An Overview of Open RAN: Basics, Recent Advances and Future Research

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Abstract

Open Radio Access Network (Open RAN) will revolutionize the next-generation mobile networks. It disassembles proprietary components of today's RAN via hardware-software disaggregation and enables a vendor-neutral interoperable ecosystem through open interfaces. Such an open environment further motivates new business, competition and innovation for fast RAN development. As a result, understanding Open RAN including its architecture and key techniques is fundamental in the wireless networking area. In this paper, we provide an overview of Open RAN. The general RAN evolution, from distributed RAN to the up-to-date Open RAN is discussed. We then describe key enabling techniques and early use cases by experimental platforms. Finally, the main research challenges are outlined for future Open RAN research directions.

Key Words

Open RAN, disaggregation, open interfaces, innovation, RAN evolution, experimental platforms

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1. Introduction

Demand for flexible, efficient and intelligent mobile networks has driven a surge of efforts in opening the Radio Access Network (RAN). Open RAN has the potential to provide multi-vendor interoperability, cost/time-efficient RAN deployment and big data-enable intelligence [Viavi21]. Today's RANs, however, are far from open. One example is shown in Figure 1 . They comprise proprietary hardware and software supplied by only a few vendors as highly integrated solutions with little interoperability [Ericsson20]. Such a "black-box" solution has hence severely hindered the evolution of mobile networks in the following aspects:

- vendor "lock-in" which disables an open, multi-vendor ecosystem and further prevents innovation and new business opportunities [CISA22].
- inefficient, mostly manual, reconfigurability to accommodate diverse traffic applications which range from band-intensive video gaming to low-rate Internet of Things (IoT) communication [Singh20].
- limited controllability of different network components which cannot host joint management and optimization [Viavi21].

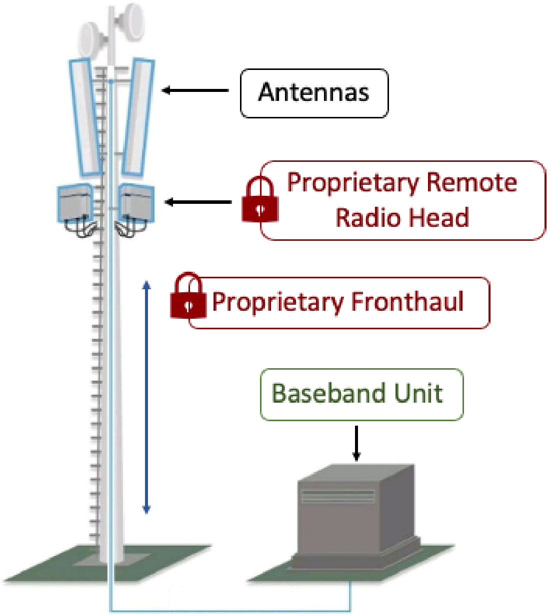

Figure 1. One Proprietary RAN Example

To address these issues, the transition towards Open RAN has been seen in the last decade. The Open RAN architecture disaggregates between hardware and software, hosts virtualized network functions in the cloud, and connects networking components via open interfaces interoperable across various vendors [Polese22a]. It further makes it possible to incorporate big data and artificial intelligence (AI)/machine learning (ML) for RAN automation and intelligent control. Compared to current RANs, Open RAN significantly improves the scalability of RAN deployment and reduces Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) [Viavi21].

Despite the promising benefits, the realization of Open RAN faces several challenges including standardization, real-world performance validation, and potential threats. In industry, Open RAN standardization is required to specify reference designs for different elements, e.g., architecture and open interfaces. Today several organizations [O-RAN][TIP] worldwide have been working on the standardization process and have published specifications for each element. Another challenge, real-world performance validation, is due to the lack of realistic wireless environments for system-level operation and end-to-end network performance evaluation. Inspired by the need, multiple wireless testbeds have showcased Open RAN and further tested its performance. Finally, potential threats introduced by the flexible disaggregation of Open RAN need to be addressed for ensuring security. [Polese22a] gives a detailed discussion of potential threats including security stakeholders and different types.

The remainder of the paper is organized as follows. Section 2 gives an overview of Open RAN including common misconceptions, RAN evolution and Open RAN's applications. In Section 3, key enabling techniques are discussed. Section 4 describes existing research platforms that can support Open RAN. Future research directions are discussed in Section 5. Finally, Section 6 summarizes the work and draws conclusions.

2. Overview of Open RAN

The rapidly growing volume and variety of mobile traffic have led to the technology trend to make RAN increasingly open and intelligent. Open RAN, as the solution, disaggregates software from hardware and supports open interfaces for interoperability among multiple vendors. To fully understand Open RAN, we give an overview in this section. Common misconceptions are first described for clarification. It is then followed by the evolution of RAN. We finally present Open RAN's flexible applications.

2.1 Common Misconceptions

Various terms in the Open RAN literature can be found including OpenRAN (one word), O-RAN, ORAN and Open RAN. They confuse people and can sometimes be used interchangeably. In order to better understand this paper, we distinguish between these terms, as shown in Table 1 .

Table 1: Common Terminologies Related to Open RAN

Terminology	**Description**	**Examples**
OpenRAN	TIP OpenRAN Project Group with the aim to develop fully programmable RAN solutions based on general-purpose processing platforms.	OpenRAN Turkey Trials Playbook published in 2020 for the Turkey trial deployment
O-RAN	theaE_O-RAN Alliance or its designated specification for next-generation RAN infrastructures.	O-RAN Hardware Reference Design Specification for Fronthaul Gateway published in October 2021
ORAN	typically used as a hashtag for denoting O-RAN or Open RAN.	#ORAN
Open RAN	generic term for disaggregated RAN functionality built upon open and interoperable interfaces.	AI techniques for RAN system automation

The term OpenRAN (one word) is used by Telecom Infra Project (TIP) to refer to the OpenRAN Project Group which aims to define and implement 2G, 3G, and 4G RAN solutions using general-purpose, vendor-neutral hardware and software. The second term, O-RAN with a hyphen, refers to the O-RAN alliance founded in 2018 and comprised of close to 30 operators and more than 200 vendor companies [Ericsson20]. This group defines specifications for open and intelligent RAN. ORAN, instead, is typically used as a hashtag on social media. Finally, Open RAN is the overall movement for opening the RAN via disaggregating software and hardware and enabling open and interoperable interfaces [Rimedo21]. To further differentiate O-RAN and Open RAN, O-RAN is one Open RAN type with specifications on the architecture, open interface and intelligent controller, etc.

2.2 RAN Evolution

With the rapid growth of mobile networks, the RAN architecture is also experiencing critical evolution from the traditional distributed model to centralized to virtualized implementations, and finally towards ongoing open interoperable RAN. The scope of each RAN architecture is shown in Figure 2 .

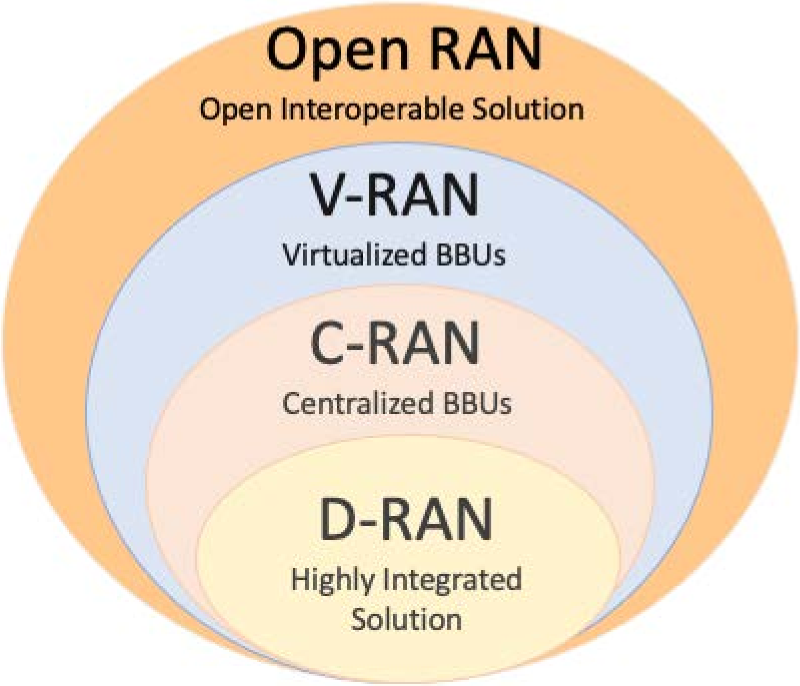

Figure 2. The Evolution of RAN

2.2.1 Distributed RAN

In the conventional distributed RAN (D-RAN) architecture, every base station (BS) is composed of a baseband unit (BBU) and remote radio heads (RRHs), all located at the cell site [Viavi21]. Figure 3 describes the general diagram of D-RAN. RRHs are, on one end, connected to the antenna, and connected to the BBU via Fronthaul transport over Fiber on the other end using the Common Public Radio Interface (CPRI) protocol. RRHs have radio frequency (RF) capabilities like power amplification, sampling and up/down conversion, whereas BBUs host baseband functions including modulation and coding for further processing. It can be seen that the conventional D-RAN is built only on proprietary hardware and software and specifications from individual vendors significantly restrict multi-vendor operability.

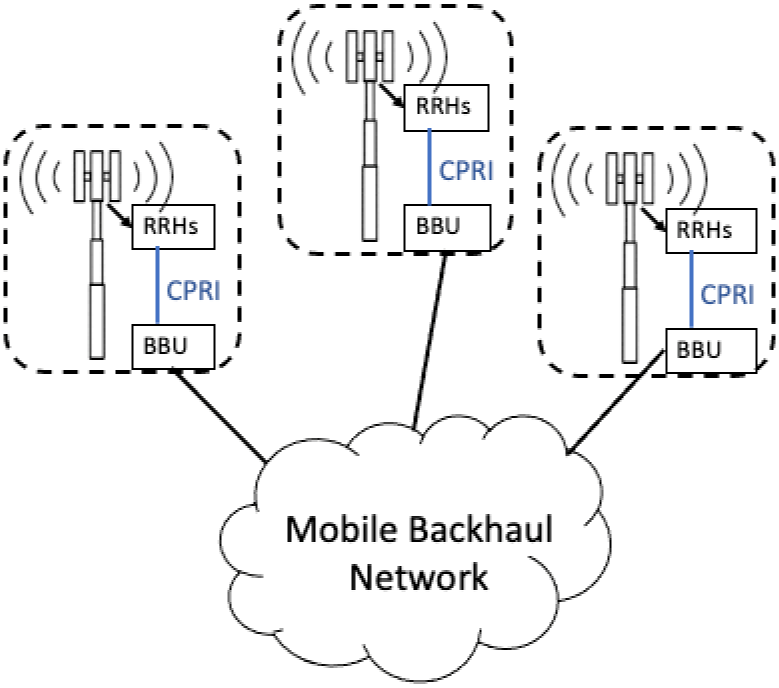

Figure 3. The general D-RAN Architecture

2.2.2 Centralized RAN

Moving towards centralized RAN (C-RAN), all BBUs are decoupled from distributed RRHs and co-located in a central office, as shown in Figure 4 . The C-RAN architecture then hosts the baseband signal processing and network functions at the central office with little operating costs [Habibi19]. CPRI-based Fronthaul interconnects the centralized BBUs and remote RRHs over fiber. C-RAN can be further upgraded into cloud RAN by clustering the centralized BBUs into a pool, i.e., cloud. In doing so, the baseband processing resources can be dynamically shared across different cell sites to meet varying user demands. Cloud RAN also makes it possible to utilize spectrum more efficiently via simple reconfiguration and scale up easily new cell site deployments by installing RRHs only. Note that C-RAN in some literature refers to more dynamic cloud RAN instead of centralized RAN.

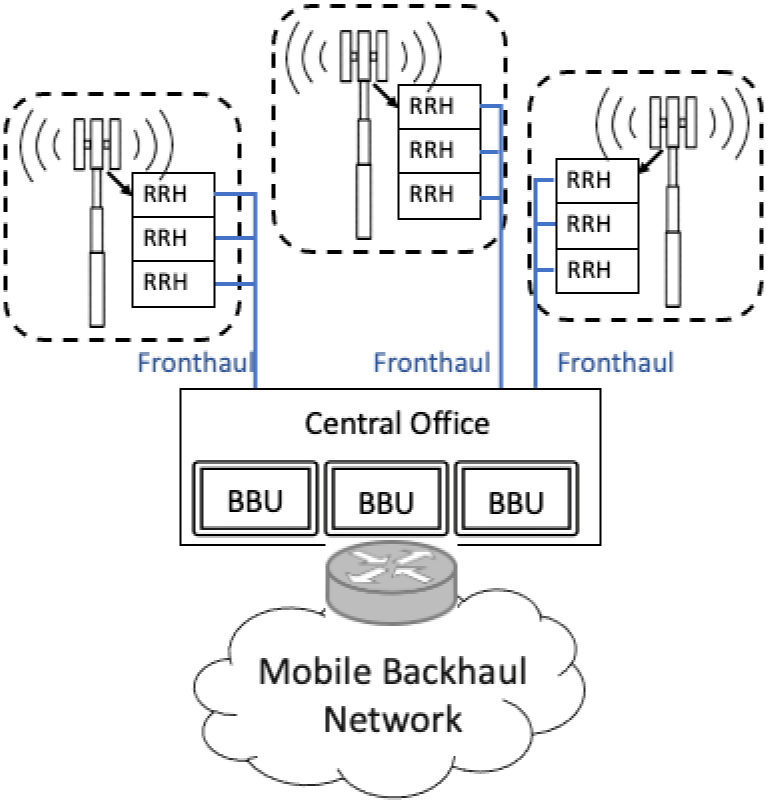

Figure 4. The C-RAN Architecture

2.2.3 Virtualized RAN

The next stage is virtualized RAN (V-RAN) which further virtualizes the BBUs for the full potential of fast, low-cost and dynamic configuration of the baseband resources. Unlike C-RAN, V-RAN decouples the network functions from the physical hardware [Gavrilovska20], as presented in Figure 5. RRHs, instead, still remain at the cell towers as proprietary radio hardware. A variety of network functions can be launched as logically isolated instances over the same commodity server hardware in a flexible and efficient manner [Intel17]. With V-RAN, future services can be easily implemented and RAN capacity can be scaled up or down with demand.

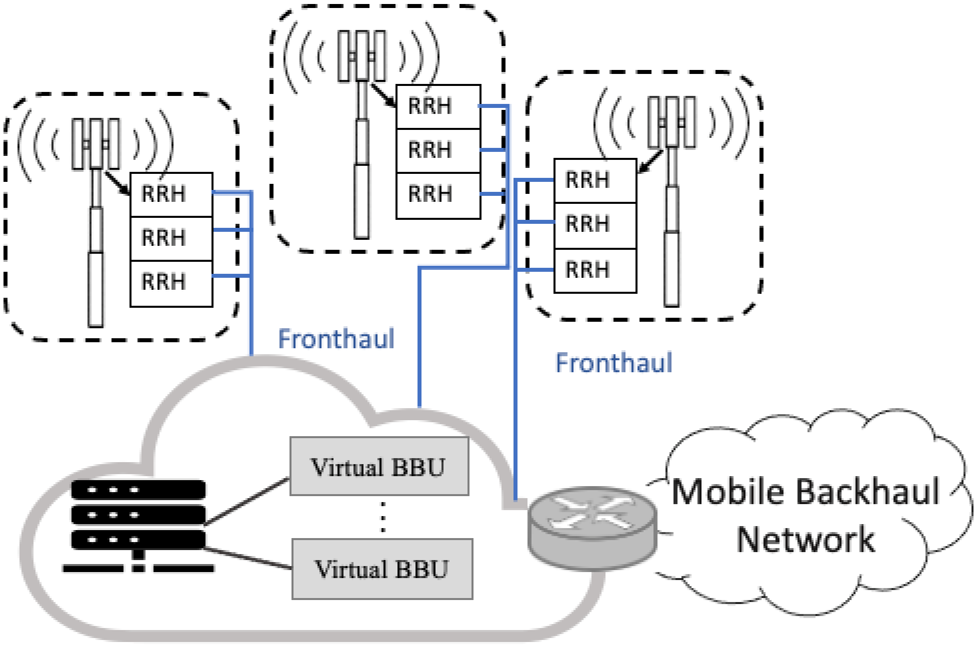

Figure 5. The Virtualized RAN Architecture

For RAN virtualization, two major technologies, hypervisor-based and container-based virtualization can be applicable [Dzogovic18, Bachiega18]. Hypervisor-based virtualization, commonly known as virtual machine monitor (VMM), creates one or more guest operating systems (OS) to run on a single host system [Xavier13]. A lightweight solution, container-based virtualization, instead creates application instances directly in isolated environments called containers [Gavrilovska20]. The comparison between hypervisor-based and container-based virtualization is in Table 2.

Table 2: Virtualization Approaches Comparison

Virtualization Approaches	**Summary**	**Examples**
Hypervisor-based	Flexible solution to enable different CPU architecture or OS emulation	Kernel-based Virtual Machine (KVM), OpenStack
Container-based	Efficient solution to develop different applications on top of the same OS	Linux Containers (LXC), Docker

2.2.4 Open RAN

Evolution towards the most up-to-date Open RAN is due to the two challenges unsolved by V-RAN: integrated hardware for radio transmission and proprietary interfaces between RRHs and virtualized BBU. As the solution, Open RAN is proposed based on two essential pillars: further disaggregation and openness. Figure 6 shows the Open RAN architecture. Disaggregation between hardware and software enables different functionalities to be designed, extended and configured via commercial-off-the-shelf (COTS) hardware and software-defined technology. Open interfaces further eliminate vendor "lock-in" by allowing multi-vendor RAN deployments. As a result, any vendor's software can be run on any vendor's deployed COTS hardware at any location. Compared to other RANs, Open RAN is vital to drive competition, new business opportunities and innovation in an open and richer market.

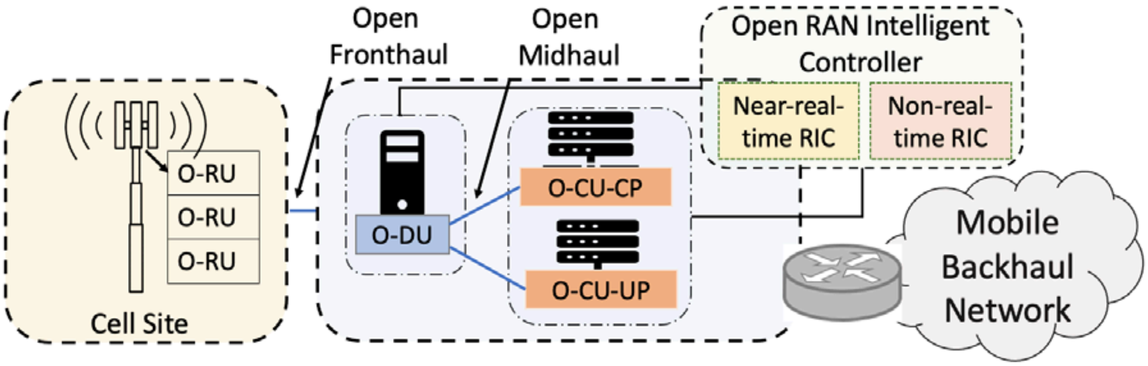

Figure 6. The Open RAN Architecture

2.3 Open RAN Applications

Open RAN advances the existing RAN structure through disaggregation techniques, open interfaces and AI-based intelligence. Such capabilities of Open RAN create opportunities for innovative applications.

RAN sharing Decoupling hardware from software and multi-vendor interoperability create great potential for two applications: spectrum sharing and infrastructure sharing. In an open ecosystem, the overall Open RAN infrastructure can be arranged and deployed entirely by vendors as infrastructure providers (InP), e.g. Crown Castle [CrownCastle]. Multiple service providers can lease BSs from an InP in a dynamic manner and provide flexible services to customers when changes are needed over frequency, time and space in terms of BS arrangements. In addition to infrastructure sharing, dynamic spectrum sharing is enabled via full-scale virtualization, i.e., RF functions can be flexibly configured through software including frequency, gain setting and bandwidth. As a result, RAN sharing can significantly improve spectrum efficiency, service quality and scalability [Hu18].

Mobility Management Similar to traditional RANs, Open RAN should be able to balance mobile user loads and tune handover and beamforming parameters. With the help of AI-enabled intelligence, Open RAN can exploit the states of multiple BS and environment inputs to predict user mobility and manage access and traffic dynamically [Polese22a].

QoS-based Resource Allocation The last two decades have witnessed an incredible increase in the number and types of mobile devices. A variety of applications, from high-speed video streaming to lower-power IoT communication, demonstrate the diverse quality of service (QoS) requirements. As Open RAN enables flexible configuration and intelligent controller, the best resource allocation scheme including spatial distribution and processing power can be obtained via QoS-based optimization. Open RAN can further dynamically adjust in response to the changing needs and thus maintain resource allocation in a closed-loop fashion [Richart16].

National Radio Dynamic Zones National Radio Dynamic Zones (NRDZ) is envisioned by [Kidd18] as a geographical area where special radio systems can dynamically operate in licensed and unlicensed spectrum as long as interference is avoided. Here interference can be either in-zone interference or to out-of-zone users. Open RAN, due to its spectrum-sharing feature, enables more flexible frequency scheduling and thus works as a critical foundation for NRDZ. Instead of fixed spectrum access, Open RAN in NRDZ allows opportunistic access to licensed yet unoccupied spectrum. With Open RAN, NRDZ can practically implement and evaluate innovative RAN sharing mechanisms in the hope to find a solution to natural spectrum scarcity.

3. Key Enabling Techniques

In this section, we discuss the key enabling techniques for Open RAN which include disaggregation, RAN Intelligent Controllers and open interfaces.

3.1 Disaggregation

The Open RAN architecture, as presented in Figure 6 , disaggregates base stations into three major building blocks:

- The open Radio Unit (O-RU)
- The open Distributed Unit (O-DU)
- The open Centralized Unit (O-CU)

Such a disaggregation scheme originates from Release 15 of 3GPP for the New Radio (NR) Next Generation Node Bases (gNBs) [3GPP]. In this release, the gNB consists of a CU, DU and RU. Compared to conventional RANs, BBU functionalities are split into DU and CU while RRH functionalities are mostly handled by RU. In the Open RAN context, they become O-RU, O-DU and O-CU.

O-RUs are used for RF signal transmission and reception, amplification, analog/digital conversion and beamforming of the physical (PHY) layer [Nokia22]. They are generally implemented on open and programmable Field Programmable Gate Arrays (FPGAs) and deployed near or integrated into RF antennas.

O-DUs handle the remaining PHY layer, the Medium Access Control (MAC) and Radio Link Control (RLC) layers as their operations are tightly synchronized [Polese22a]. O-DUs are usually physically close to the O-RU and their operations are controlled by O-CUs.

O-CUs in Open RAN are further split into logical elements for the Control Plane (CP) and the User Plane (UP) respectively, which then enables separate deployments on different hardware platforms [ParallelWireless20]. O-CUs run higher layers including the Radio Resource Control (RRC) layer [3GPP18a], the Service Data Adaptation Protocol (SDAP) layer [3GPP22] and the Packet Data Convergence Protocol (PDCP) layer [3GPP18b]. O-CUs are located near the Core Network.

3.2 RAN Intelligent Controllers

RAN Intelligent Controllers (RICs) are another key element in Open RAN. They are software-defined components that are capable of orchestrating and optimizing RAN functions with closed-loop control [Polese22a]. RICs make various applications, as discussed in Section 2.3, available as apps on the controller. Different from general enabling techniques like disaggregation and open interfaces, RICs are proposed and developed specifically by the O-RAN Alliance. The RIC functionality can be realized by Virtualized Network Functions (VNFs) and Software-defined Networking (SDN) where the former creates a cloud environment and software app infrastructure for RIC and the latter allows the apps for network management [ParallelWireless20].

RICs, according to the O-RAN vision, can be either non-real-time (non-RT) or near-real-time (near RT). The non-RT RIC orchestrates events with an operation scale longer than 1 s [O-RAN22a] whereas the near RT RIC typically takes 10 ms to 1 s to complete optimization actions [O-RAN22b]. The details of the two logical controllers are given below.

Non-RT RIC: The non-RT RIC's functionalities include intelligent device/configuration/performance management and lifecycle management for all network elements in the network. With the help of the non-RT RIC, new radio units can be potentially self-configured with little manual intervention. It complements the near-RT RIC for Mobile Network Operators (MNOs) to better understand and operate on a relatively larger time scale. It is part of the Service Management and Orchestration (SMO) framework which provides an open interface to the near RT RIC. It can further utilize SMO services like data collection and AI-enabled analytics for optimal RAN action determination. Note that the non-RT RIC can reversely impact SMO operations, via which it can potentially control the components connected to the SMO [Polese22a].

Near-RT RIC: The near RT RIC controls RAN nodes at the cloud edge and has open interfaces to O-CU and O-DU for interaction. Due to the connection to multiple nodes, the near RT RIC's control loops may have an impact on the QoS of numerous User Equipment (UEs). The near RT RIC hosts one or more microservices called xApps. A xApp collects near real-time information and manages radio resources via standardized interfaces and service models. To support xApps, the near-RT RIC first provides internal messaging infrastructure across distributed components of the platform. It also maintains a database containing information on the RAN, e.g., connected RAN nodes, and supplies xApps with Application Programming Interfaces (APIs) for access to the database.

3.3 Open Interfaces

Open interfaces for RANs are not new. 3GPP has standardized two interfaces: the air interface and the S1 interface [ParallelWireless20]. The air interface, also known as LTE-Uu, utilizes the RRC protocol and connects the UE to the RRHs. The S1 interface instead connects the RAN to the Core Network for both the user and the control planes. Note that 3GPP defines, in addition to the open interfaces, also the X2 Interface as an optional interface to support information exchange between two or more BSs. However, the X2 interfaces are not open and have not been largely implemented.

While two open interfaces exist, they are not sufficient to enable Open RAN. First of all, the interface between RU and DU, known as Fronthaul, relies heavily on the CPRI protocol. This protocol is generally vendor-specific and thus not necessarily open. As a result, open interfaces are required for the Fronthaul for Open RAN development. Second, the Open RAN architecture splits virtualized BBU into O-CU and O-DU. Therefore, similar demand for open interfaces applies to O-CU and O-DU connections. Additionally, Open RAN incorporates the controller concept in 3G and further develops RIC for RAN configuration, optimization and control [ParallelWireless20]. By doing so, more open interfaces need to be standardized for Open RAN.

A well-known interface option Today is the set of interfaces defined and specified by the O-RAN Alliance. Specifically, Work Groups 2, 3, 4 and 5 have been actively working on different open interfaces for Open RAN [O-RAN], as discussed in Table 3.

Table 3: VWork Groups for Open Interface Specification

Work Groups (WG)	**Focus**	**Latest Specification Version**
WG 2	Non-real-time RIC and A1 interface	O-RAN A1 interface: Application Protocol 3.02
WG 3	Near-real-time RIC and E2 interface	O-RAN E2 Application Protocol (E2AP) 2.03
WG 4	Open Fronthaul interfaces	O-RAN Conformance Test Specification 6.0
WG 5	Open F1/W1/E1/X2/Xn interface	O-RAN Interoperability Test Specification (IoT) 5.0

The open interfaces specified by the O-RAN Alliance mainly include the following five categories and are illustrated in Figure 7.

1. ***E2 interface***. It connects the near-RT RIC to the RAN nodes, e.g., DUs and CUs. Accordingly, the E2 interface can not only control and monitor the functionalities of the RAN nodes but also enable data collection from the nodes to the near-RT RIC.
2. ***O1 interface***. It specifies the connection between the non-RT RIC and nearly every other RAN component, i.e, CU-UP, CU-CP, DU, RU and near-RT RIC, for network orchestration and management.
3. ***A1 interface***. It connects the near-RT RIC and the non-RT RIC. With this interface, near-RT RIC can provide guidance, and ML model design/updates for near-RT RIC to give back the policy feedback.
4. ***O-RAN Fronthaul***. It is used to connect a DU to one or more RUs. It specifies protocols for four planes, i.e., aspects: user (U-plane), control (C-plane), synchronization (S-plane) and management (M-plane).
5. ***O2 interface***. The connection between the Open RAN Cloud and the SMO is enabled by this interface which then allows programmable management of the network functions.

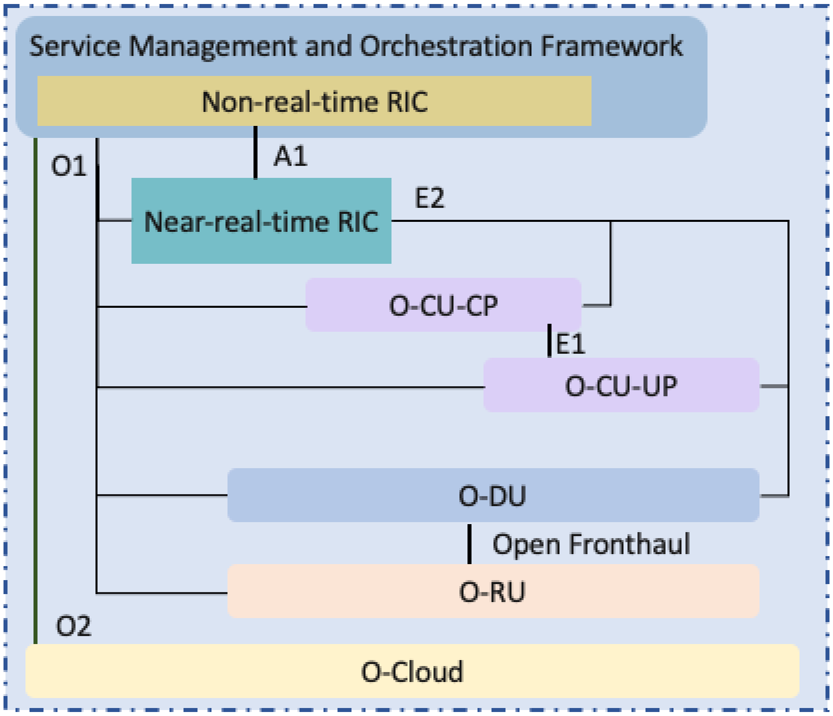

Figure 7. Open Interfaces Specification from the O-RAN Alliance

4. Experimental Platforms for Open RAN

Open RAN has demonstrated unprecedented flexibility and intelligence, which, however, leads to the inherent complexity of Open RAN realization. An Open RAN use case requires multiple software-defined radios (SDRs), e.g., NI USRPs, as the RU and also COTS hardware as both the DU and CU. Additionally, open-source protocol stacks, e.g., srsRAN [Miguelez16], are necessary to instantiate a complete mobile network. To address such a challenge, the joint academic and industrial effort has been put into experimental platforms for Open RAN implementation and performance evaluation. Existing experimental platforms, as in Table 4, can be categorized into (1) OpenRAN Gym, (2) Platforms for Advanced Wireless Research (PAWR) and (3) Colosseum and Arena.

Table 4: Experimental Platforms and Frameworks for Open RAN Use Case

Platform/ Framework	Description	Open RAN Use Cases
OpenRAN Gym	end-to-end pipeline for data-driven Open RAN research	Open toolbox at [OpenRANGym]
POWDER	Sub-6 GHz outdoor and indoor testbed	NexRAN [Johnson21]
COSMOS	mmWave outdoor testbed	Open RAN AI/ML development [Bonati22b]
AERPAW	aerial wireless testbed	Not Available

Colosseum	sub-6 GHz network wireless emulator	ColO-RAN [Polese22b]
Arena	sub-6 GHz indoor wireless platform	SCOPE [Bonati21a]

4.1 OpenRAN Gym Framework

OpenRAN Gym [Bonati22a] is a publicly-available research toolbox for data collection, design and experimentation of next-generation Open RAN systems. It provides E2 termination through which the O-RAN-compliant near-RT RIC can connect to the E2 nodes, e.g., CUs/DUs. In doing so, software management and control of the RAN can be realized via a data collection and control framework, e.g., SCOPE [Bonati21a]. Furthermore, OpenRAN Gym makes an LXC-based Open RAN implementation available. Users can not only instantiate it on any bare-mental compute node but also add any external xApp to the xApp space [Polese22a].

4.2 Platforms for Advanced Wireless Research

Other remotely accessible experimental wireless infrastructure for Open RAN exploration is POWDER, COSMOS and AERPAW platforms deployed as part of the US NSF's Platforms for Advanced Wireless Research (PAWR) program [PAWR].

POWDER [Breen20], deployed in Salt Lake City, is a city-scale scientific infrastructure that aims to enable experimental exploration of next-generation communication networks. It focuses on sub-6GHz technology and has shown an O-RAN-compliant Open RAN use case in [Johnson21]. COSMOS [Raychaudhuri20] shares a similar architecture with POWDER but is deployed in New York City with high population density and emphasizes mmWave technologies. It has served as one of the sites for the O-RAN Global PlugFest since 2021 [COSMOS21]. AEPRAW [Panicker21] is the first-of-its-kind testbed, particularly for aerial wireless experimentation. It also supports open protocol stacks including OpenAirInterface [Kaltenberger20], and srsRAN [Miguelez16] based on SDRs. Note that no use case from AEPRAW is available.

4.3 Colosseum and Arena

Colosseum and Arena are the other two major platforms that allow O-RAN-compliant network instantiation [Polese22a]. Colosseum [Bonati21b] is the world's most powerful wireless network emulator with 256 programmable SDRs. It also offers GPU computing and data storage capabilities with which data-driven AI training is possible for Open RAN optimization. OpenRAN Gym-based AI modeling research for Open RAN is conducted in [Bonati22b] and tested on Colosseum and PAWR platforms. Arena [Bertizzolo20] is an indoor wireless platform with 24 SDRs to explore 5G-and-beyond technologies and MIMO applications. It can realize private indoor mobile networks. An O-RAN control architecture ColO-RAN [Polese22b] combines Colosseum and Arena together.

5. Future Research Directions

Despite much progress made towards technology development and standardization for Open RAN, there are still open issues that need to be addressed. We discuss, based on these issues, future research directions in this section.

5.1 Interoperability Testing

One of the key benefits of Open RAN is the enabling interoperability across multiple vendors and network components. However, such a principle requires real-world testing to ensure practicality. Research on Open RAN with the involvement of different vendors, hardware and software wise, is expected to experimentally evaluate Open RAN's performance, especially its interoperability.

5.2 AI/ML Algorithm Design

AI/ML has the potential to further advance Open RAN by incorporating data-driven intelligence. An AI/ML workflow has been proposed by the O-RAN Alliance and its specification is underway. However, challenges still exist including: (1) how to handle large datasets collected on heterogeneous networks and at distributed deployments, (2) AI/ML modeling to represent characteristics of Open RAN, e.g., low-latency demand, and (3) Reinforcement learning to adaptively adjust, based on environmental changes, the Open RAN functionality. Detailed AI/ML workflow specifications and more AI-related studies will help solve the problem.

5.3 Open RAN Security

Opening the RAN introduces simultaneously flexibility and complexity. Potential attacks on different components of Open RAN, e.g., open software and interfaces, at multiple layers need to be taken into consideration. According to [Polese22a], there could be threats against the open cloud, open-source code, the overall system and physical infrastructure. New advances can be made by considering the key security objectives at each layer and standardizing corresponding security policies to possible threats.

6. Conclusion

This paper has provided an overview of the ongoing Open RAN research. It is proposed to address the restrictions shown in the existing RANs including vendor "lock-in", manual reconfigurability and limited joint control. We first introduced Open RAN by describing the limited capability of existing RANs and the benefits Open RAN can bring. A high-level overview is then given where we distinguish common Open RAN related terminologies, discussed the RAN evolution milestones, and envisioned multiple applications based on Open RAN. It is followed by key enabling techniques including disaggregation, RIC and open Interfaces with details. Finally, we reviewed several experimental platforms which enable or have Open RAN use cases available, and further some future research directions for Open RAN.

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6. List of Acronyms

RAN	Radio Access Network
AI	Artificial Intelligence
ML	Machine Learning
CAPEX	Capital Expenditure
OPEX	Operational Expenditure
TIP	Telecom Infra Project
D-RAN	Distributed RAN
BS	Base Station
CPRI	Public Radio Interface
BBU	Baseband Unit
RRH	Remote Radio Head
RF	Radio Frequency
C-RAN	Centralized RAN
V-RAN	Virtualized RAN
VMM	Virtual Machine Monitor
OS	Operating System
KVM	Kernel-based Virtual Machine
LXC	Linux Containers
COTS	Commercial-Off-The-Shelf
InP	Infrastructure Provider
QoS	Quality of Service
NRDZ	National Radio Dynamic Zones
O-RU	Open Radio Unit
O-DU	Open Distributed Unit
O-CU	Open Centralized Unit

gNBs	Next Generation Node Bases
NR	New Radio
FPGA	programmable Field Programmable Gate Array
MAC	Medium Access Control
RLC	Radio Link Control
SDAP	Service Data Adaptation Protocol
PDCP	Packet Data Convergence Protocol
RRC	Radio Resource Control
RIC	RAN Intelligent Controller
VNF	Virtualized Network Function
SDN	Software-defined Networking
MNO	Mobile Network Operator
SMO	Service Management and Orchestration
WG	Work Group
IoT	Internet of Things
PAWR	Platforms for Advanced Wireless Research
3GPP	3rd Generation Partnership Project
POWDER	Platform for Open Wireless Data-driven Experimental Research
UE	User Equipment

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