Open Radio Access Networks

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The open radio access network (RAN) aims to bring openness and intelligence to the traditional closed and proprietary RAN technology and offer flexibility, performance improvement, and cost-efficiency in the RAN's deployment and operation.

Keywords: open RAN ; O-RAN ; open source

1. Introduction

The radio access network (RAN) is one of the main components in cellular networks [1]. The RAN connects the user equipment (UE) to the core network (CN). The RAN component has evolved throughout the years as a solution to the growing number of subscribers and rising user demands. The first version of RAN is distributed RAN (D-RAN), followed by centralized RAN (C-RAN), and lastly, virtualized RAN (vRAN). However, the vRAN solution hardly meets the expectations of the current 5G network requirements. The next generation of RAN is looking to open the interfaces in the RAN ecosystem.

The cellular network industry offers the next generation of RAN as a solution to fulfill 5G network requirements. Open RAN is proposed as an evolution of the vRAN [2]. To answer the challenges faced by vRAN, Open RAN breaks the closed nature of the previous RAN generations. Open RAN is essential for cost reduction in the RAN by promoting innovation that leads to competition among vendors due to its open nature. The architecture of Open RAN facilitates intelligent components within the RAN, driving innovation towards achieving energy savings and enabling dynamic power management [3]. Open RAN aims to deliver the expected quality of service (QoS) and quality of experience (QoE) of the latest 5G network requirement while preventing economic expenditure from skyrocketing. While advancing the previous RAN generations, Open RAN still faces challenges today.

The Open RAN movement and its goal to make an open-interface system have existed for the past few years. Even though Open RAN's development has been around for years, there still needs to be more references or research that covers information about Open RAN holistically. The RAN advancement history and the Open RAN concept can be found in [1][2]. Open 5G network projects from the RAN and CN side, as well as their problems, are explained in [4]. The O-RAN Alliance architecture, summarized in [5], does not include the bigger picture of the Open RAN movement. O-RAN Alliance architecture is also discussed in [6][7], including its advantages and limitations that could be addressed in future research. However, these references could not serve the complete picture of Open RAN's history, present condition, and what opportunities Open RAN can open up in the future.

2. Evolution from Traditional RAN to vRAN

2.1. Traditional RAN or D-RAN

The first version of RAN was equipped with an integrated system between radio unit (RU) and baseband unit (BBU). BBU was usually installed in a room right below BS. RU could be installed in the room or at the top of a tower, enabling the RU to support connectivity in a large area [1]. In this context, the RU can also be called the remote RU (RRU). Either way, the distance between RU/RRU and BBU is short. This traditional RAN framework was called D-RAN [8]. Implementing D-RAN is straightforward as it does not require a high-speed interface between RU and BBU. Each RAN operates independently. The network densifies as the number of UEs increases and more BS are built.

Mobile Network Operators (MNOs) initiated a search for a solution to reduce Operating Expenditure (OpEx) due to substantial costs for renting the space for BS and the required cooling systems to operate the network, ultimately leading to the proposal of the C-RAN framework.

2.2. C-RAN

The "C" in C-RAN could be an abbreviation of "Centralized" or "Cloud". However, both have the same idea: cluster the BBUs into a pool [2][9]. Initially, Centralized RAN is proposed to reduce the space rental cost and the power consumption of the air conditioner of the BBU by pooling BBUs from different BS into a single physical location. The fronthaul (FH) interface is introduced to connect the BBU pool and RRUs. **Figure 1** shows how the FH interface (FHI) connects one BBU pool to many RRUs. Despite reducing the overall OpEx, Centralized RAN requires the FH to have high bandwidth and low time latency requirement [10][11].

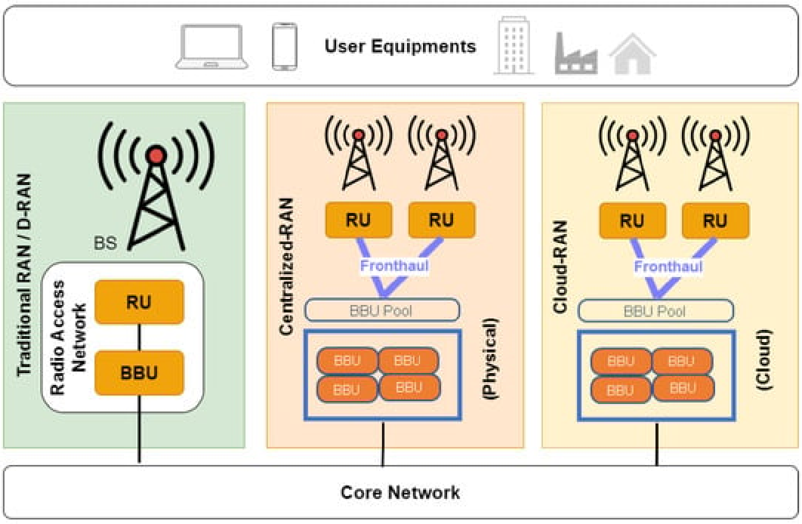

Figure 1. RAN architecture per generation.

The fundamental difference between Centralized RAN and Cloud RAN is the cloud system. In Centralized RAN, the BBUs are pooled in a physical location. In Cloud RAN, BBUs from each BS were pooled in a cloud server [1]. Cloud RAN is superior because the cloud control in Cloud RAN made it easier for the number of BBUs to be changed with time. The cloud also increased the baseband processing by exploiting general-purpose processors [2]. Cloud RAN further reduced energy consumption, increased network throughput, improved network scalability, reduced Capital Expenditure (CapEx), and reduced OpEx [8][12].

The C-RAN has been acknowledged as one of the most potential technologies to fulfill radio access's 5G technical requirements [2]. However, it still has limitations, such as the huge FH overhead, trust problems, security problems, and single-point failure. These problems forced the C-RAN framework to shift its focus to advanced computing technologies. Some of these advanced technologies were virtualization and edge computing. Virtualization is the key to the shifting from C-RAN to vRAN.

2.3. vRAN

Virtualization means creating virtual instances over abstracted physical hardware [2]. In the context of vRAN, the virtual instances are network resources. Virtualization in RAN is heavily related to concepts such as software-defined networking (SDN) and network function virtualization (NFV) [8]. Simply, vRAN brings virtualization to Cloud RAN. In the cloud server, multiple virtual BBUs (vBBUs) are deployed. vBBU can be deployed on a Virtual Machine (VM) or container. This system enables orchestration and resource scaling in vRAN. Ease to scale up and down network resources led to lower energy consumption, dynamic capacity scaling, efficient use of network resources, improved service reliability, and better service quality [2][13]. Approximately 50% of data-processing resources required can be reduced when virtualization is applied on Cloud RAN [14].

Overall, vRAN minimizes the operational and investment costs for MNOs. However, vRAN has to deal with the properties of the wireless channel. Network resources must be shared and distributed fairly and efficiently to different RRUs while considering QoS requirements. This made the vRAN system to be significantly complex. vRAN also still uses proprietary interfaces that prevent interoperability and a multivendor environment. As a result, vendor lock-in and monopoly prevent the network equipment price from being cheaper.

3. Open RAN Movement and the Related Technologies

3.1. Open RAN Movement

The growing cellular network market demand forces MNOs to optimize each network component, including the RAN. Several challenges should be addressed to deploy a good and reliable RAN. One of them is how to meet specific QoS requirements. 5G introduces new three use cases domain, namely Enhanced Mobile Broadband (eMBB), Ultra-Reliable Low-Latency Communication (URLLC), and Massive Machine Type Communication (mMTC) [15]. Every application and every wireless device has its own specific QoS requirements [1]. The existing monolithic RAN could not satisfy the diverse requirements of these use cases. Centralizing all use cases on a single network due to the limitations of the monolithic RAN would reduce both QoS and QoE [16].

Network upgrade for enhanced flexibility and adaptability is essential to meet different QoS requirements for each application. This flexibility can only be achieved by disaggregating RAN components [1]. It enables the RAN to behave differently to each application's particular QoS requirement, leading to a more intelligent and versatile RAN. RAN's architecture should support multiple levels of QoS in handoff scenarios at one time [17].

Another challenge for RAN is combining the existing NFV with artificial intelligence (AI). The trend of NFV has existed since the development from C-RAN to vRAN. However, the virtualization concept proposed in vRAN is complicated, needing mechanisms for management and orchestration [2]. Management and orchestration can be performed by leveraging AI. RAN needs NFV with AI embedded in it. AI has impacted the computing and networking world significantly until today [18]. AI can be used to analyze the enormous amount of RAN-generated data. Then, the information gathered can be used to anticipate problems in the network and take necessary action to ensure network QoS is delivered to the users. AI can make the NFV system more intelligent, optimized, and improved. Further explanation about NFV can be seen in the next subsection.

It has already been stated that RAN's improvement is happening by introducing cloud-native principles.The previous generations of RAN had a similar weakness: MNOs needed more control over their software and hardware innovation. Before Open RAN, RAN's software and hardware were proprietary and remained optimized to one vendor only [19]. It caused an economic monopoly with extreme overhead and led to unsupervised systems because the only vendor that could supply the hardware and software was that one vendor. MNOs depend heavily on vendors to provide innovation and new features on RAN technologies.

The remaining challenge for RAN involves the need for efficient interconnection among components within the network architecture [16]. It was caused by the uneven standards used for cellular networks around the globe due to the proprietary interfaces used. Because of these different characteristics of each vendor's interfaces, hardware and software from different vendors could not interconnect easily. This led to plenty of waste of wireless infrastructures and spectrum resources. When MNOs try to ignore these differences and treat all the cellular networks the same, their users will experience low QoS and QoE of the network.

Another fundamental pillar of Open RAN is disaggregation. Generally, disaggregation means the software is detached from its hardware [19].

Vendor develops their software to make it compatible with hardware from different providers. Through disaggregation, RAN software can run in general-purpose processors in commercial off-the-shelf (COTS) hardware, further extending its interoperability. RAN's software can now run on any vendor's hardware. Because softwarization is performed in RAN, acceleration techniques in software development can also be implemented, such as continuous integration and continuous deployment (CI/CD). In turn, RAN's time to market and deployment time can be reduced. Disaggregation and softwarization will be explained in further detail in the next subsection.

Open RAN has open interfaces in its architecture, which has become a fundamental pillar.

An open interface means these connections are standardized, and everyone can see the specifications freely. One of the most notable examples of an open interface is the internet, where everyone uses the same protocol to communicate. Other terms have the same meaning as the "open interface" terms, such as "open API", "open standard", "open technology", or even just "open". When a vendor declares that their solution is "open", it usually means that the vendor offers an open interface.

Open source software is characterized by its accessible source code, written in programming languages, allowing programmers to create or modify their software in a non-proprietary and collaborative way. It has an Open Source Initiative compatible license that allows anyone with the software's source codes to re-distribute, modify the software, or even derive codes from the software [20]. In the RAN context, open-source code RAN software means that the software source code to run the RAN network function can be accessed by everyone. Open-source RAN software is available. However, it is a relatively immature and comparatively limited feature set compared to commercial alternatives.

Rakuten has proven to be the world's first, which is currently the only commercial-scale nationwide network that uses Open RAN standards and architectures [21]. It was supported by Umlaut, who evaluated several performance metrics by comparing Rakuten Mobile data in Tokyo to other MNOs in major cities worldwide. The report is decidedly positive, scoring 920 out of 1000 and a "very good" rating. Compared to other cities, Rakuten can provide connectivity at a much higher speed than other MNOs. It proves that applying Open RAN in network architecture improves network connectivity performance.

Besides improving performance, Open RAN can also make the network connectivity be more cost-efficient. Because the framework includes AI in its architecture, the Open RAN framework will be able to facilitate automated operational network functions [2]. Open RAN is built to perform some complex tasks that had never been done before by its predecessor. The existence of machine learning (ML) and AI reduces RAN dependency on human force, thereby reducing operational costs. Cost reduction will be much more significant in the future with the development multivendor environment. The disappearance of a monopoly relationship between hardware and software in the Open RAN framework is designed to enhance the cost efficiency. MNOs can change a particular part that needs an upgrade or is broken without needing to change the whole network [19].

Rakuten serves as the proof. Rakuten Mobile 4G tech's CapEx and OpEx are approximately 40% and 30% lower than traditional RAN deployment's expenditures [21]. Furthermore, it is also mentioned that the cost spent by Rakuten is much more efficient when deploying a 5G network, saving up to 50%. This cost efficiency can benefit rural regions to enjoy economical network connectivity. These two advantages can be reached through Open RAN's openness and intelligence fundamental pillars. By solving the previous RAN problems, the network's performance will be improved and its cost will be more efficient.

Open RAN started to develop rapidly in these last six years. The first development of Open RAN occurred in February 2016, when Telecom Infra Project (TIP) formed the OpenRAN Project Group [19]. Since then, TIP has brought together more than 500 MNOs, suppliers, vendors, developers, and integrators that are using open source technologies and open approaches [19][22]. Further details about TIP OpenRAN project group are written in the next section. A year after the formation of the community, the first trials of Open RAN started in India and Latin America [19].

3.2. Technologies Related to Open RAN

To make an open and intelligent RAN architecture, Open RAN is supported by several technologies or approaches. Disaggregation, SDN, NFV, functional split, cloudification, automation, intelligence, network slicing, open source, and mobile edge computing (MEC) are some of them. These technologies and approaches will be introduced briefly in this subsection.

RAN disaggregation can refer to the separation of RAN into software and hardware or dividing it vertically and horizontally [23][24]. The former is a separation process between the network's software and hardware that occurred in a network architecture. As explained before, RAN's software and hardware used to be proprietary and integrated. Through disaggregation, the term RAN's functionality softwarization emerges where the software does not depend on specific hardware and vice versa. The main differences between non-disaggregated and disaggregated network architecture are shown in **Figure 2**. Software used to be integrated with hardware, whether it is in the CN or RAN. In a disaggregated network architecture, software and hardware are now separated. Through softwarization, the further separation of control and data is carried out, thus the term SDN emerges [4][25][26].

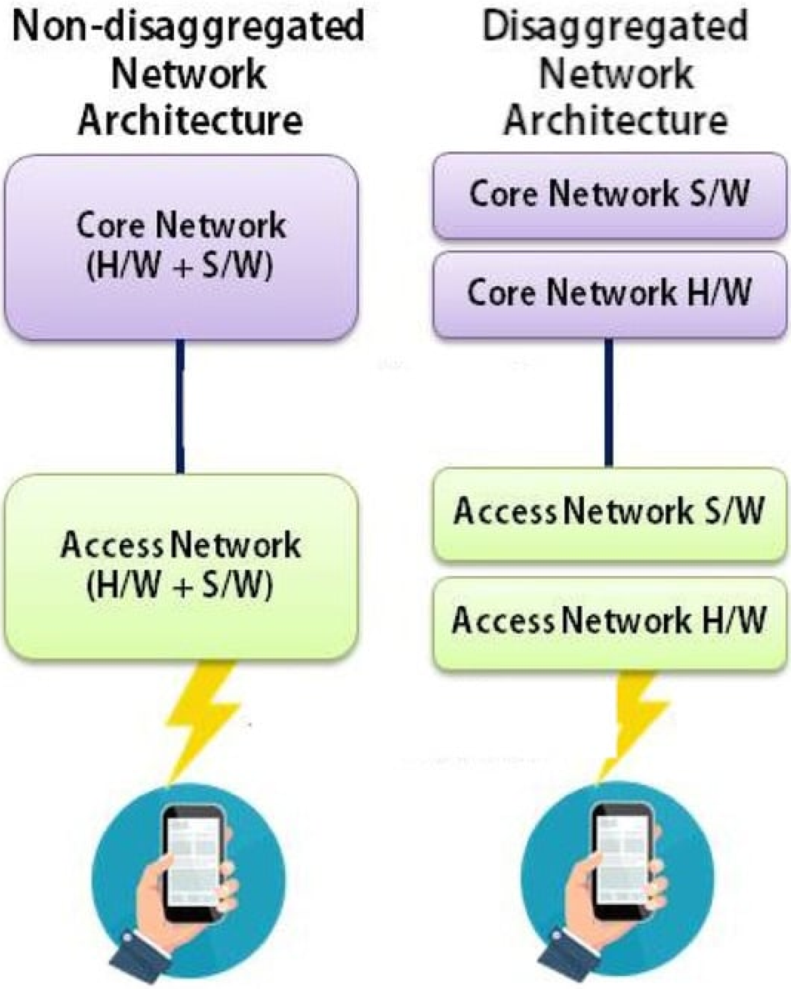

Figure 2. Comparison between a non-disaggregated and disaggregated network architecture.

Vertical and horizontal RAN disaggregation is also known as functional splits. Horizontal functional split is a selection process of the appropriate centralization level in RAN framework [27]. It separates the integrated BBU into two separate units: Central Unit (CU) and Distributed Unit (DU). Horizontal functional split also refers to the DU and RU separation. The degree of centralization in the horizontal functional split is flexible [28]. However, trade-offs should be considered when choosing these functional split options [11]. On the other hand, the vertical split is the separation between the control plane (CP) and user plane (UP) of the RAN. The CP and UP splitting (CUPS) is the extension of the SDN concept. The difference between vertical and horizontal split can be seen in **Figure 3**. Further explanation about functional splits will be discussed in Section 4.

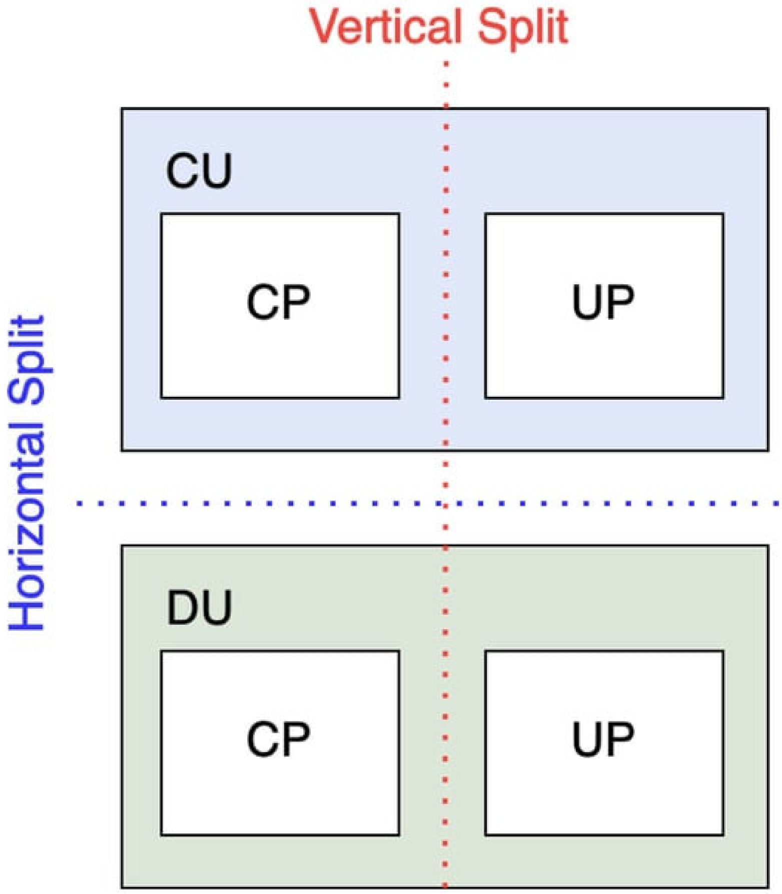

Figure 3. Vertical and horizontal functional split of Open RAN.

Virtualization enables the softwarized RAN to be sub-divided into smaller parts within single hardware that enhances softwarization [29]. There are two virtualization technologies, which are hypervisor-based and container-based virtualization [2].

Virtualization allows hardware to host functions of multiple virtualized units, leading to a term called NFV, which virtualizes all network services, such as virtual CU or virtual DU. These virtualized functionalities are called Virtual Network Functions (VNFs) and they run on top of VMs. NFV uses hypervisors named Virtual Machine Monitor (VMM) or virtualizer. The VMM hosts and runs VMs that host VNFs.

Another related technology is called network slicing. Network slicing branches from NFV. Network slicing is the concept to slice or partition the physical network to form virtual resources [4][30]. Slicing is performed in all parts of the network. Through the network slicing, there are multiple virtualized network that lies in the same physical network. Each virtualized network can flexibly be allocated for different use cases requirement in 5G. Different services can be allocated to each of the slices to satisfy specific user needs. Network resources can also be allocated dynamically according to each slice's needs. Network slicing contradicts the former "one size fits all" service model.

Disaggregated RAN allows its software to operate on different hardware. MNOs can use COTS server or a cloud instead of using dedicated hardware to run their software. This condition is called cloudification, where the hardware's roles are replaced by the cloud or COTS. MNOs might choose to use cloud or COTS because the deployment cost is cheaper than investing in their own hardware to run their software. There are also several types of cloud deployment. Choosing the right cloud deployment is the first step a MNO should make in cloudification. MNOs might want to choose public cloud deployment, where the cloud resources are owned and operated by a cloud service provider. A public cloud may have lower costs and be easier to manage, but the MNO has less control over the cloud resources and the level of security might be low. MNOs can also choose private cloud deployment, where the cloud resources can only be used exclusively by one business or organization. Private cloud deployment allows for more flexibility, customization, and control. However, it requires advanced technical skills and is more costly. MNOs can also choose the hybrid cloud deployment, where data and functions move back and forth between private and public environments.

Since there is a cloud deployment option, MNOs can choose different approaches to provide their service, namely a brownfield or a greenfield strategy. In the greenfield strategy, they have to make their network from the ground, which means that the MNOs should deploy the software and hardware from scratch. They do not use existing third-party cloud infrastructure. After they do the groundwork, they move those network components to the new cloud infrastructure. The greenfield strategy is the opposite of the brownfield strategy, where many of a network's functions of the previous architecture are retained. Simply, it means that in a brownfield project, the MNO needs to upgrade or add new features to an existing cloud network and use some legacy cloud components. Brownfield projects are mostly carried out after a greenfield project, with the purpose of developing or improving an existing application infrastructure. MNOs should consider trade-offs between the two approaches.

Through softwarization, the RAN's characteristics and behaviors are easier to reprogram, thus making the RAN programmable. The advantages of Open RAN programmable behavior is its network performance will be more optimized, the network resources can be dynamically allocated, the software and hardware functions can be controlled automatically, and novel algorithm can be leveraged to improve their own networking system performance [31]. The more advanced technology of programmability is called automation, where characteristics and behaviors of RAN are all reprogrammed automatically not by humans, but by computer programs.

There are two types of automation, namely orchestration and management. Orchestration is the automation of the softwarized RAN deployment process. Management automates RAN monitoring, configuring, coordinating, and task managing. The management system of RAN is called radio resource management (RRM). From RAN management, there is a new term called self-organizing network (SON). With SON, the RAN is requested to do its self-configuration, which includes new deployment of nodes, performance optimization, and fault management [32]. The intelligence of RAN is proved through AI/ML embedded in the RAN. AI/ML turns RRM into a more intelligent one, namely RAN Intelligent Controller (RIC) [2]. The RIC facilitates the optimization of RAN through closed-control loops between RAN components and their controllers [33]. RICs have made the Open RAN more adaptable, effective, and economical. As shown in **Figure 4**, these loops operate at different times, ranging from 1 ms to thousands of milliseconds. Real-time RIC (RT RIC) loop works for less than ten milliseconds. Near-RT RIC loop time range is between 10 ms to 1 s. The Near-RT RIC is responsible for deploying AI-enabled optimization and giving feedback for UEs and cells. The Non-RT RIC loop time typically spans 1 s or more, and it is responsible for releasing AI-enabled service policies and running analytics for the entire RAN.

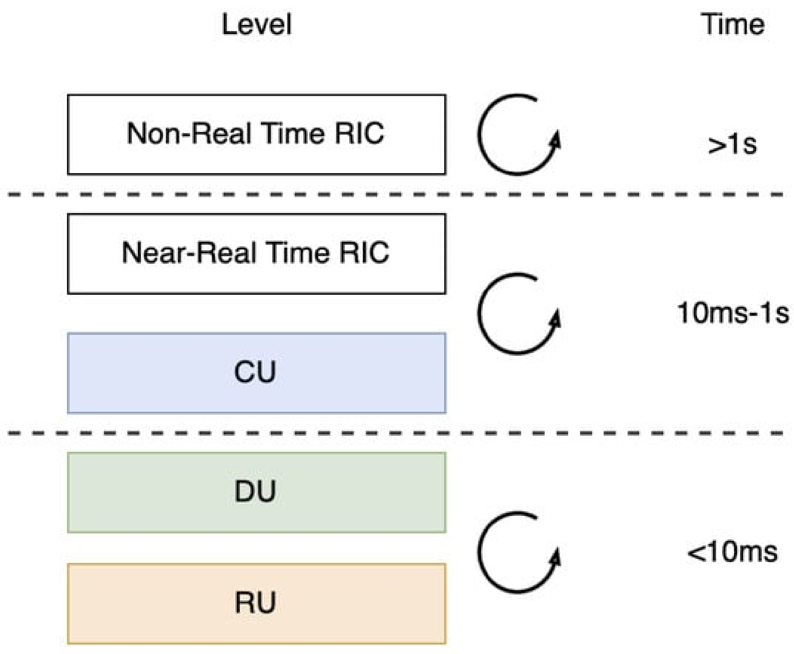

Figure 4. Three types of RIC.

Even though not mandatory like open interface, open source accelerates improvement of network infrastructure. In the past, RAN software has been largely proprietary and developed for specific hardware. The virtualization concept introduced by vRAN caused a significant change in the way network systems were designed. This change has significantly increased the use of server-based platforms and virtualized network functions in vRAN, and also in Open RAN, thus opening new chances for companies and network vendors to rebuild their RAN hardware and software to server-based platforms based on open-source software. Simply, open-source software has become a major solution to overcome challenges for RAN's software infrastructures. Its big contribution to RAN's software caused O-RAN Alliance and other communities and groups to develop open source solutions and adopted them to Open RAN's significant functions. Although these open source solutions are still in the early deployments stage, the telecommunication industry is mostly expecting companies to use open source-based software infrastructure solutions to run RAN applications.

Another related RAN technology is the smart network interface card (NIC). A smart NIC is a programmable accelerator that can increase the efficiency and flexibility of the data center network, data security, and data storage. Smart NIC can offload computation from its host processor [34]. Smart NIC can transparently unpack virtual switching data path processing for networking functions, such as network overlays, network security, load balancing, and telemetry. Through the use of Smart NIC or accelerator cards, a regular server performance and latency can be enhanced to meet the requirements needed to function as vBBU. Xilinx T1, T2, and T3 Telco Accelerator Card are some example of accelerators.

The other technology related to Open RAN is MEC. MEC is a cloud service that runs at the edge of a network. It performs several specific tasks that would be processed in centralized core or cloud infrastructures. MEC moves the computing process closer to the users for enabling applications and services requiring some specific network characteristics that differ from other applications or services. MEC is capable to move content and functionalities to the edge; providing any private cellular network services by using its localized data process; deploying computational offloading to IoT devices; leveraging the proximity of edge devices to end users; and enhancing the privacy and security of mobile applications [4][35]. Until today, there are several researches remaining for MEC, some of them are binary and partial offloading for MEC; MEC resource management system; MEC-open RAN-network slicing integration and their combined orchestrators; and MEC-embedded-RIC or called inter-near-RT RIC [32][35].

- SDN and NFV: The deployment of SDN and NFV concept in 5G network can save for about 25% 5G's total cost of ownership (TCO). This 25% savings are covered both from RAN and core virtualization. In the future 5G era, NFV will be a potential-generating tool, and maybe people will heavily rely on NFV when using 5G network.

- Automation and intelligence: Automation and intelligence are heavily related to AI. AI in 5G will be expected to save about 25% 5G's TCO.

- Network slicing: Network slicing will not be a part of a cost-saving element in 5G, but the one that can reduce cost is network sharing. Network sharing can make savings for about 40% TCO.

- Cloudification and open source: The deployment of cloud and open-sourced software in 5G network can save up to 5% 5G's TCO.

The cost efficiency mentioned in this section can also be further improved by implementing Open RAN in 5G networks. Before Open RAN era, the previous RAN hardware infrastructure was the part that had the highest cost of all parts in RAN infrastructure. Basically, to make good RAN hardware, there must be cabinets, radio antennas, baseband processing tools, power tools, cooling tools, and other tools. These tools had made for about 45% until 50% out of RAN's TCO. In 5G technology, the infrastructure cost has increased by 65% in some deployments. This 65% cost is probably the maximum possibility for any Open RAN scenario. This cost can be less than 65% for some Open RAN's lower-cost deployment scenarios.

This wide gap depends on some modifications used in the 5G Open RAN architecture. One of those modifications is adopting C-RAN's architecture deployment into the Open RAN. At least, this C-RAN adoption has saved 25%, compared to the previous generation of C-RAN cost, which is D-RAN. While C-RAN adoption has saved 25%, this number is predicted to be up to 45% in the future.

While the FH has made its way to reduce the RAN's TCO, the backhaul will not be similar to FH. Because 5G connectivity requires higher capacity with lower latency, backhaul has its cost increased by 55% in some higher Open RAN deployments. This 55% number is not definitive, because the increased cost can probably be lower than this number in some lower Open RAN deployments.

4. Projects, Activities, and Standards Related to Open RAN

4.1. Projects and Activities

The first project explain is the O-RAN Alliance. This community name is shortened to O-RAN. Because the term is tightly related is Open RAN, many people assumed that O-RAN, like ORAN, is also a shorter version of Open RAN. In addition, those two terms are used by industries interchangeably. There are also many journals that used these two terms at the same time, and with the same meaning. That is not the case. To make it clear, O-RAN is the short form of O-RAN Alliance, a name of a software community [19].

O-RAN Alliance is a community that has tried to standardize and detail the Open RAN specifications so they can be implemented in real life [36]. O-RAN Alliance was founded in February 2018 [37]. To form O-RAN Alliance, five big MNOs at that time gathered, which were AT&T, China Mobile, Deutsche Telekom, Orange, and NTT Docomo. The main purpose of making O-RAN Alliance is to promote an open and intelligent RAN. This alliance is a combined version of xRAN Forum and C-RAN Alliance [19][37]. All these communities were involved in deploying open interfaces, big data intelligent control, and virtualization in RAN. These communities had also recognized the need to make an open network. After these communities were merged into O-RAN Alliance, these communities had become official members of O-RAN Alliance, but they still kept their original purposes to deploy a more reliable and faster network. The first O-RAN Alliance board meeting was held in June 2018, and the first work group (WG) meeting in September 2019 [37].

The O-RAN Alliance has its own core principles. Basically, there are two core principles of O-RAN Alliance. These core principles are openness and intelligence [2][38]. To achieve these two high-level core principles, O-RAN Alliance has given some reference designs about how the architecture of the Open RAN should be [37]. These reference designs from the O-RAN Alliance are called O-RAN vision, which consists of standardization design, virtualization design, and white box design [38][39]. To be able to achieve the three visions, the O-RAN Alliance divides itself into smaller groups. There are two kinds of groups in the O-RAN Alliance. The first groups are the groups divided based on each work description, called WGs. There are ten WGs, and these ten WGs' objectives and chairpersons can be seen in **Figure 5**. The second groups are groups divided, not based on each work description, but based on their scopes or their focuses.

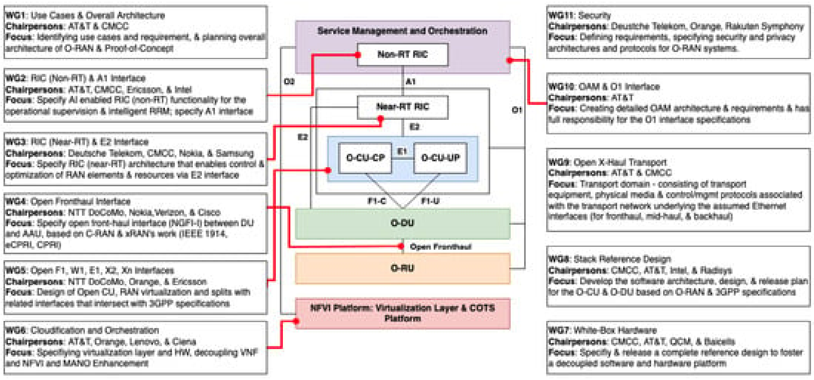

Figure 5. O-RAN Alliance's WGs and their objectives.

There are six focus groups (FGs) [36]:

- Standard Development Focus Group (SDFG): SDFG is responsible to make the standardization of O-RAN Alliance and to make the main interface to other Standard Development Organizations (SDOs) that will be relevant for the alliance's work. SDFG also coordinates incoming and outgoing liaison statements.
- Test and Integration Focus Group (TIFG): TIFG's task is to define O-RAN Alliance's overall approach for doing tests and integration, including coordination and specifications tests for WGs.
- Open Source Focus Group (OSFG): OSFG is responsible for dealing with open source-related issues for O-RAN Alliance. OSFG is the parents of O-RAN Software Community (OSC), which will be explained briefly.
- Industry Engagement Focus Group (IEFG): IEFG is responsible for promoting, accelerating the adoption and innovation of O-RAN-based technology in industry and O-RAN Ecosystem engagement.
- next Generation Research Group (nGRG): nGRG is responsible for researching open and intelligent RAN principles in the 6G system and beyond.
- Sustainability Focus Group (SuFG): SuFG is responsible for creating energy-efficient and environmentally friendly mobile networks.

To maintain the healthy relationships among WGs and FGs, the O-RAN Alliance formed a special committee, whose position is above all of these WGs and FGs. This committee is called the O-RAN Technical Steering Committee (TSC). TSC consists of member representatives and the technical leader from every WG, and this community represents both the members' side and the contributors' side in making decisions for every technical innovation made by WGs and FGs for the O-RAN Alliance. TSC is tasked to provide technical guidelines to every WG and FG, and to approve O-RAN's specifications, which were created by WGs and FGs based on members' approvals and publications [36].

Another important committee within the O-RAN Alliance is the minimum viable plan (MVP) Committee (MVP-C). MVP-C is relatively new in O-RAN Alliance. MVP-C's main job is to prepare a MVP for O-RAN's WGs and the public. MVP will provide a priority list of work items and is used to coordinate WGs. MVP helps the O-RAN Alliance to work more effectively. For the public, MVP gives a clear understanding of O-RAN's roadmap and priorities.

As mentioned earlier, the third FG, called OSFG, serves as the parent entity for OSC. OSC was founded in April 2019 as a collaboration between O-RAN Alliance and Linux Foundation (LF) [19][40]. This collaboration aims to support the creation of RAN's specific software. OSC is responsible for dealing with open source-related issues for O-RAN Alliance [36]. The software community is focused on aligning a software reference implementation with the O-RAN Alliance's Open RAN architecture and specifications [41]. Due to this focus, OSC's responsibilities are developing the open-source software, coordinating with other open-source communities, promoting the open-source software, and addressing wireless technology support for essential patents [36][40][41].

The workflow of OSC can also be seen in **Figure 6**. In the figure, OSC and the O-RAN Alliance work together in a loop. Firstly, 11 WGs contribute to making RAN specifications, architectures, and reference designs. These specs and architectures are checked to 3GPP and 5G network standards. Besides checking to 3GPP and 5G standard, these specs and architectures are also given to TIFG. TIFG tests whether OSC's software aligns with the specifications defined by the O-RAN Alliance. If there is any OSC code that works differently than the original specification, TIFG will request TOC to resolve these variance problems so that it aligns with the standard specification. After that, TOC prioritizes and negotiates with the O-RAN Alliance about solving these variance problems. The result of this negotiation is passed to the Requirements and Software Architecture Committee (RSAC). On the other hand, the O-RAN Alliance's WG1 also gives recommendations to RSAC about RAN specs or design features for inclusion in a particular release. Until this process,

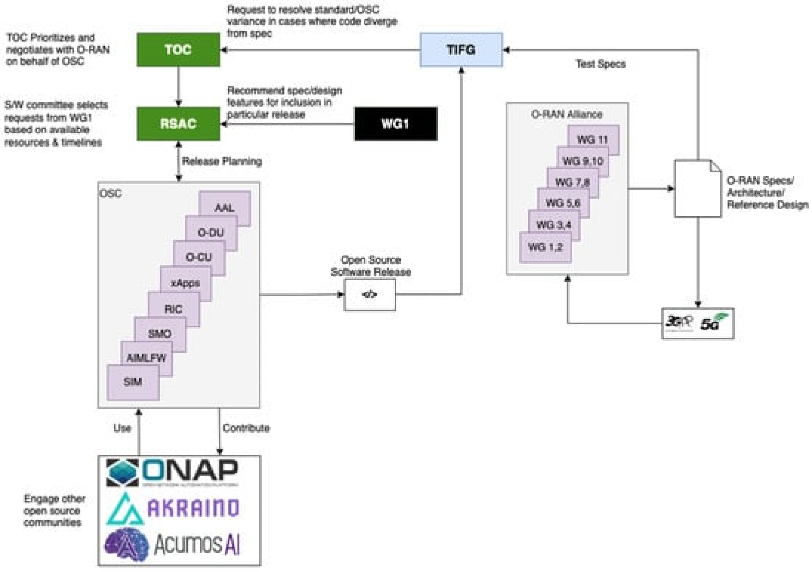

Figure 6. OSC's workflow.

The O-RAN Alliance supplies further support to the Open RAN movement by providing Open Testing and Integration Centers (OTICs) and conducting the O-RAN Global PlugFest. OTIC provides a working laboratory environment for Open RAN E2E system testing, certification, and badging [42][43]. OTIC's environment is designed to be vendor independent, open, collaborative, and secure. Currently, there are 15 OTIC labs around the globe [42] that usually held PlugFest to do interoperability test among vendors. PlugFest is a worldwide testing and integration event to demonstrate the O-RAN ecosystem [42]. The scope of PlugFest includes testing using the O-RAN Test Specifications; Validation and Demo of the O-RAN architecture elements, concepts, feature packages, reference implementation, and reference design; and O-RAN certification and badging dry-run.

Besides O-RAN Alliance related projects and activities, there are other projects that stem from the Open RAN movement. OpenAirInterface (OAI) is one of them. Started in 2009, OAI is an open software for RAN and CN developed by Eurecom. Since 2014, OAI is managed by OAI Software Alliance. This alliance originated in France and is divided into several project groups. OAI 5G RAN project group aims to develop an open source 3GPP compatible 5G next generation node B (gNB) RAN stack software [44] for its community members. Currently, OAI provides software-based implementations of evolved node Bs (eNBs), UEs and Evolved Packet Core (EPC) that are suitable with Long-Term Evolution (LTE) Release 8.6 [4]. Besides OAI 5G RAN, OAI also has the Mosaic5G project group with other projects, such as FlexRIC, FlexCN, and Trirematics.

OAI RAN's source code is written in C programming language, and this source code is distributed under OAI Public License, which is the combination of Apache License v2.0 and fair, reasonable, and non-discriminatory (FRAND) clause [4][45]. In this OAI framework implementations are compatible with Intel x86 architectures running the Ubuntu Linux OS. These implementations also require some modifications, mostly in kernel and BIOS-level modifications. These requirements should be fulfilled to make the OAI-RAN platform can perform in real-time, including installing a low-latency kernel, disabling power management, central processing unit (CPU) frequency scaling functionalities, and can also be used for field experimentation and evaluations with emulated wireless links [4][46].

The second related project is srsRAN. srsRAN is a free open-source software radio suite for 4G and 5G started in 2014 [47]. The project was formerly known as srsLTE and was originally developed by a startup called Software Radio System. Originally, srsLTE provided software implementations of LTE. Similar to OAI-RAN, the software implementations performed by srsLTE is in eNB, UEs, and EPC are suitable for LTE Release 10 [4]. The additional features for srsLTE are worked in 3GPP's Release 15. Also similar with OAI-RAN, srsLTE's software codes are written in C and C++ programming languages. srsRAN codes are distributed under GNU Affero General Public License (AGPL) version 3 or commercial license. The software is also compatible with Ubuntu plus Fedora Linux distributions. Different than OAI-RAN, srsLTE does not require kernel or BIOS-level modifications. srsLTE does need to disable the CPU framework scaling to do the real-time performance. srsLTE has now transformed to srsRAN as the project expands focus to 5G New Radio (NR) [47].

The third project is the TIP OpenRAN Project Group. The project group was started in February 2016 [19]. At that time, vRAN was widely discussed but still, that version of vRAN was considered impractical to implement and deploy for commercial traffic [31]. The project group consisted of MNOs who felt that the telecommunication industry was lacking innovation and the equipment needed for deploying network connectivity were extremely costly, especially in a highly concentrated or closed ecosystem [19]. TIP OpenRAN project group is an initiative to develop RAN solutions based on an open interface that can run on general-purpose hardware [31]. This project's scope includes multiple generations of the mobile communication system, from 2G to 5G. However, unlike previous projects, this project is closed source [4]. OpenRAN project group has goals to encourage innovation through building an ecosystem that can enable openness of the network; enable multi-vendor and software-based RAN; and reduce network deployment and maintenance costs [19][31]. All work carried out by TIP OpenRAN Project Group is reviewed and approved by TIP technical committee. The members of the project group are mostly companies who have become members of TIP. They include Vodafone and Telefonica, along with Intel as TIP co-chair [31].

The fourth project is ONAP. ONAP is an open source project started in 2017 that provides a common platform for telecommunication companies, providers, and MNOs to design, implement, and manage differentiated services [48]. ONAP project is one of LF projects [4] which is linked to Open RAN, primarily through the SMO project in OSC [49]. The project automates 5G by using SDN and NFV technologies. ONAP includes all the Management and Orchestration (MANO) layer functionality that compliant with NFV architecture from European Telecommunication Standards Institute (ETSI). ONAP includes network service design framework and fault, configuration, accounting, performance, and security (FCAPS) functionality.

The fifth Open RAN related project is SD-RAN. SD-RAN is one of ONF's projects. ONF is a community of MNOs that contribute to their own open source codes and frameworks for their networks' deployments [4]. ONF always works closely with O-RAN Alliance, TIP, Broadband Forum, LF, and Open Compute Project in every network deployments [24][50]. Started in 2020, SD-RAN's purpose is to build open source RAN components. In particular, SD-RAN is an ONF's component project that focuses on building the near Real-Time (RT) RAN Intelligent Controller (RIC) and xApps [4][6][51]. The xApps-SDK code made by SD-RAN is shared with OSC. SD-RAN has made its initial release in January 2021, called SD-RAN v1.0.

In addition to the projects above, there are also testbeds that can instantiate software 5G networks by leveraging some of the open-source components above. POWDER-RENEW, COSMOS, and Colosseum are a few examples [4]. The three testbeds are part of the Platforms for Advanced Wireless Research (PAWR) program [4][52]. POWDER-RENEW and COSMOS have worked with O-RAN and can support indoor and city-scale outdoor scenarios [4]. On the other hand, Colosseum is advertised as the world's most powerful wireless network emulator. Colosseum can support a large-scale network emulator scenario with 256 programmable software radios [4][52].

4.2. 5G, 3GPP, and Open RAN

3GPP is a standard development organization for the cellular telecommunications technologies [53]. It was assigned to work with the International Telecommunication Union Radiocommunication Sector (ITU-R) on scheduling and formulating the 5G technology standard, as ITU-R is the authority for radio communication [54].

The 3GPP releases introduce the new three use cases domain of 5G, which are eMBB, URLLC, and mMTC [55]. From these releases, 3GPP introduced a new term called NR. NR is a new radio access technology (RAT) that 3GPP developed for 5G technology. Simply, NR is the term for 5G RAN. 3GPP defines some specifications for the 5G NR technology, such as Standalone (SA) configuration, Non-Standalone (NSA) configuration, CU-DU functional split, and CUPS [54][56].

The 5G NR configuration can support either SA or NSA configuration. As the name implies, the NR SA means the 5G NR framework works independently without having another generation technology connected. NR NSA is the opposite of the NR SA. The NR NSA still connects to 4G CN or EPC to support the NR. 3GPP also defines the interface differences between NSA and SA configurations. SA and NSA have their CN and RAN involved differently in each configuration:

- NSA Configuration: The NR's eNBs connect to the gNB through an X2 interface. Another interface used in NSA is S1 interface, connecting eNBs and gNBs to EPC. NSA uses EPC as its CN, and its users can connect both to eNB or gNB to deliver the network.

- SA Configuration: SA enables operation service to be provided solely on the basis of gNB. The gNB connects to other gNBs with Xn interface and connects to the 5G core (5GC) through NG interface. SA uses 5GC as its CN. SA's UEs will only connect to gNB. CU and DU are parts of gNB.

There are two kinds of functional splits: horizontal and vertical split. The CU–DU functional split is called horizontal functional split. 3GPP defines the interface between the CU and DU as the F1 interface. Another further specification that 3GPP defines is the vertical functional split. A vertical functional split is performed to separate the UP and CP radio protocol. UP carries the network user traffic. UP protocol stacks consist of three layers, which are packet data convergence protocol (PDPC), radio link control (RLC), and medium access control (MAC). CP radio protocol contains radio resource control (RRC) layer which is responsible for controlling or configuring the lower layers, broadcasting information from a terminal to a cell, and deploying RRC connection functions. Further details about UP and CP can be seen in [56].

After many years of planning, the 5G technology became a reality in 2019 [57]. The 5G launch already existed for about 36 deployments across Asia, Europe, and North America. The telecommunication companies had also worked hard to implement 5G in real life. However, the 5G technology still has so many elements that need improvements today. One of these improvements should be optimizing 5G network costs.

The unclear RAN standard was not enough to provide interoperability for existing mobile terminals and smartphones, especially if a multivendor environment was introduced. It was necessary to create a new movement in the telecommunication industry by cooperating with other companies in industries and releasing new RAN functions and interface standards that can enhance its value. This is why the open framework network movement was started. **Figure 7** summarizes the new additional functions and interfaces that the O-RAN Alliance provides to supplement the 3GPP specifications.

3GPP	O-RAN
Functions • Management & Orchestration • CU-CP/CU-UP • DU	Additional Functions • SMO • Non-RT RIC • Near-RT RIC
Interfaces • E1 • F1-C/F1-U • NG-C/NG-U • X2-C/X2-U • Xn-C/Xn-U • Uu	Additional Interfaces • A1 • E2 • O1 • O2 • Open Fronthaul • O-Cloud Notification Interface • Y1

Figure 7. Comparison between 3GPP and O-RAN network functions and interfaces.

As an introduction to the following section, and to better understand the difference between 3GPP and O-RAN specifications, **Figure 8** shows how the functions and interfaces are positioned in the RAN architecture. The specifications that O-RAN Alliance provides are more detailed than the more generalized 3GPP specifications. This is important, particularly in the multivendor environment. For example, the X2 interface becomes essential for multi-vendor networks to function seamlessly [19]. In addition, it is known from the previous section that the 5G RAN needs to support SA and NSA deployment. The current 5G deployments are still NSA and it will be challenging to move to the future 5G SA RAN deployment if the X2 interface is not open [19]. Open RAN's multi-vendor RAN system dream also helps reduce costs for MNOs by introducing more software vendors and diversifying the supply chains. Despite that, Open RAN standards still need to comply with 3GPP specifications because 3GPP's specification is the universal standard for the 5G RAN technology.

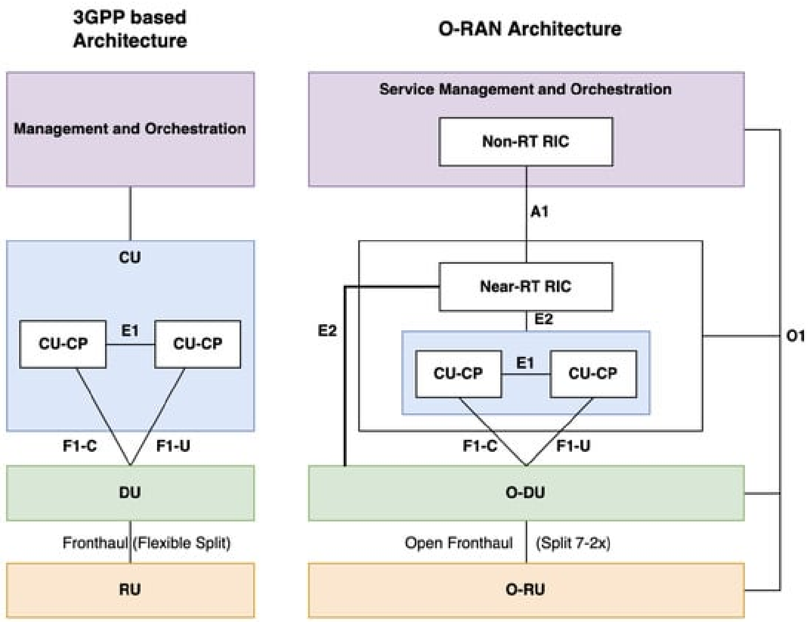

Figure 8. Comparison between 3GPP and O-RAN architecture.

However, Open RAN's principles are not only applicable to the 5G RAN technology. The purpose of Open RAN movement is to define and build RAN solutions based on general-purpose, vendor-neutral hardware and software-defined technology in 2G, 3G, 4G, and 5G [19]. Even though Open RAN can be used for other cellular generations, the current O-RAN Alliance's standardization still focuses on 5G because it is the latest trend that the telecommunication industry and companies follow.

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