DESCRIPTION OF THE ORAN ARCHITECTURE: DESIGN, PROTOTYPES, AND EXISTING COMMERCIAL PRODUCTS

WRITTEN BY

AMOGU J. UDUKA

APRIL 2023.

1.0 INTRODUCTION

1.1 What is RAN?

Before delving into the study of ORAN architecture, it was very important to know and understand the basic structures that make for its actualization. One such structure is the Radio Access Network, which consists of radio base stations with large antennas [1]. RAN is the part of a mobile network that connects end-user devices, like smartphones, to the internet. Radio waves from end-user devices are used to send information to RAN's transceivers, and finally from the transceivers to the core network which connects to the global internet (cloud in this context) [7].

The traditional RAN consists of 3 major components namely the baseband, radio, and antennas. RANs have also evolved over the years as cellular technology is now at 5G. Today, RANs can support multiple-input, multiple-output (MIMO) antennas, wide spectrum bandwidths, multi-band carrier aggregation and more [2]. However, this implementation is now more and more disaggregated. This composition makes the network highly capable and efficiently implements massive MIMO [7].

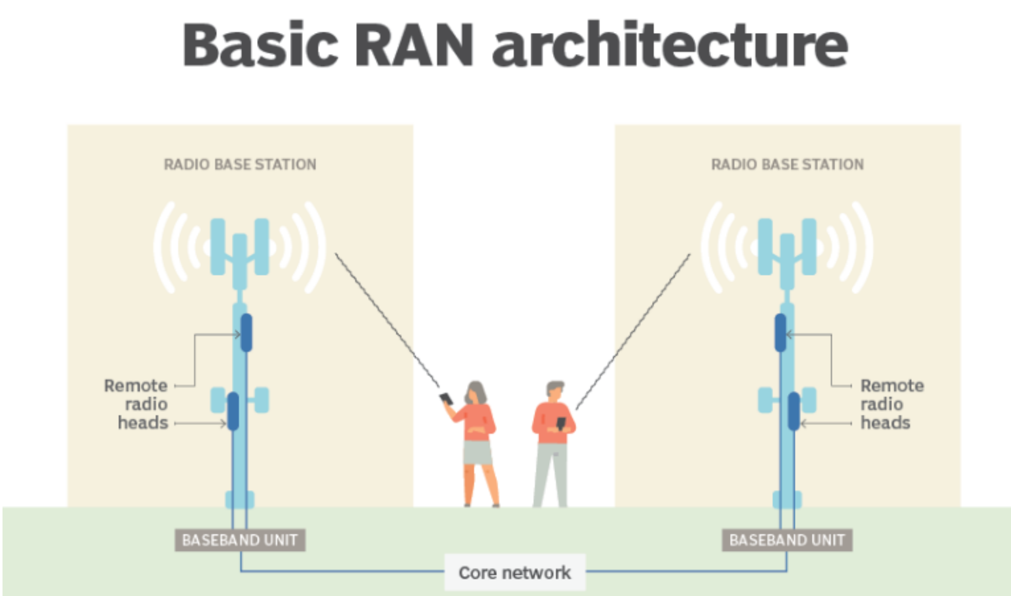

Figure 1: The Basic RAN architecture [8]

1.2 LIMITATIONS OF RAN AND THE EVENTUAL PUSH FOR O-RAN

ORAN gets its motivation due to the bottlenecks associated with the legacy RAN, especially as regards to overall network expenses, performing complex processing because they represent vital connection points to telecommunication network operators for the dynamic telco space [7]. Built on a closed architecture, the legacy RAN restricted the Communication Service Provider (CSP) into using the same vendor for both their radio and baseband equipment.

Given the rapid advancement of technology, especially with tools such as Artificial Intelligence (AI) and Machine Learning (ML), it is imperative that flexible structures are being deployed to accommodate these changes. The key players must transcend the traditional closed networks towards open ones. ORAN provides a more open radio access network architecture, which increases interoperability between various vendors and creates more scalable, efficient networks, and the faster innovation of features and services, as it will change the confidential nature of the RAN market, where RAN vendors have proprietary equipment and software.

ORAN is a collaboration of equipment makers and telecoms in various working groups to solve this interoperability problem by creating standards. It takes a totally disaggregated approach towards deploying mobile fronthaul and midhaul networks built entirely on cloud native principles [3].

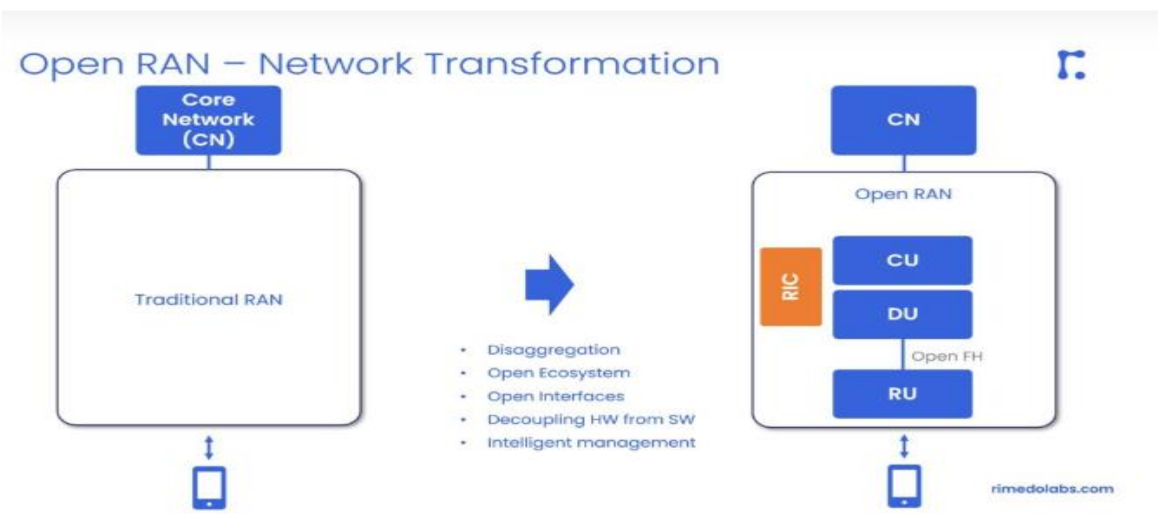

Figure 2: RAN Transformation [3]

1.3 THE ORAN ALLIANCE

The ORAN Alliance is a group that is defining specifications for radio access networks. It is a global alliance founded in 2018 and it now comprises close to 30 operators and more than 200 vendor companies.

The O-RAN Alliance is a relatively new organization that took the 3GPP standards work as its baseline and set out to create extensions specifically for the RAN. The goals are to provide detailed blueprints for how to build the RAN solution enabling parts from different vendors, including mechanisms for enabling AI and ML for more efficient network management and orchestration [8].

According to [9], ORAN can be discussed based on three scopes.

1. Its Architecture
2. Its Interface
3. Its Workflows

According to the O-RAN working group technical specification, ORAN's activities are guided by the following objectives.

1. Leading the industry towards open, interoperable interfaces, RAN virtualization, and big data and AI enabled RAN intelligence.
2. Maximizing the use of common-off-the-shelf hardware and merchant silicon and minimizing proprietary hardware
3. Specifying APIs and interfaces, driving standards to adopt them as appropriate, and exploring open source where appropriate.
4. The O-RAN Architecture identifies the key functions and interfaces adopted in O-RAN.

1.4 ORAN ARCHITECTURE

In the O-RAN architecture, the radio side includes Near-RT RIC, O-CU-CP, O-CU-UP, O-DU, and O-RU. The management side includes Service Management and Orchestration Framework that contains a Non-RT-RIC function [29].

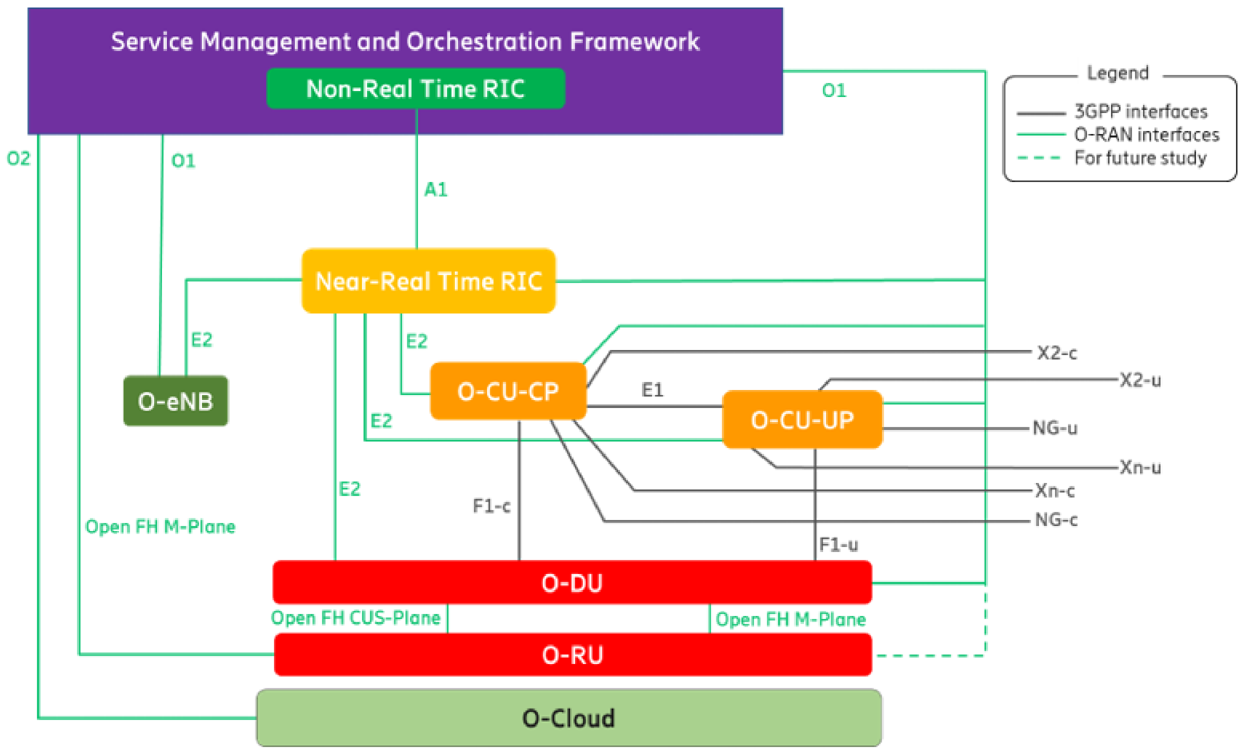

Figure 3: High Level View of ORAN Architecture and 3GPP interfaces [29]

1.5 RAN Intelligent Controller (RIC)

RIC is a central software component of the ORAN architecture that is responsible for both the optimization and controlling of RAN functions. It is a crucial element in the management of 5G network functions like network slicing, high-bandwidth, low-latency applications, prioritized communications, and more [11].

It enables the onboarding of third-party applications that automate and optimize RAN operations at scale while supporting innovative use cases that lower mobile operators' total cost of ownership (TCO) and enhance customers' quality of experience (QoE) [10].

It is split into the following.

- Non-Real Time RIC
- Near-Real Time RIC

1.6 Non-Real Time RIC

It operates from within the RIC's Service Management and Orchestration (SMO) platform. As such, it handles lifecycle management for all network elements, configuration management, and many other essential network functions. It also supports the execution of third-party applications (rApps), which are used to provide value-added services to support and facilitate RAN optimization and operations, including policy guidance, enrichment information, configuration management and data analytics [9, 11, 12].

It is a component typically built on a separate physical server or data center infrastructure, separate from the Radio Access Network (RAN) or the Baseband Unit (BBU).

This open design hinders individual RAN software vendors from locking down network features, as their products can easily be replaced with another app from another vendor. It is also worthy to note that the placement of the Non-RT RIC in the SMO is to ensure secure access to contextual data for the optimization of the RAN.

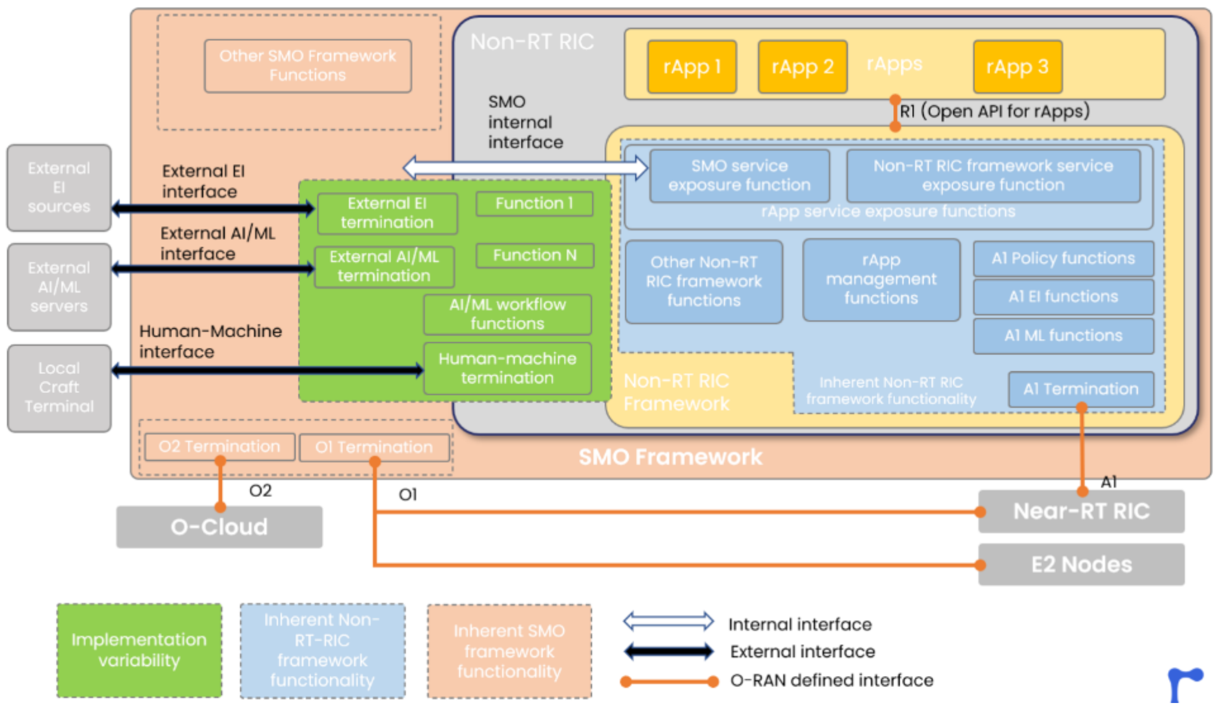

Figure 4: Detailed Non-RT RIC and SMO architecture [29]

Fig. 4 gives the detailed diagram of the internals of the SMO framework including the Non-RT RIC. The component in blue shows functions that are used basically for managing the rApps which are external to the Non-RT RIC framework accessible through an open Application Programming Interface (API), using R1 interface. The other set of blue elements include those that create the data to be transmitted over the A1 interface, namely: A1 policy functions, A1 enrichment information functions, A1 ML functions [29].

There are also parts in the SMO framework that are out of Non-RT RIC scope, marked with a pink-ish color. They are basically related to the O1/O2 termination as well as other SMO framework functions, e.g., for network slicing lifecycle management. Those are inherent to the SMO framework [29].

Finally, the green part refers to the functionality which implementation is flexible. Those functions could be part of non-RT RIC and they could be also external to non-RT RIC and sit in the SMO. They are not inherent to any of those [29].

The main difference between Near-RT and non-RT is the response time they take to effect changes in the RAN. The Near RT RIC will turn around decisions in between 1 millisecond and 1 second. The non-RT RIC has a response time of 1 second or greater, gathers data from RAN elements and provides a source of data into the Near-RT RIC [14].

1.7 Near-Real Time RIC

The near-RT RIC is the core of the control and optimization of the RAN, thanks to the capabilities offered by the E2 interface. It resides within a telco edge or regional cloud and typically enables network optimization actions that take between 10 milliseconds to one second to complete. It is a software platform that allows the xApps (cloud-native microservice-based applications) to control the RAN through it. It also hosts the termination of three interfaces (O1, A1, and E2).

It enables near real-time control optimization of the RAN elements via actions sent over the E2 interface. Examples of xApps functionalities include handover optimization, radio link monitoring, mobility management, load balancing, slicing policy updates, traffic steering, and interference management [12].

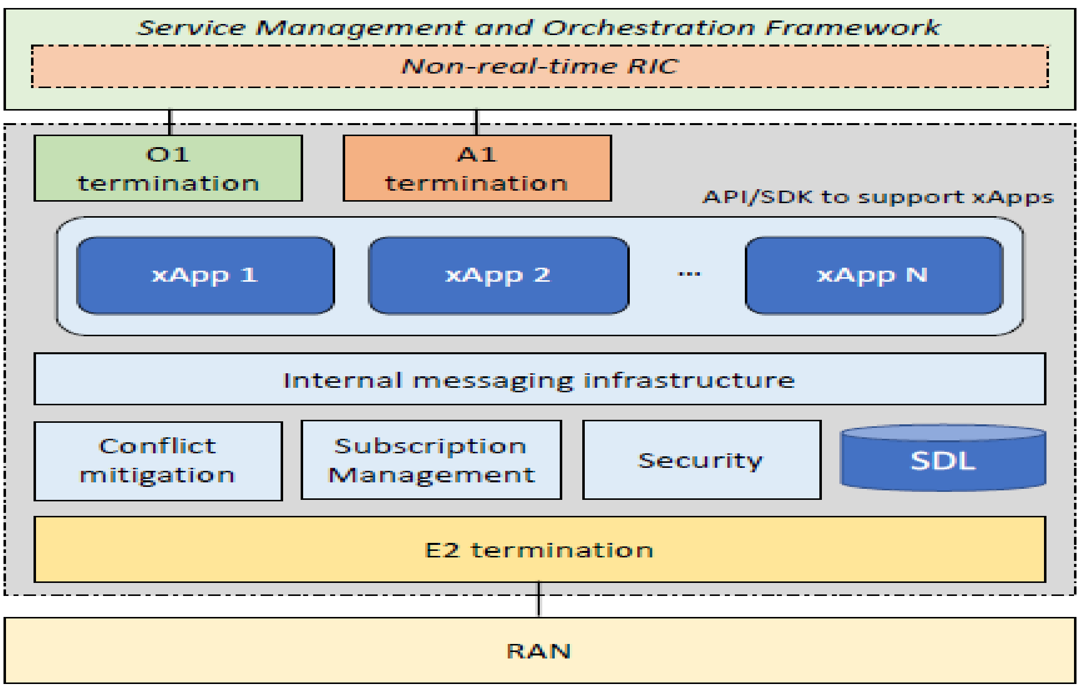

Figure 5: Near-RT RIC architecture [9]

1.8 RIC Automation Apps

RICs host two types of software automation applications called rApps and xApps, the first running on non-RT RICs and the second on Near RT RICs. From Ericsson's perspective, there are five general areas of rApp application, which includes Network evolutions, Network deployment, Network optimization, Network healing, and Automation and AI [14].

xApps use inputs to perform computations and propose changes to improve an aspect of the RAN such as Network admission control, resource utilization, QoS fulfillment and other RAN network Key Performance Indicators (KPIs) [14].

2.0 KEY PLAYERS AND PROTOTYPES: RICS IN THE REAL WORLD

2.1 NOKIA

Nokia's Service Enablement Platform (SEP) delivers network programmability and introduces AI/ML into the O-RAN ecosystem. It is unique to the other providers given that it is the first to combine near-RT and Mobile and Edge Computing (MEC) capabilities into one platform, which may be configured to specific CSP or enterprise requirements [17]. Utilizing Nokia's edge-optimized AirFrame servers, SEP can run on the edge and share infrastructure with Cloud RAN and other virtualized network functions. AirFrame Open Edge provides secured and high-performance ultra-small footprint edge cloud infrastructure for indoor and outdoor environments [30].

Figure 6: NOKIA SEP Solution [31]

Around July 2018, Nokia and AT&T announced a successful trial of a RIC on the carrier's millimeter wave 5G network in New York City. According to [13], it met its goals of improving spectral efficiency and proving out functionality of this set of technologies derived from O-RAN Alliance technical work. In this trial, the RIC was deployed as a software instance. Measurement and optimization applications were used to collect live network data.

Mazin Gilbert, VP of Technology and Innovation at AT&T stated that the successful trial was a testament to what we can achieve through openness and collaboration. Together with the O-RAN Alliance, AT&T and Nokia will continue to develop and contribute to the E2 interface and the near-real-time RIC platform to help enable an intelligent and flexible 5G network.

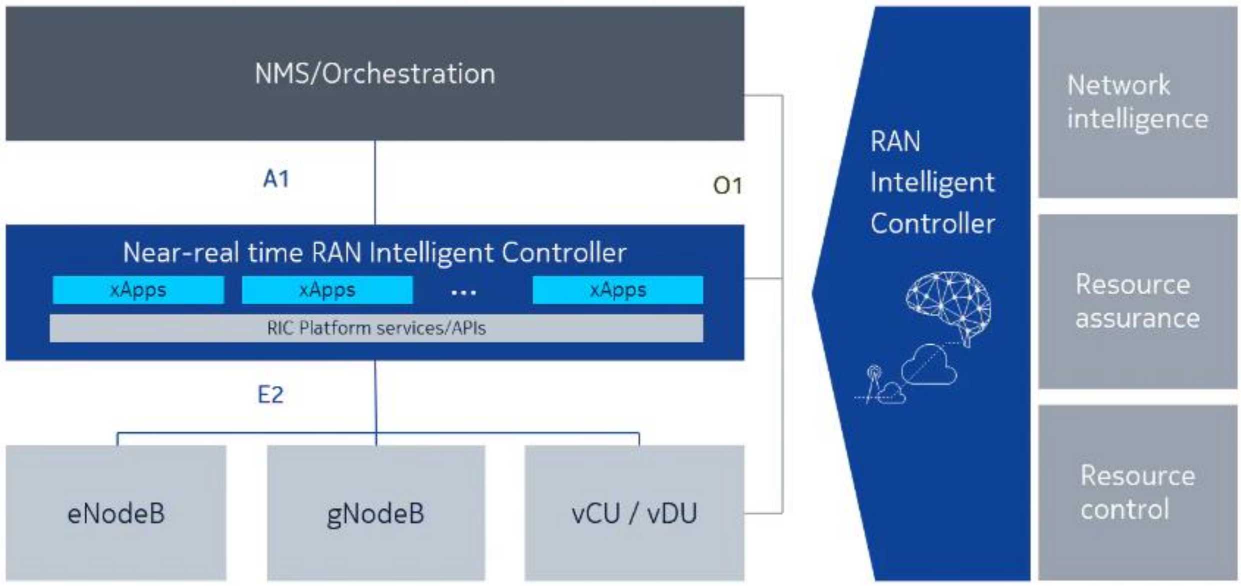

Figure 7: Nokia's ORAN Setup [31]

2.2 ERICSSON

Ericsson's demo of the Ericsson Frequency Layer Management rApp is a good example of a network optimization rApp as it optimizes the automated load balancing features of the radio network between different frequency layers. This rApp is composed of several smaller functions to provide the load balance recommendations, and some of these functions are also shared with other centralized SON algorithms such as Ericsson 5GCentralized Neighbor Relations rApp [15].

The Frequency Layer Manager rApp algorithm flow can be broken down into three distinct phases that serve to identify and implement load-balancing.

- Network insights
- Load-balancing quantum
- Network changes

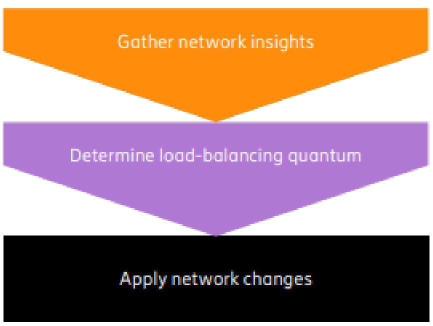

Figure 8: Ericsson Frequency Layer manager rApp flow [32]

Ericsson's Intelligent Automation Platform uses AI and radio network applications (rApps) with different functionalities to automate the radio access network. The platform also enables software developers to build products through a software defined toolkit (SDK), thereby supporting ecosystem innovation [16].

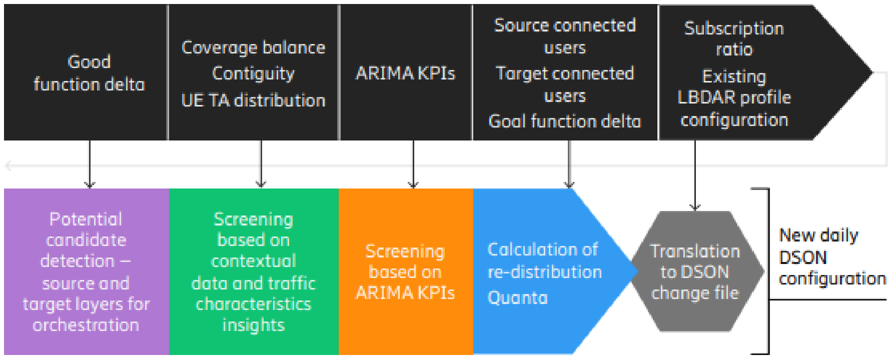

Figure 9: Ericsson Frequency layer Manager rApp automation processes [32]

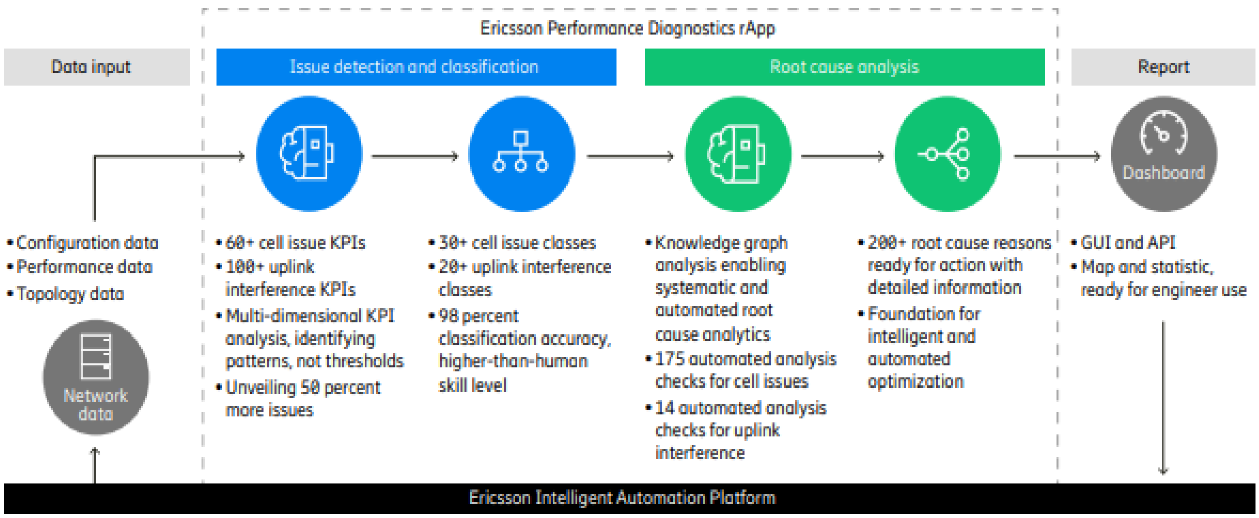

Figure 10: Ericsson Performance Diagnostics rApp architecture [33]

2.3 ACCELLERAN

On the 21st of June 2021, Accelleran, a leading provider of O-RAN software solutions for 4G/5G networks, announced the immediate availability of 5G standalone dRAX cloud-native O-RAN software components. It offers a production-ready O-RAN development platform, enabling real-time RAN data to be leveraged to create AI-based xApps and enhanced RAN intelligence and automation. It supports everything from small-scale office deployments to large-scale solutions with multi-node clustering, load balancing, benefiting mobile network operators, neutral host operators and system integrators alike [17].

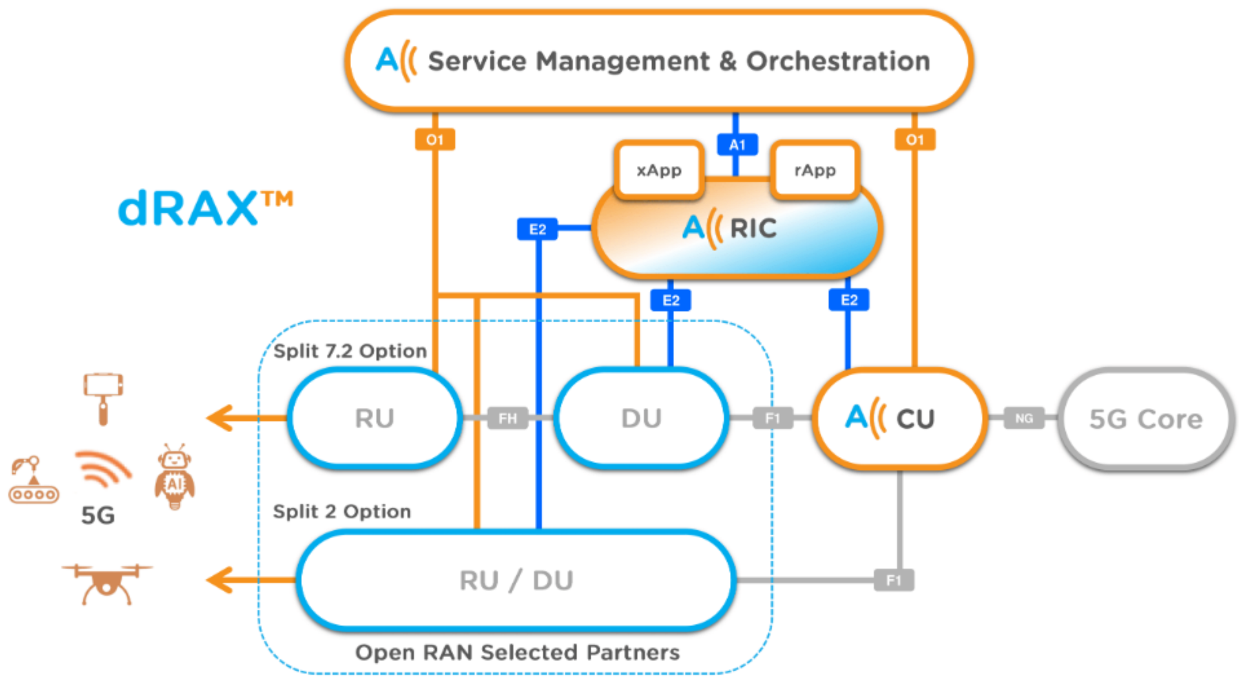

Figure 11: Accelleran's dRAX O-RAN [34]

2.4 JUNIPER NETWORKS

In partnership with Turk Telekom’s Netsia subsidiary, Juniper Networks entered the O-RAN space with its newly developed RIC. Juniper Networks has licensed the RIC technology from Netsia and is using its own kit to develop the code and ensure it works with Turk Telecom’s Open RAN integration. As part of this partnership, Netsia will transfer its RIC technology, related source code, patents, rights, and technical domain experts to Juniper to support the integration into the latter’s product portfolio. Its RIC comes in both near-RT and non-RT forms, with the ability to host both xApps and rApps from any third-party providers [18].

2.5 MAVENIR

Mavenir demonstrated its O-RAN RIC at the Global O-RAN Alliance Plugfest in India towards the end of 2020, alongside its partnership with Airtel. Its RIC incorporates advanced ML for network performance enhancements through the ingestion of a demonstration RAN’s performance metrics and configuration data [18].

2.6 PARALLEL WIRELESS

Parallel Wireless developed its own O-RAN Controller to enable O-RAN solutions. Its controller is the first to provide an “all G” RAN, offering virtualized 2G BSC, 3G RNC, 4G eNB, X2/S1 Gateway in any combination. As a 5G native platform, it can also provide a straightforward migration pathway to 5G. Further, Parallel Wireless provides both near-RT and non-RT controllers [18].

2.7 STERLITE TECHNOLOGIES (STL) AND ASOCS

Its demo at the Global O-RAN Alliance Plugfest in India in 2020, demonstrated that different possible scenarios of 4G/5G networks could be deployed with open and disaggregated RAN and will no doubt help operators expedite commercial 5G enterprise and macro network rollouts [18].

2.8 VIAVI

In 2020, in partnership with AT&T, Samsung and Nokia, Viavi demonstrated its TeraVM O-RAN RIC Tester at the O-RAN Alliance Plugfest. Tera VM is an AI-Assisted, virtualized tool enabling operators to test their RIC to ensure they can optimize RAN resources, reduce signaling and improve capacity. Developers can use this tool to test that the RIC is working as it should be. TeraVM provides the emulated RAN (the measurements) to the RIC under test and then receives the outputs/decisions from the RIC and modifies according to the proposed changes from the RIC [19, 20].

2.9 ALTIOSTAR

Altiostar has developed an ORAN solution that is based on cloud-native architecture. The company's solution uses virtualization, containerization, and microservices to enable service providers to deploy flexible, scalable, and efficient RANs. In 2020, Telefónica’s O2 completed an ORAN trial on its core network in the U.K., with NEC acting as system integrator to design a customized architecture that used Altiostar vRAN software [25].

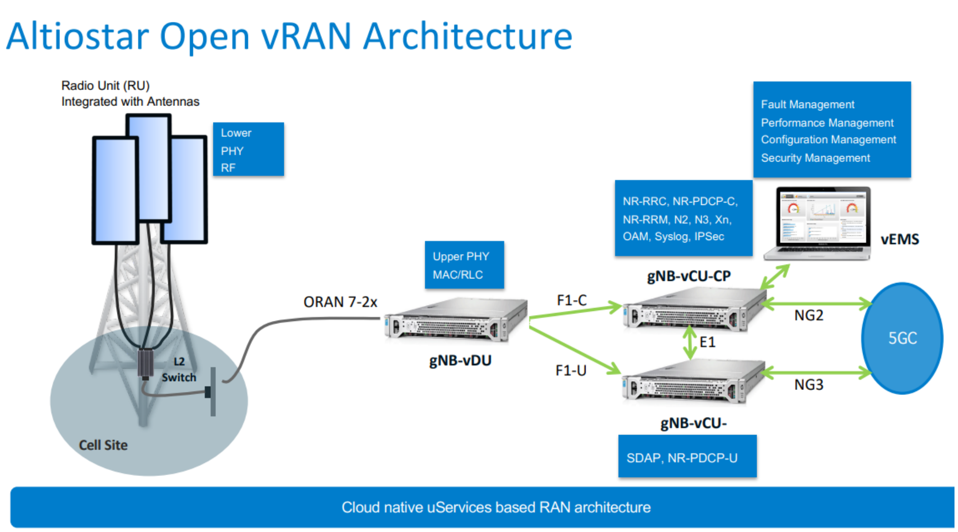

Figure 12: Altiostar Architecture [25]

3.0 O-RAN CONTROL UNIT (O-CU), DISTRIBUTED UNIT (O-DU) AND RADIO UNIT (O-RU)

RAN disaggregation splits base stations into different functional units, thus effectively extending the functional disaggregation paradigm proposed by 3GPP for the New Radio (NR) Next Generation Node Bases (gNBs). The gNB is split into a Central Unit (CU), a Distributed Unit (DU), and a Radio Unit (RU) (called O-CU, O-DU, and O-RU in O-RAN specifications).

3.1 O-CU

CU provides support for the higher layers of the protocol stack such as SDAP, PDCP and RRC. In 5G, there are two defined entities in the CU, namely CU-CP (Control Plane – for connection management) and CU-UP (User Plane – for UP data processing. This logical split allows different functionalities to be deployed at different locations of the network, as well as on different hardware platforms [10, 13]. The CU controls the operation of several DUs over the mid-haul interface. CU software can be co-located with DU software on the same server on site [21].

3.2 O-DU

DU provides support for the lower layers of the protocol stack such as RLC, MAC, and the Physical layer. This logical node includes a subset of the eNodeB (eNB)/gNodeB (gNB) functions, depending on the functional split option, and its operation is controlled by the CU [21].

3.3 O-RU

The RU is the radio hardware unit that converts radio signals sent to and from the antenna into a digital signal for transmission over packet networks. It handles the digital front end (DFE) and the lower PHY layer, as well as the digital beamforming functionality. They are generally implemented on Field Programmable Gate Arrays (FPGAs) and Application-specific Integrated Circuits (ASICs) boards and deployed close to RF antennas [21].

3.4 Split option 7.2x

The O-RAN Alliance has evaluated the different RU/DU split options proposed by the 3GPP, with specific interest in alternatives for physical layer split across the RU and the DU In this option, the PHY layer's functional modules are distributed between Low_PHY and High-PHY based on Open RAN specifications. According to [19], the Split 7.2x objectives are:

- Minimize impact on transport bandwidth while maximizing virtualization in gNB CU and gNB DU.
- Enable simple, low-cost RRR designs for wide adoption.
- Eliminate performance loss compared to integrated solutions with ideal fronthaul.
- Eliminate limitations on receiver architecture for performance.
- Eliminate redesign for NR as opposed to LTE.
- Support advanced signal processing such as UL compression.
- Centralized scheduling.

In split 7.2x, the RU only performs Fast Fourier Transform (FFT) and cyclic prefix addition/removal operations, which makes the RU inexpensive and easy to deploy. The DU then takes care of the remaining functionalities of the physical layer and of the Medium Access Control (MAC) and Radio Link Control (RLC) layers [9, 20].

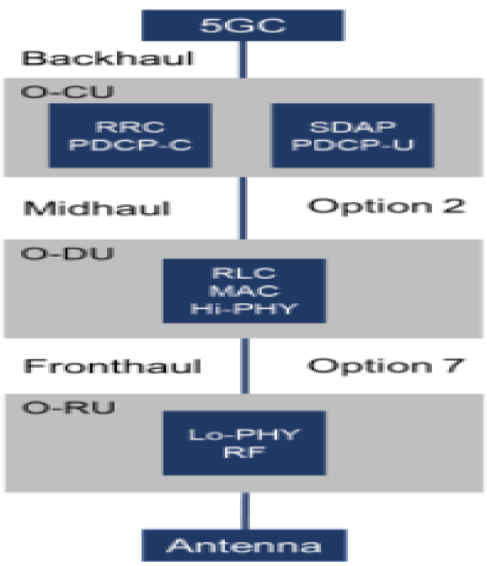

Figure 13: Split Option 7.2x [20]

3.5 O-CLOUD

It is a cloud computing platform that comprises physical infrastructure nodes to host O-RAN functions. It supports software components like Operating Systems (OS), Virtual Machine (VM) monitoring, container runtime, management, and orchestration functions.

To ensure openness, O-RAN decouples hardware and software into 3 layers:

- The commercial off the shelf (COTS) merchant silicon (including x86),
- A hardware abstraction layer
- An application layer, where the RAN functions reside.

Ensuring each layer is vendor agnostic, the O-RAN alliance has specified a list of requirements for a cloud platform which supports the execution of O-RAN network functions. This is referred to as the O-RAN Cloud Platform, or O-Cloud. [3, 23].

4.0 O-RAN INTERFACES

The O-RAN Alliance introduces technical specifications that describe open interfaces connecting several different components of the O-RAN architecture. There are several interfaces at work within an O-RAN architecture. They include:

- Open fronthaul interface
- O1
- A1
- O2
- X2
- Xn
- NG
- E1
- E2
- F1

4.1 OPEN FRONTHAUL INTERFACE

This connects the O-DU to one or multiple O-Rus inside the same gNB. It makes it possible to distribute the physical layer functionalities between the RU and the DU, and to control RU operations from the DU. The O-RAN breaks down into the management plane (M-Plane) and the control user synchronization plane (CUS-Plane). The M-Plane connects the O-RU to the O-DU, and only optionally connects the O-RU to the Service Management and Orchestration (SMO). The O-DU uses the M-Plane to manage the O-RU, while the SMO can provide FCAPS services to the O-RU [10, 24].

4.2 O1 INTERFACE

This interface connects the SMO to the RAN managed elements. These include the near real-time RIC, O-CU, O-DU, O-RU, and the open evolved NodeB (O-eNB). The O-eNB is the hardware aspect of a 4G RAN. The management and orchestration functions are received by the managed elements via the O1 interface. The SMO in turn receives data from the managed elements via the O1 interface for AI model training. It supports Management Services (MnS), which include the management of the life cycle of O-RAN components, performance assurance and trace collections through KPIs reports and software and file management. It generally connects one MnS provider to one MnS consumer [10, 24].

4.3 AI INTERFACE

It connects two O-RAN specific components (non-RT RIC and near-RT RIC). This enables communication between the two RICs and supports policy management, data transfer, and machine learning management. The data, called enrichment information, is specifically for assisting the model training for the AI and machine learning in the near-RT RIC. It is based on the A1AP application protocol, whose functionalities are then further specified for each service it supports [10, 24].

4.4 O2 INTERFACE

O2 interface is how the SMO communicates with the O-Cloud it resides in, thus enabling the management and provisioning of network functions in a programmatic manner. Network operators that are connected to the O-Cloud can then operate and maintain the network with the O1 or O2 interfaces by reconfiguring network elements, updating the system, or upgrading the system. It also allows the definition of an inventory of the facilities controlled by the O-Cloud, monitoring, provisioning, fault tolerance and updates [10, 24].

4.5 X2 AND XN INTERFACES

The X2 interface is broken up into the X2-c and X2-u interfaces, where the former is for the control plane and the latter is for the user plane. Both were originally designed by 3GPP for sending information between a 4G network's eNBs, or between an eNB and a 5G network's en-gNB. In the O-RAN Alliance's documentation, the interface has the same principles and protocols [23].

Xn interface is also broken into control and user subtypes – Xn-c and Xn-u. They transfer control and user plane information between next generation NodeBs (gNBs), between ng-eNBs (4G nodes capable of connecting to a 5G core), or between the two different types [23].

4.6 NG INTERFACES

The NG control and user plane interfaces connect an O-CU control plane and O-CU user plane to the 5G core, which supports the exchange of signaling information. It defines the interconnection of NG-RAN nodes with Access and Mobility Management Functions (AMFs) supplied by different manufacturers and specifies the separation of NG interface Radio Network functionality and Transport Network functionality to facilitate introduction of future technology [24, 25]. The user plane information goes to the 5G user plane function (UPF), which handles many aspects of routing, forwarding, and tunneling [24, 25].

4.7 E1 AND E2 INTERFACES

E1 connects two disaggregated O-CU user and control planes. It supports the exchange of signalling information between the gNB-CU-CP and a gNB-CU-UP. It also enables the exchange of User Equipment (UE) associated information and non-UE associated information. The E! interface separates the Radio Network Layer and Transport Network layer [24].

The near RT RIC in the O-RAN architecture connects to the O-CU, O-DU, and O-eNB with the E2 interface. The protocols that go over the E2 interface are only control plane protocols. The protocols are for controlling and optimizing the E2 node elements and the resources they use [23].

4.8 F1 INTERFACES

This interface is broken into control and user planes subtypes, connecting the O-CU-CP and O-CU-UP to the O-DU. It exchanges data about the frequency resource sharing and other network statuses. It supports control plane and user plane separation, separates Radio Network Layer and Transport Network Layer [24, 25].

5.0 AREAS OF CONCERN/DRAWBACKS FOR O-RAN

5.1 SECURITY

Architectural changes and broader technological developments in both 5G and 3GPP have created the opportunity for new use cases and virtualized network deployments (O-RAN) to increase flexibility and reduce costs to meet use case-specific requirements [27].

While 3GPP has standardized many new security improvements with 5G, virtualization throughout the network and a service-based architecture means that security needs to be handled in a new way [27].

According to [26], industry will move away from acute security supply chain issues toward a broader attack surface with a more-difficult-to-control supply chain. As the O-RAN architecture is a network consisting of many vendors, all with different technological components, network operators will be tasked with the difficult responsibility of managing such a complex and integrated network.

Network operators can pick and choose between different vendors that may have different strengths across a range of RAN components with the O-RAN compliance.

5.2 ENERGY

Another area of concern is the energy utilization of the O-RAN architecture. Will energy consumption increase or decrease relative to the traditional RAN infrastructure is a question that the researchers and professionals will also have to find out. Some argue that it will increase power efficiency by 40%, while others argue its energy consumption will be competitive. However, the efficiency of O-RAN systems will depend on a variety of factors, which will take time to unveil and hence cannot be guaranteed [26].

REFERENCES

1. What is a radio access network (RAN) ?. [Online]. Available: https://www.redhat.com/en/topics/5g-networks/what-is-radio-access-network, March 23, 2021.

2. What are Radio Access Networks and 5G RAN ? [Online]. Available: https://www.verizon.com/about/our-company/5g/5g-radio-access-networks, February 02, 2020.

3. What is an Open Radio Access Network (O-RAN)? [Online]. Available: https://www.metaswitch.com/knowledge-center/reference/what-is-an-open-radio-access-network-o-ran, April 2020.

4. What is Open RAN (ORAN). [Online]. Available: https://www.cisco.com/c/en/us/solutions/what-is-open-ran.html#~ran-basics

5. Sanjay Kaul, "Why Innovation Is Key To Connecting The Next 3 Billion" [Online]. Available: https://blogs.cisco.com/sp/why-innovation-is-key-to-connecting-the-next-3-billion, August 05, 2021.

6. Shweta Mali, "O-RAN Architecture". [Online]. Available: https://www.stl.tech/blog/understanding-o-ran-from-the-basics (benefits, ORAN Architecture), April 22, 2021.

7. 5 key facts about 5G radio access. [Online]. Available: https://www.ericsson.com/en/public-policy-and-government-affairs/5-key-facts-about-5g-radio-access-networks

8. O-RAN ALLIANCE Specifications and Working Groups. [Online]. Available: https://moniem-tech.com/2022/07/25/o-ran-alliance-specifications-and-working-groups/, July 25, 2022.

9. P. Michele et al., "Understanding O-RAN: Architecture, Interfaces, Algorithms, Security, and Research Challenges.", March 2022.

10. What Is a RAN Intelligent Controller (RIC)? [Online]. Available: https://www.juniper.net/us/en/research-topics/what-is-ric.html

11. RCR Wireless News, "Non-real time RIC vs. near-real RIC" . [Online]. Available: https://www.rcrwireless.com/20211129/network-function-virtualization-nfv/non-real-time-ric-vs-near-real-time-ric, November 29, 2021.

12. Marcin Dryjanski, "RAN Intelligent Controller (RIC): Overview, xApps, and rApps. [Online]. Available: https://rimedolabs.com/blog/ran-intelligent-controller-ric-overview-xapps-and-rapps/, December 13, 2021.

13. Sean Kinney, "Optimizing open RAN: Nokia, AT&T trial cloud-native RIC" . [Online]. Available: https://www.rcrwireless.com/20200618/5g/optimizing-open-ran-nokia-att-cloud-native-ric, June 18, 2020.

14. Owen O'Donnell, "RAN INTELLIGENT CONTROLLER – NEAR – RT AND NON-RT. [Online]. Available: https://blog.viavisolutions.com/2022/05/06/ran-intelligent-real-time-and-non-real-time-ric-the-test-challenges/, May 06, 2022.

15. Intelligent Automation rApps [Online]. Available: https://www.ericsson.com/en/ran/intelligent-ran-automation/intelligent-automation-platform/rapps

16. Ray Sharma, "Intelligent Automation rApps" . [Online]. Available: https://www.thefastmode.com/technology-solutions/21441-ericssons-new-intelligent-automation-platform-automates-ran-using-ai-and-rapps, November 17, 2021.

17. Accelleran's 5G dRAX cloud-native Open RAN software now available. [Online]. Available: https://accelleran.com/accellerans-5g-drax-cloud-native-open-ran-software-now-available/, June 21, 2021.

18. Grace Donnelly, "RIC, xApps, rApps: Who are the key players?" [Online]. Available: https://stlpartners.com/articles/telco-cloud/ric-xapps-rapps-who-are-the-key-players/

19. Owen O'Donnell, "OPEN RAN Q&A: RAN INTELLIGENT CONTROLLER (RIC)". [Online]. Available: https://blog.viavisolutions.com/2021/06/01/open-ran-qa-ran-intelligent-controller-ric/, June 01, 2021.

20. Split option 7.2x. [Online]. Available: https://infohub.delltechnologies.com/l/dell-technologies-vmware-and-mavenir-5g-o-ran-reference-architecture-guide/split-option-7-2x-5

21. What are radio unit, distributed units, and centralized units in Open Ran functional split? [Online]. Available: https://www.techchannel.news/26/02/2021/what-are-radio-unit-distributed-units-and-centralised-units-in-open-ran-functional-split/

22. Marcin Dryjanski, "O-RAN Architecture, Nodes, and Interfaces" . [Online]. Available: https://rimedolabs.com/blog/o-ran-architecture-nodes-interfaces/, May 01, 2021.

23. Connor Craven, "What Are the Open RAN Standards?" [Online]. Available: https://www.sdxcentral.com/5g/ran/definitions/what-are-open-ran-standards/, February 17, 2021.

24. 5G NR network interfaces – Xn, NG, E1, F1, F2 interface types in 5G [Online]. Available: https://www.rfwireless-world.com/Tutorials/5G-NR-network-interfaces.html

25. Bevin Fletcher, "Telefonica's O2 trials open RAN with NEC using Altiostar software" . [Online]. Available: https://www.fiercewireless.com/tech/telefonica-s-o2-trials-open-ran-nec-using-altiostar-software, February 01, 2021.

26. Robert D. Atkinson, Doug Brake, and Alexandra Bruer, "Open Radio Access Networks: A Primer for Policymakers" . [Online]. Available: https://itif.org/publications/2021/11/01/open-radio-access-networks-primer-policymakers/, November 01, 2021.

27. Jason S. Boswell, "Making sure that Open RAN doesn't open the door for new risks in 5G" . [Online]. Available: https://www.ericsson.com/en/blog/2020/9/open-ran-security-5g, September 10, 2020.

28. ORAN Architecture Overview. [Online]. Available: https://docs.o-ran-sc.org/en/latest/architecture/architecture.html

29. Marcin Dryjanski, "O-RAN Non-RT RIC: Architecture and rApps". [Online]. Available: https://rimedolabs.com/blog/o-ran-non-rt-ric-architecture-and-rapps/, December 12, 2021.

30. Nokia Press Release. [Online]. Available: https://www.nokia.com/about-us/news/releases/2021/03/11/nokia-launches-first-commercial-service-enablement-platform-to-drive-open-ran-innovation/, March 21, 2021.

31. Service Enablement Platform: Introduce AI/ML-based innovation to the radio access network. [Online]. Available: Service Enablement Platform | Nokia.

32. Ericsson Frequency Layer Manager rApp: Solution sheet. [Online]. Available: Ericsson Frequency Layer Manager rApp

33. Ericsson Performance Diagnostics rApp: Solution sheet. [Online]. Available: Performance Diagnostics (ericsson.com)

34. What is Open RAN? [Online]. Available: https://accelleran.com/whatisopenran/.