation tests.

In the carrier / cell on / off use case test, RICtest simulates multiple E2 nodes connecting to Non-RT RIC via the O1 interface and Near-RT RIC via the E2 interface. These E2 nodes provide coverage and capacity cell services to multiple groups of UEs with mobility and data traffic activities. RICtest allows designing a cell map via a visual editor, as shown in Figure 20, and configuring the cell with rich parameters, as shown in Figure 21.

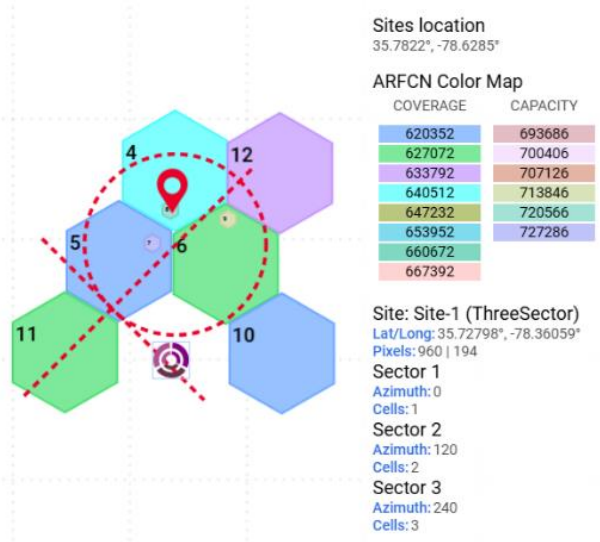

Figure 20. Keysight RICtest map designer

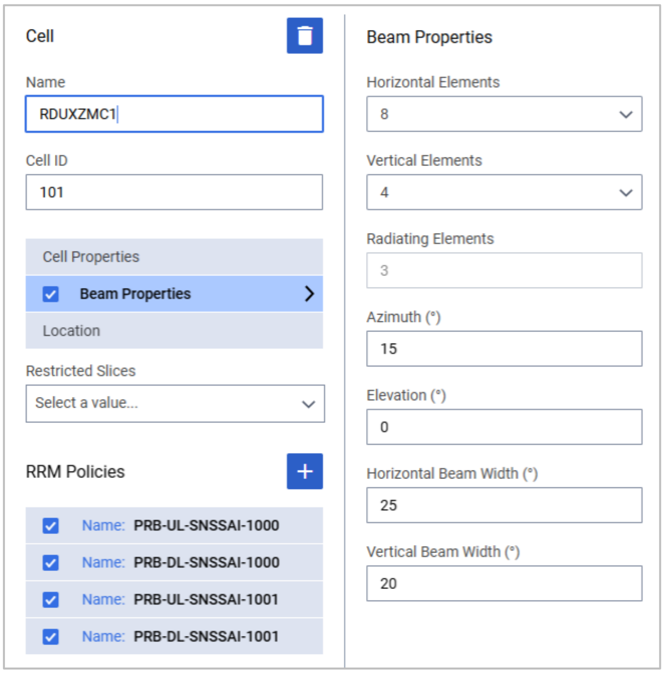

Figure 21. Keysight RICtest cell configuration

RICtest can simulate idle capacity cell and busy coverage cell by UE behaviors to trigger energy-saving rApp to turn off and on capacity cell / carrier. Moreover, the UEs can be handed over between the capacity cell and the coverage cell by traffic steering xApp. All the behaviors can be observed in the RICtest dashboard, as shown in Figure 22.

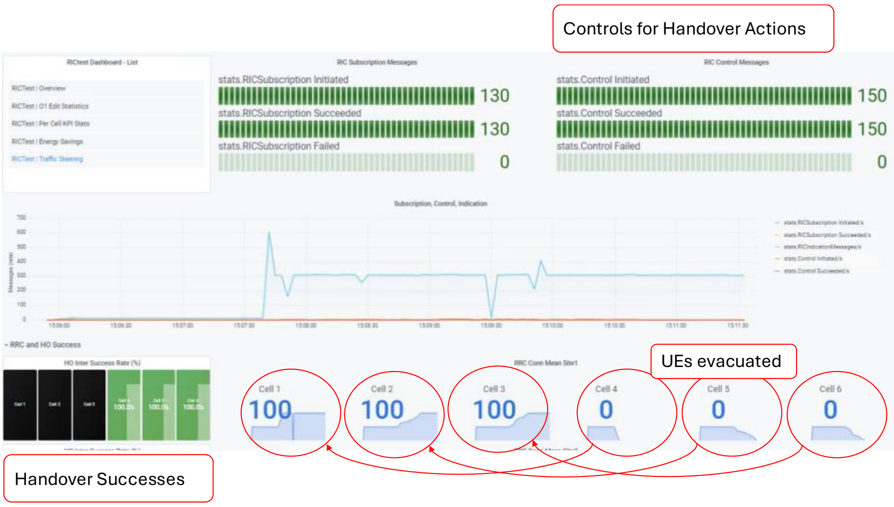

Figure 22. Keysight RICtest statistics dashboard

6.3.6 Procedural flows

The following paragraphs describe how each option operates step by step and the procedural flows for triggering the energy-saving mechanism using the two approaches (A1 policy-based notification and E2SM-CCC-based notification) for Traffic Steering (TS) xApp in the context of the ES use case.

Option 1: Traffic Steering xApp Notification through the A1 Policy (A1 Interface)

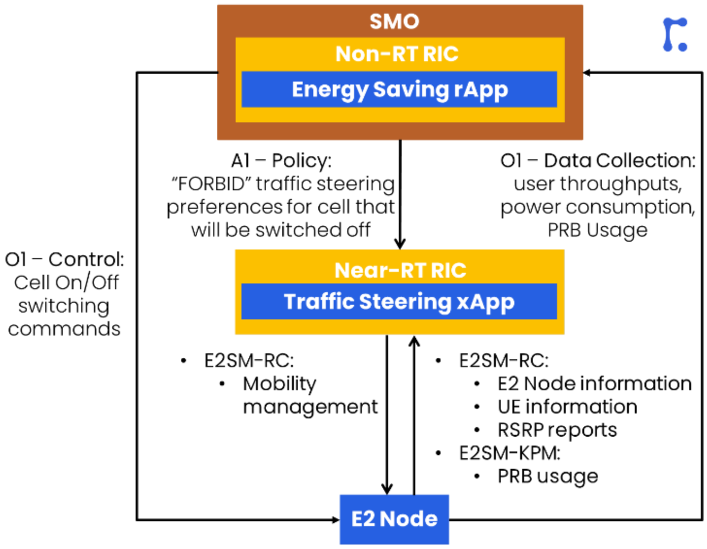

Figure 23. Option 1 topology (image provided by Rimedo Labs)

Setup Overview:

- **ES-rApp**: Deployed in the Non-RT RIC, responsible for deciding which cells to switch on / off based on network KPIs.
- **TS-xApp**: Deployed in the Near-RT RIC, handles Traffic Steering (TS) actions like offloading users when cells are to be switched off.
- **Interfaces:**
  - **A1 Interface**: Used by the ES-rApp to notify the TS-xApp via policies.
  - **O1 Interface**: Used by the ES-rApp to manage cell on/off operations.
  - **E2 Interface**: Used by the TS-xApp to perform TS actions and retrieve real-time data from the RAN.

Procedural Flow:

1. **ES-rApp Decision**: The ES-rApp in the Non-RT RIC continuously monitors KPIs such as user throughput, power consumption, and PRB usage. It identifies candidate cells for energy saving and decides to switch off certain cells.
2. **A1 Policy Creation**: The ES-rApp formulates an A1 policy that contains a "FORBID" clause for the selected cells, instructing the TS-xApp that no new users should be allowed on these cells.
3. **A1 Policy Notification**: The is Non-RT RIC sends the A1 policy to the Near-RT RIC, notifying the TS-xApp of the candidate cells for switch-off.

4. **TS-xApp Action**: Upon receiving the A1 policy, the TS-xApp starts offloading users from the candidate cells. The xApp retrieves real-time data (e.g., UE information, cell load) from the RAN using the E2 interface and directs users to neighboring cells via E2SM-RC (RAN Control).
5. **ES-rApp Monitoring**: The ES-rApp monitors the number of RRC connections in the candidate cells. Once the number of connections reaches zero, it confirms that all users have been successfully offloaded.
6. **Cell Switch-Off**: After user offloading is complete, the ES-rApp uses the O1 interface to deactivate the cell, putting it into energy-saving mode.
7. **Cell Switch-On**: When traffic conditions change, the ES-rApp may decide to reactivate a cell. The ES-rApp switches the cell on via the O1 interface and sends a request to delete the "FORBID" policy through the A1 interface.
8. **TS-xApp Action for Reactivation**: Once the "FORBID" policy is deleted, the TS-xApp begins using the reactivated cell for user traffic, ensuring that the load is balanced across the network.

<u>Option 2</u>: Traffic Steering xApp Notification through E2SM-CCC (E2 Interface)

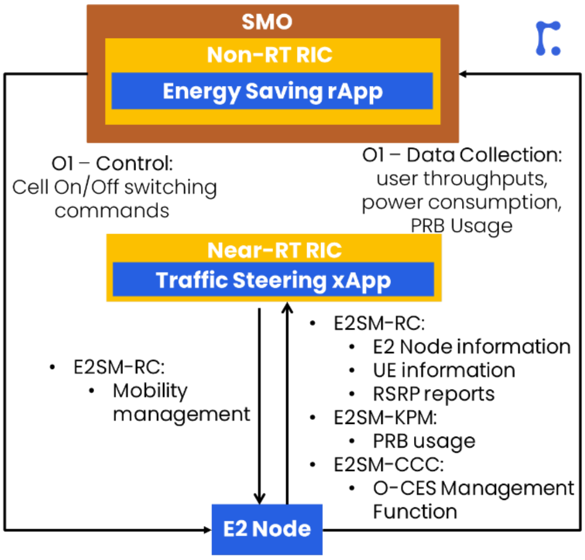

Figure 24. Option 2 topology (image provided by Rimedo Labs)

Setup Overview:

- **ES-rApp**: Deployed in the Non-RT RIC, responsible for deciding which cells to switch on/off based on network KPIs.
- **TS-xApp**: Deployed in the Near-RT RIC, handles Traffic Steering actions based on cell configuration changes.
- **Interfaces**:

- **E2 Interface**: Used by the TS-xApp to receive notifications of cell configuration changes and perform TS actions.
- **O1 Interface:** Used by the ES-rApp to manage cell on/off operations as well as for KPI data collection from the RAN nodes.

Procedural Flow:

1. **ES-rApp Decision**: The ES-rApp in the Non-RT RIC continuously monitors KPIs such as user throughput, power consumption, and PRB usage. It identifies candidate cells for energy saving and decides to switch off certain cells.
2. **ES-rApp Triggers Cell Configuration Change**: Instead of using the A1 interface, the ES-rApp directly triggers a cell configuration change via the E2SM-CCC service on the E2 interface. This change updates the O-CES (O-RAN Cell Energy Saving) Management Function parameters for the affected cell.
3. **TS-xApp Notification**: The TS-xApp subscribes to the E2SM-CCC service and receives an indication message whenever the O-CES Management Function attributes change. Specifically, it receives notifications about changes to parameters such as cesSwitch, energySavingState, and energySavingControl.
4. **TS-xApp Action**: When the TS-xApp detects that a cell is transitioning to the “toBeEnergySaving” state, it begins offloading users from the cell. The xApp retrieves real-time information (such as UE IDs, and cell load) through the E2 interface and controls handovers using E2SM-RC.
5. **Cell Transition to Energy-Saving Mode**: Once all users are offloaded, the cell automatically transitions to the “isEnergySaving” state, during which most of its hardware components are deactivated, and the cell stops serving users.
6. **Cell Reactivation**: When the ES-rApp decides to reactivate a cell, it changes its configuration via the E2SM-CCC to the “toBeNotEnergySaving” state.
7. **TS-xApp Action for Reactivation**: The TS-xApp waits for the cell to transition to the “isNotEnergySaving” state, indicating that it is fully reactivated. The TS-xApp then begins onboarding users back to the cell, managing traffic across the network accordingly.

6.3.7 Findings and results

The implementation of the Energy Savings for Multi-Carrier (ESMC) rApp, which leverages AI-driven algorithms and RAN programmability, demonstrated significant improvements in energy efficiency while maintaining high network accessibility. The AI-based approach enabled dynamic switching of RAN elements by differentiating between the coverage and capacity layers to ensure activation for additional capacity only when necessary. By analysing network conditions, predicting load variations, and making load-based decisions, the ESMC rApp optimized energy usage without compromising user Quality of Experience (QoE).

The Keysight RICtest solution evaluated the ESMC rApp, simulating a representative network based on a comprehensive Vodafone dataset; refer to Figure 25. This dataset included information from 13 sites and 41 sectors across five frequency bands, with a granularity of 15 minutes over two weeks. Key metrics included Physical Resource Block (PRB) utilization, power consumption, user QoE satisfaction (accessibility), the number of on-off transitions, and model complexity.

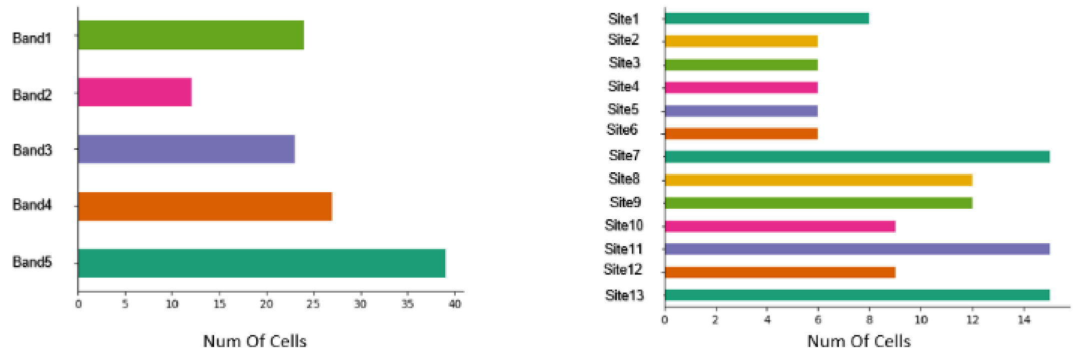

Figure 25. Number of cells across different frequency bands and sites in the Vodafone dataset

The results showed that the ESMC rApp successfully reduced energy consumption on the capacity layers by approximately 25 percent (refer to Figure 26). It was possible to achieve this goal through the intelligent management of capacity carriers, dynamically switching them to a low-energy state during periods of low traffic and reactivating them as needed during high traffic. Despite these energy-saving measures, the system maintained an exceptional accessibility level of 99.999 percent, ensuring that the user experience was not adversely affected.

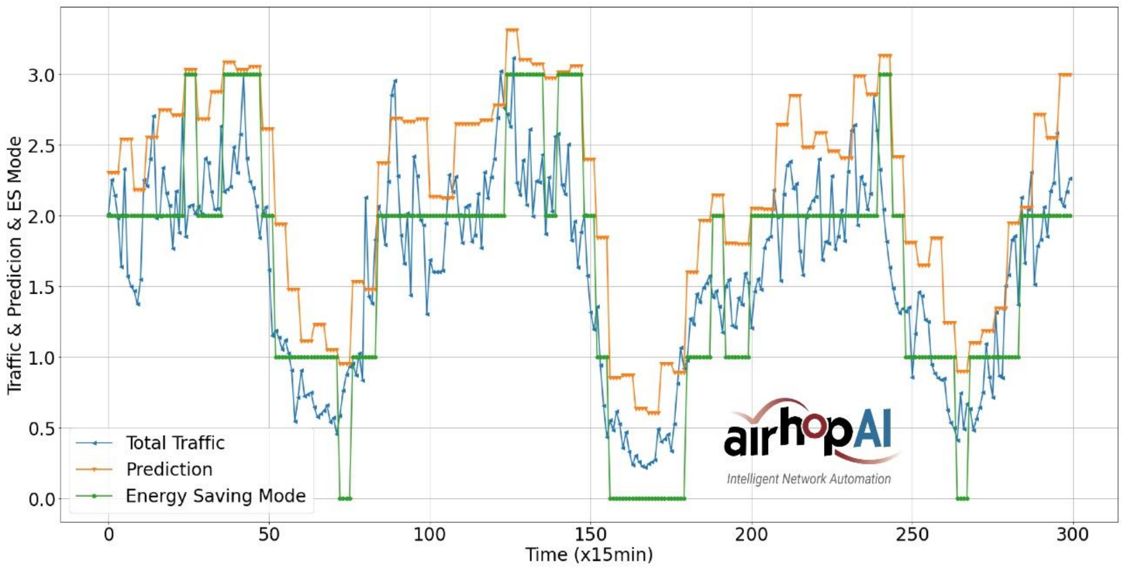

Figure 26. Traffic load, prediction, and energy-saving modes over time with AirHop's ESMC rApp (image provided by AirHop Communications)

The test is based on Vodafone dataset which applying the following O-RU characterization:

- Power is 2 x 40W
- FDD mode
- Band of 700M/800M/1800M/2100M/2600M
- 2T2R without MIMO
- Outdoor coverage.

The 25 percent energy saving gain is based on the percentage of time that the AI model decided to turn off the capacity layers and took an average over all capacity layers.

For example: ES percentage for carriers of sector 0: [0. 0.10714286 0.33333333 0.73214286 0.98214286] shows the energy saving percentage.

These numbers indicate the percentage of time the layers were turned off based on the AI decision. In this example, we have 5 cells (1 coverage and 4 capacity layers).

The coverage layer is always ON, so the ES percentage is zero. The first capacity layer is OFF around 10 percent of the time, the second capacity layer 33 percent, the third capacity layer 73 percent, and the fifth capacity layer 98 percent.

The 25 percent energy saving gain reported as a percentage number is averaged over all capacity layers of OFF ratio decided by the AI model in the dataset.

Furthermore, the AI-driven approach efficiently balanced energy savings and performance, even during transitions between different energy-saving modes. By minimizing the number of active capacity carriers when network load was low and adapting as traffic increased, the rApp maximized energy efficiency while preserving network performance.

One of the critical challenges addressed by the ESMC rApp was the coordination between multi-vendor rApps and xApps on the RIC platform, particularly between the Energy Savings rApp and the Traffic Steering xApp from two different providers. This coordination prevented conflicting interactions that could degrade network performance. The cooperation between the two applications was demonstrated during the National Telecommunications and Information Administration (NTIA) RIC Forum [9], enabled service providers to achieve energy savings without impacting service quality. In partnership with Juniper Networks, Vodafone, AirHop, Rimedo Labs, and Keysight, the demonstration highlighted the ability to achieve 25% energy savings through coordinated multi-vendor rApp / xApp interactions.

6.3.8 Recommendations

1. **Standardization**

- **Enhance O-RAN Specifications:** The O-RAN ALLIANCE should continue refining the A1, E2, and O1 interface specifications to ensure greater compatibility between multi-vendor rApps and xApps, enabling a more seamless integration of energy-saving and traffic-steering functions. 3GPP R18/R19 has multiple study items working on network energy-saving features. O-RAN ALLIANCE should create work items to leverage these outcomes from the 3GPP effort to help mobile operators save energy costs and improve subscriber quality of service.

- **Develop Common Test Methodologies:** Standardized test methodology and specifications, like what Keysight's RICtest does, should be further developed to allow for consistent benchmarking across different network configurations and vendor implementations.

  Keysight has contributed the performance test case "Network Energy Saving with Carrier and Cell switch off / on using Non-RT RIC" to the O-RAN ALLIANCE TIFG (Test and Integration Focus Group) E2E (End to End) test specification.

2. Operators

- **Adopt AI-driven Energy Management:** Operators should be aware of the potential of AI-based rApps to manage energy consumption dynamically, particularly in multi-carrier deployments where traffic demand fluctuates significantly across the carrier layers.

- **Leverage Open RAN Flexibility:** By adopting Open RAN principles and RIC-based architectures, operators can increase vendor diversity, which allows for more tailored and efficient network solutions, ultimately reducing both costs and environmental impact.

  This chapter highlights the technical capabilities and strategic advantages of implementing energy-saving and traffic-steering solutions in Open RAN networks. It provides operators with a pathway to enhance energy efficiency while maintaining network performance and user satisfaction.

7 Summary and Recommendations

RAN consumes more than 70 percent of the total energy consumption in MNOs' wireless networks. Optimization of the energy consumption and efficiency of RAN products is, therefore, a priority for the MNOs, considering their corporate sustainability responsibilities and the topline standpoint of rising energy costs globally (both CapEx and OpEx). Being a new entrant to the market, Open RAN needs to demonstrate on par or better energy consumption and efficiency compared to traditional monolithic RANs for each of the Open RAN products and in a multi-vendor Open RAN system.

Standards organizations such as the 3GPP and O-RAN ALLIANCE have been prioritizing the development of network energy savings features in their respective standards. The O-RAN ALLIANCE standards are complementary to the 3GPP standards: O-RAN ALLIANCE fully leverages 3GPP standardization while specifying energy savings features for Open RAN components which are not in 3GPP's scope, such as the O-Cloud and RIC-enabled energy savings optimization, while ensuring that multi-vendors interoperability aspects are well supported.

Starting in 2022, Vodafone has been exploring with its partners innovating new testing methods to evaluate Open RAN product's energy consumption, efficiency, and savings features, as there has been limited standardization in this space. We have shared the testing methodologies and test results for the O-RU, O-DU / O-CU / O-Cloud, and RIC-enabled energy savings optimization used in these test campaigns at multiple O-RAN Global PlugFests events. This handbook summarizes this information together with the significant findings and recommendations for testing and evaluation approaches, improvements in Open RAN products, and standardization.

The **O-RU** energy consumption has been evaluated using the Keysight automated Energy Plane Test Suite, which references the ETSI-defined test methodology standardized in ETSI ES 202 706 for static energy consumption measurement for the base station. The category A O-RU energy savings feature (micro DTX energy savings feature, which switches on / off its power amplifier at the symbol level) has been characterized and demonstrated significant energy savings gains compared to when this feature is not enabled.

The **O-DU / O-CU / O-Cloud** energy consumption and efficiency have been evaluated for multiple objectives with the Keysight automated Energy Plane Test Suite. These objectives include:

1. Benchmarking energy consumption and efficiency referencing the ETSI-defined test methodology standardized in ETSI TS 103-786 for dynamic energy consumption and efficiency measurement for the base station.

2. Exploring energy savings optimization with close to real world's traffic patterns; this goal is achieved by emulating Vodafone commercial network cluster of base stations traffic profiles in a lab environment and ensuring that energy savings implementation doesn't adversely impact customers experiences and network performances.

3. Instrumented payloads to assist with the development and characterization of the energy profile of the O-DU / O-CU / O-Cloud to assist with the design of RIC-enabled optimization algorithms.

4. Collection of energy consumption measurements of the cloud virtual workloads in run-time without degrading the application performance.

Testing with both points 1 and 2 has demonstrated that a significant amount of energy can be saved when the O-DU / O-CU workloads can be optimally designed to dynamically manage the processors' C and P-States and Uncore Frequency in response to changing workloads.

Testing with point 3 has shown early results that the multi-vendors O-DU / O-CU / O-Cloud system will have differing energy profiles. These will influence the dynamic close loop design of the RIC-enabled optimization models and will need to be further investigated.

Testing with point 4 has revealed the possibilities of estimating the energy consumption and efficiency of virtual workloads (DU / CU) in a virtual / cloud environment where multi-tenancy may be expected.

RIC-enabled optimization enables real-time control and automation of RAN elements with the xApps and rApps operating on RIC platforms. Vodafone has established a RIC-enabled optimization closed loop testbed that requires close to real-world traffic scenarios to be emulated and performs close loop interaction with the RIC and RIC applications in the lab environment; the target of this closed loop testbed is to test, evaluate, and benchmark RIC energy savings applications which leverages AI-driven algorithms and RAN programmability. It has been demonstrated that significant energy savings can be achieved with an AI-based approach, which has enabled dynamic switching of RAN elements through sensing of network conditions, utilizing network load predictions, and making load-based decisions usage without compromising user QoE.

Vodafone is committed to continuing to innovate with our industry partners to develop and validate testing and optimization methods. These methods are instrumental in driving significant improvements in energy consumption, energy efficiency, and energy savings techniques for Open RAN products, thereby paving the way for open and greener mobile network deployments.

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9 Glossary of Terms

3GPP	3rd Generation Partnership Project
AC	Alternate current
AI	Artificial intelligence
BLER	Block error rate
BS	Base station
CaaS	Cloud as a Service
CapEx	Capital expenditures
CCC	Cell configuration and control
CPU	Central processing unit
CSI-RS	Channel state information reference signal
C-Plane	Control plane
DC	Direct current
DPU	Data processing unit
DRX	Discontinuous reception
DTX	Discontinuous transmission
DV	Data volume
E2E	End-to-end
E2SM	E2 Service model
EC	Energy consumption
EE	Energy efficiency
eNB	Evolved node B
ES	Energy savings
ESF	Energy saving feature
ESMC	Energy savings for multi-carrier
ETSI	Europe Telecommunication Standard Institute
FDD	Frequency division duplexing
FFT	Fast Fourier transform

FR	Frequency range
gNB	Next generation node B
GPU	Graphical processing unit
iFFT	Inverse fast Fourier transform
KEPLER	Kubernetes-based efficient power level exporter
KPI	Key performance indicator
ML	Machine learning
MNO	Mobile network operator
MWC	Mobile World Congress
M-Plane	Management plane
Near-RT RIC	Near real-time RAN intelligent controller
Non-RT RIC	Non-real-time RAN intelligent controller
NG-RAN	Next-generation radio access network
NR	New radio
NTIA	National Telecommunications and Information Administration
OFDM	Orthogonal frequency division multiplexing
OTA	Over-the-air
O-CU	Open central unit
O-DU	Open distributed unit
O-RAN	Open radio access network
O-RU	Open radio unit
OpEx	Operating expense
PA	Power amplifier
PDSCH	Physical downlink shared channel
POD	Point of delivery
PRB	Physical resource block
QoE	Quality of experience
QoS	Quality of service

RAN	Radio access network
RF	Radio frequency
RIC	Radio intelligent controller
RMSI	Remaining minimum system information
RP	Release proposal
RU	Radio unit
SSB	Synchronization signal block
TDD	Time-division duplexing
TIFG	Test and integration focus group
TR	Technical report
TRX	Transceiver
TS	Traffic steering
SCell	Serving-cell
SIB1	System information block type 1
SLA	Service level agreement
SMO	Service management orchestration
S-Plane	Synchronization plane
SSB	Synchronization signal block
UE	User equipment
ULPI	UpLink performance improvement
UPT	User perceived throughput
U-Plane	User plane
WG	Working group
Wh	Watts per hour