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Review

Open RAN—Radio Access Network Evolution, Benefits and Market Trends

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Abstract: Open RAN (radio access network) movement is perceived as a game changer, having robust potential to introduce shifts in mobile radio access networks towards tailor-made solutions based on the architecture decomposition. It is widely assumed that those changes will affect the approach to network deployments and supply chains of network elements and their further integration and maintenance. First deployments of O-RAN-based networks have already delivered broadband services to end users. In parallel, many proof-of-concept feature evaluations and theoretical studies are being conducted by academia and the industry. In this review, the authors describe the RAN evolution towards open models and make an attempt to indicate potential open RAN benefits and market trends.

Keywords: open RAN; O-RAN; C-RAN; 5G networks

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1. Introduction

The development of mobile cellular systems is a continuous process that began in the 1970s [1,2]. Over the years, many standards of those systems have been published and released. Evolution from analogue to the digital era happened in the 1980s. Then, in the late nineties, the third generation of mobile networks facilitated packet switch communication. Until 5G, all legacy generations had some commonalities: at the least, (a) they were mainly intended for the consumer market; (b) the main goal was to deliver higher throughput to end users; (c) they were able to utilize wider bandwidth and new frequency bands than previously; (d) the main application scenarios were related to voice communication and Internet connectivity. Comparing these legacy systems, new requirement areas were set for 5G [3,4]. By design, 5G RAN has to be at least compliant with an energy-efficient paradigm, needs to be extremely reliable, and has to support 1,000,000 users per km^2. Such an approach should allow to deliver mobile/wireless services not only for the consumer market but also for industries and private and corporate users. As many scenarios are expected to be supported, during specification, the decision was made that RAN architecture needs to be more modular than before [5].

In the past, attempts were made to deploy base stations in a decomposed way and by more than a single vendor per site, based on standardized reference architectures. Wideband Code-Division Multiple Access (WCDMA) in the 3G era brings the split of RAN to Radio Network Controller (RNC) and base station (called NodeB), enabling one-to-many connections among those entities. Fourth Generation (4G) Long Term Evolution (LTE), deployments, multi-vendor connections between RAN base stations (eNB), and core networks (CN) based on a standardized interface all have commonalities. However, interfaces applied in RAN among proper nodes are still proprietary. Despite the advances and complexity of the mobile access network, the mature solutions implemented in base stations are delivered by a single vendor, which used to be defined as vendor lock-in. Although the Third Generation Partnership Project (3GPP) has defined some interfaces and released public specifications, vendors are deploying proprietary solutions and interfaces.

This has finally led to the implementation of RAN networks in given bands and in a given geographical area by a single supplier. Currently, we are observing the single-vendor monolithic approach to RAN (eNBs) deployment around the world, i.e., networks are not open across the defined protocol stack.

The amount of subscribers of mobile networks is higher than the world total population. It is expected that the number of cells and sites will continue to grow in the future due to network densification and implementation of new frequency bands. According to [6], it is forecasted that 8.8 billion mobile subscriptions will be active in 2026, including 3.5 billion subscriptions of 5G. It shows that we need flexible and more centralized deployed networks by design. Flexibility may be guaranteed by network element decomposition within the architecture of radio access protocol stack. However, such an approach does not still mean openness from the proprietary perspective. In the last decade, the need for flexible and *open* approach in RAN development was identified by mobile network operators and network equipment suppliers, which has finally been called Open RAN. Open RAN is a broad term that encompasses the willingness of industry players (operators, vendors, neutral hosts, integrators, private business, etc.) to open the RAN architecture with the aim to facilitate deployment and integration of multi-vendor mobile radio access networks, eliminating potential blockers in further developments. Such openness has been guaranteed due to the specification of proper interfaces between logical nodes and the introduction to new network elements which are able to incorporate intelligence by means of Artificial Intelligence/Machine Learning (AI/ML) implementation and the data driven network paradigm. Open RAN is also about the evolution of network element hardware (HW) and software (SW) decomposition, which, in practice, means: (a) many vendors may deliver solutions, (b) commercial off-the-shelf (COTS) hardware may be used, and (c) products may be updated via software in an agile way.

This work is motivated by a relatively low number of studies concerning Open RAN architecture that can be found in the literature which, at the same time, is accompanied by a huge effort invested in developing Open RAN solutions. The authors' goal is to present Open RAN landscape and current Open RAN trends together with state-of-the-art research activities, with the aim to recognize the current and foreseen prospect of this approach in 5G network deployments. To the best of our knowledge, such an overview paper concerning Open RAN in the literature is missing.

The article is organized as follows: in Section 2, chronological changes in mobile network architecture are presented; Section 3 describes Open RAN organizations, players, standardization bodies, as well as introduces O-RAN—the world-leading reference architecture; in Section 4, the open xHaul transport network is described; Section 5 presents market expectations; in Section 6, review of state-of-the-art academia research are presented; finally, Section 7 contains conclusions including listed challenges and open issues related to Open RAN deployments.

2. Mobile Network Architecture Evolution

In the early days, mobile network deployment was based on a monolithic approach in which baseband processing units and radio modules where placed near an antenna. These two main elements constitute which we commonly call RAN—which is a principal part of mobile networks next to core network, terminals and transport. In 4G/LTE, vendors started to deliver eNB nodes disaggregated into Radio Remote Heads (RRHs) and Baseband Units (BBUs), which are placed within close site proximity, which is commonly referred to as distributed RAN (D-RAN)—see Figure 1. Note that RRH is named Remote Unit (RU) in 3GPP 5G New Radio (5G NR) related specifications. BBU performs computing–hungry operations related to the RAN stack such as signal processing for many cells, managing resources, correcting transmission errors, etc. [7]. In such D-RAN deployments, proprietary interfaces are used to provide communication between RRHs and BBUs, e.g., based on Common Public Radio Interface (CPRI) or Open Base Station Architecture Initiative (OBSAI) protocols [8,9]. Taking into account statistical behaviours of users connected to cells, i.e., call time and instantaneous data transfer, to mitigate resource overestimation in a baseband, resources may be pooled together. Thus, network densification motivates to move those resources to centralized offices and data centres.

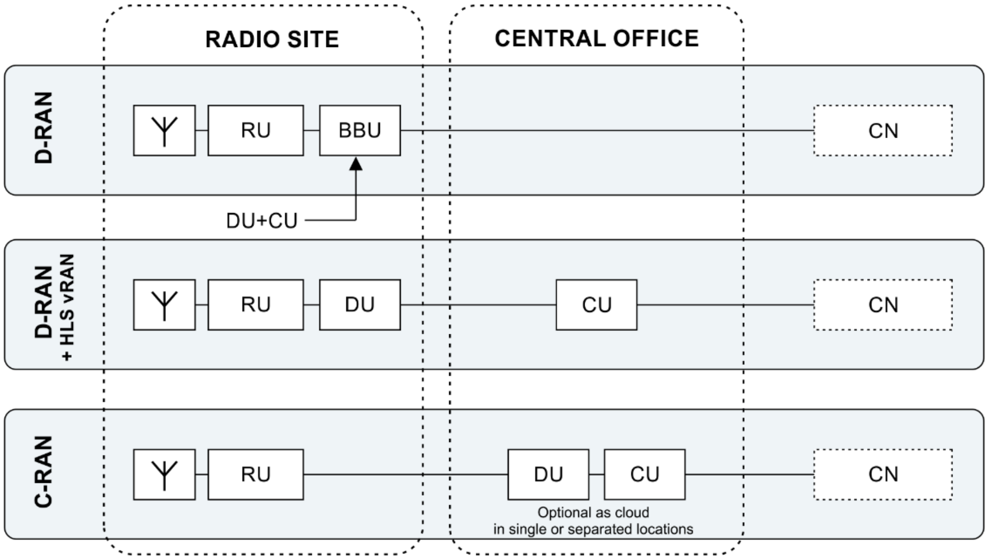

Figure 1. Difference between D-RAN, D-RAN partially cloudified and C-RAN. C-RAN does not define whether the 3GPP radio stack is running in Cloud (Cloud-RAN).

The concept of centralized RAN (C-RAN) is about moving part of the baseband processing to a central office (hub). C-RAN was proposed by China Mobile in 2009 to support high-bandwidth applications [10]. BBU centralization is motivated by maximization of data transmission efficiency and coordination of resources, among others. Another step towards decomposition of RAN was achieved by Small Cell Forum, which identified and announced the benefits from virtualization and centralization in small cells networks together with implementation of MAC/PHY split in 2015 [11]. From that time, many evolutions of potential future network architecture functional splitting were conducted. Functional splitting determines how much the network is centralized. According to [12], RAN functional decomposition is needed to diverse transport demands in terms of different performance requirements and to adjust to various traffic types of different performance goals, e.g., very high throughput vs. extremely low latency. The authors of [13] reviewed different studies concerning functional splits and evaluated advantages and drawbacks of those splits. According to [14], centralized baseband processing enables better inter-cell coordination and, by these means, allows for load balancing and cost reduction due to increased hardware/software pooling and decreased site rental costs.

3GPP in an early phase of 5G NR specification works (i.e., in Release 14) evaluated an extended approach to functional splits, which is reflected in splitting the architecture into Centralized Unit (CU), Distributed Unit (DU), and RU entities. In this approach, the CU and DU take a role of a baseband unit and are mutual linked via a midhaul F1 interface [15], where CU performs non-real time L2/L3 operations and DU realizes near-real time L1/L2 functions, e.g., scheduling. RU is responsible for converting signals to and from radio frequency (RF), and is either connected to an antenna or integrated with an antenna, e.g., in the case of multi-input multi-output (mMIMO) systems. According to 3GPP TS 38.470 specifications [16], the F1 interface is open and facilitates connection of a CU and a DU supplied by different manufacturers. CU and DU may be collocated and linked internally. 3GPP TR 38.913 [17] states that different functional split options should be allowed in the RAN. Particular split options are presented in Figure 2.

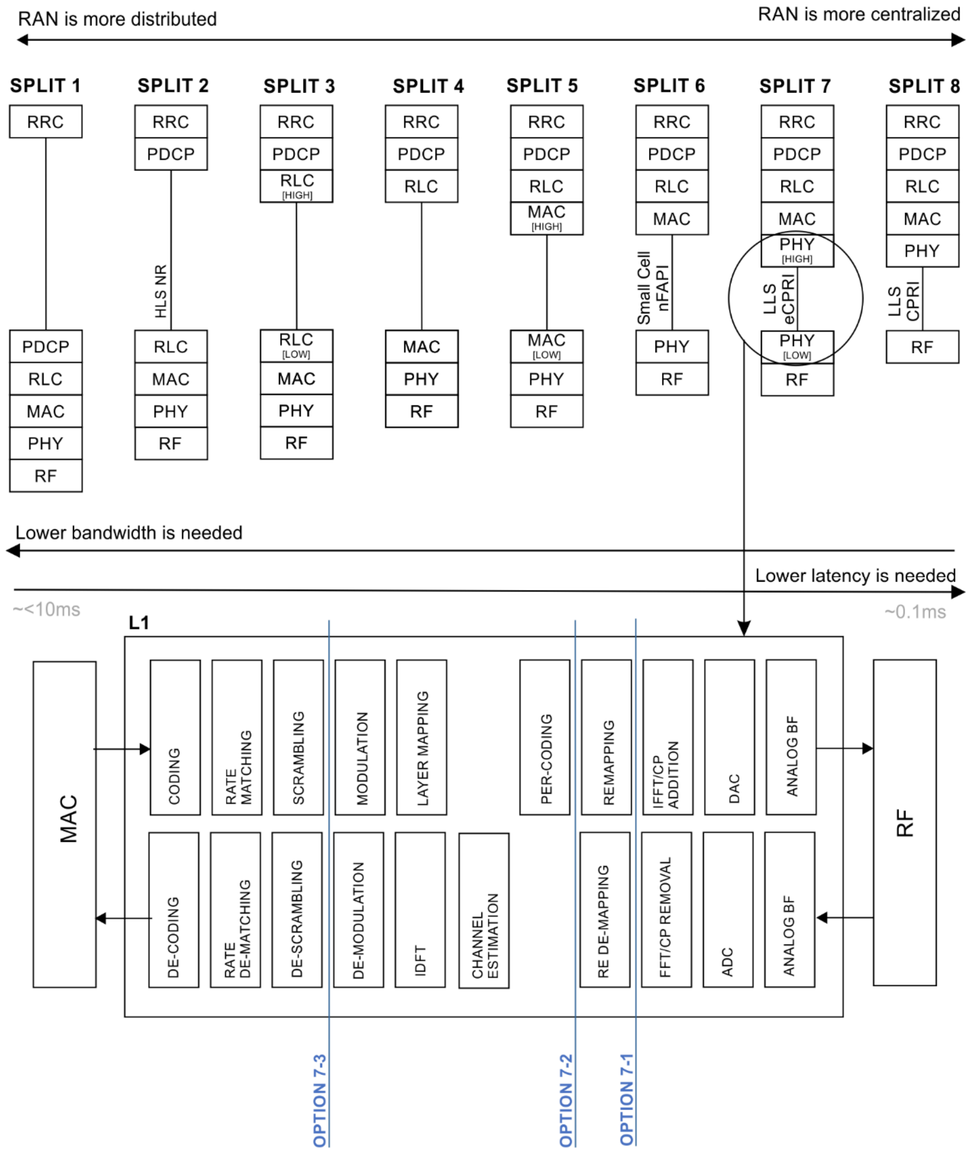

Figure 2. Review of functional splitting options with respect to 3GPP 4G/5G RAN stack (above) and differences among Option 7 split from PHY layer perspective.

In 5G NR, two different splits are distinguished, where Higher Layer Split (HLS) is the interface in a midhaul link between CU and DU, and Lower Layer Split (LLS) is the interface in a fronthaul link between DU and RU. In the report [5], the overall functional split assessment and justification for 5G is presented. The report's conclusion on functional split between central and distributed unit states that Option 2 should be used for HLS; however, lower layer split (LLS) needs further study. It is also indicated that high performance transport connection (in terms of bandwidth and delay) between CU/DU can enable scheduling optimization, which is a particularly desirable feature where the cross cell coordination brings gains. According to [5], higher layer splits may be applied in transport networks with higher transport latency, whereas lower layer splits can be applied in transport networks with lower latencies to achieve enhanced performance (e.g., centralized scheduling, coordinated multi-point (CMP) transmission and reception, higher efficient resource pooling). In the case of LLS, the use of a lower split results in a less complex RU. Regarding Open RAN, a key factor is opening the fronthaul (FH) interface, which has never been common before. The O-RAN specification decided that the split called 7-2x will be standardised together with Control, User and Synchronization Plane (CUS-Plane), with the aim to separate transmission of control, user and synchronization data [18].

Such an approach allowed to exploit the enhanced Common Public Radio Interface (eCPRI) protocol [8], used to transmit radio data encapsulated into Ethernet frames (as discussed in Section 5), in a multivendor environment both in LTE and NR Radio Access Technology (RAT). Three different versions of split Option 7 (shown in Figure 2) were evaluated and identified [19]: O-RAN selected split 7-2x, in which bandwidth demand scales according to the number of spatial layers, whereas splits 7-1 and 7-3 scale according to the number of antenna elements and coded bits, respectively [20]. Moreover, two categories of split 7-2x were defined by O-RAN, i.e., Category A and Category B. These categories differ in the placement of decoding function, namely, in DU for Category A and in RU for Category B, where the latter is supposed to support more complex mMIMO scenarios. The details of O-RAN fronthaul specification are described in [18].

The RAN architecture evolution towards splitting and node decomposition among different RAN stack protocol and layers is perceived as horizontal openness. Overall, Open RAN is related to disaggregation, which could be defined in at least four dimensions [21]—see Figure 3—(1) separation of control and user planes, which has been already performed in 5G/new radio (NR) systems; (2) horizontal disaggregation related to opening the interfaces; (3) vertical disaggregation related to decoupling hardware and software; (4) disaggregation of software and data pipe, by introduction of AI/ML techniques and connectivity to external contextual data sinks which are able to take a vital role in RRM (Radio Resource Management) optimization and performance.

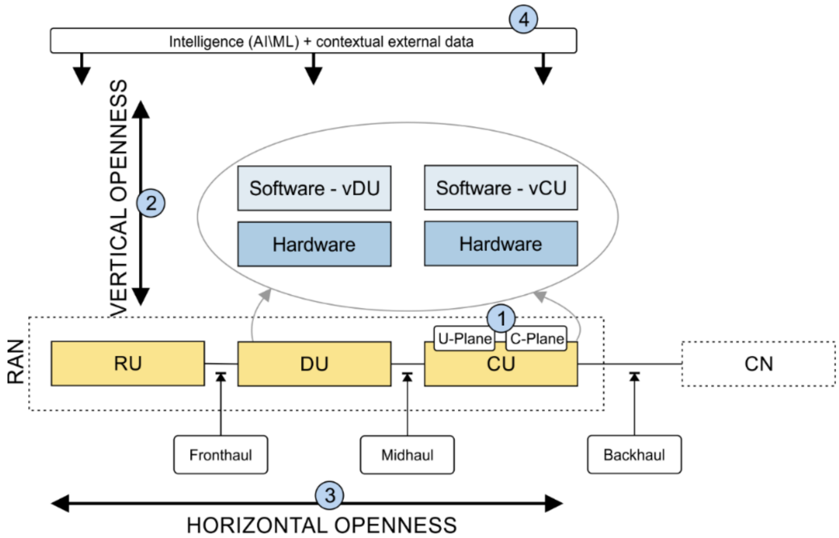

Figure 3. Four dimensions of openness and disaggregation: (1) User and Control Plane separation; (2) Vertical openness enabling shifts bare-metal deployment to towards HW and SW disaggregation; (3) Horizontal openness thanks to open interface standardization; (4) ML approach instead of software developed in a static way.

Open RAN does not mean the disaggregated dimensions mentioned above are deployed completely within a particular solution. In case of the vertical disaggregation, hardware and software are decomposed and allow to run network functions (NFs) on COTS solutions. A next step is a successive RAN virtualization (vRAN), where NFs are run as virtual network functions (VNF), and containerization, where NFs are run in containers as containerized network functions (CNFs). Such a cloudify approach allows for better orchestration and service management. CNFs are more flexible than VNFs, which are maintained by hypervisors [22], as VNFs tend to be single-purpose appliances, which are not enough scalable in cloud deployment, contrary to CNFs. The deployment of NFs and CNFs in the network may be based on defined hardware and software incorporating general purpose solutions (e.g., servers, hypervisors, software development kits) that were not primary foreseen only for telco-related scenarios. In effect, mobile network supply chain joined IT companies was not previously associated directly with RAN development. A wide review of Open RAN-related projects and Open virtualization and management frameworks are presented in [23]. The authors of [24] described the current research trends in C-RAN and vRAN, with cross comparison among them describing applicable scenarios. In [25], the benefits and challenges of vRAN are listed.

3. Open RAN Landscape

The transformation of radio access networks towards Open RAN is driven by operators, vendors and other R&D organizations. Within this section, the selected main players who are involved in RAN transformation towards its openness are presented. In addition, some crucial public activities and events are grouped and listed together on a timeline shown in Figure 4. The commercial and proof-of-concepts field deployments are not presented here, as some of up-to-date operators activities may not be communicated to wider public, which finally may lead to inaccuracies in the review. The Open RAN race engages greenfield vendors which see the business potential to develop and further deploy their solutions. Overall, the Open RAN activities should be also assessed from a (geo)political perspective [26]. In Table 1, only selected main organizations related to Open RAN and its open-source software development are presented.

Table 1. Main organizations related to Open RAN development.

Organization	Main Tasks in Brief	Source
O-RAN Alliance	• O-RAN specification; • The open-source software development for the RAN (together with Linux Foundation); • Support of members in testing and integration of their implementations.	[27]
O-RAN Software Community (under Linux foundation)	• Collaboration between the O-RAN Alliance and Linux Foundation; • RAN Software implementation; • SW testing, integration and O-RAN specification alignment.	[28–30]
Telecom Infra Project (Project group OpenRAN)	• Focus on the RAN implementation on General Purpose Processing (GPP) HW deployment; • Demonstration of performance (via GPP HW); • Identification of requirements for virtualized environments; • Interoperability testing.	[31–33]
Small Cell Forum	• Specification of FAPI/nFAPI; • Open LLS Interface.	[34]
ONF (SD-RAN Project)	• Open source SW platform for multi-vendor 4G/5G RAN solutions; • Project is initially focus on O-RAN nRT-RIC; • Cooperation with TIP, O-RAN Alliance, O-RAN SC.	[35,36]
Open RAN Policy Coalition	• Promotion of policies moving on the adoption of Open RAN and interoperable solution; • Promotion solution to enable expanding the wireless technologies supply chain.	[37]

The evaluated Open RAN solutions are generally related to 3GPP standardization activity, i.e., the future open networks are perceived as enhanced 4G/LTE and 5G/NR RATs (Radio Access Technology) with new functions, logical blocks and platforms. One of the most important in this field is a reference architecture—called O-RAN—was developed by O-RAN Alliance founded by AT&T, China Mobile, Deutsche Telekom, NTT DOCOMO and Orange in August 2018 [27]. O-RAN Alliance was established as a fusion of two former organizations, C-RAN Alliance and xRAN Forum [38,39]. Those two organizations had different origins, i.e., Chinese from one side and United States, European, Japanese and Korean from the other. Since that time, O-RAN Alliance has signed some liaisons and collaboration agreements as well as published a set of specifications (see Figure 4).

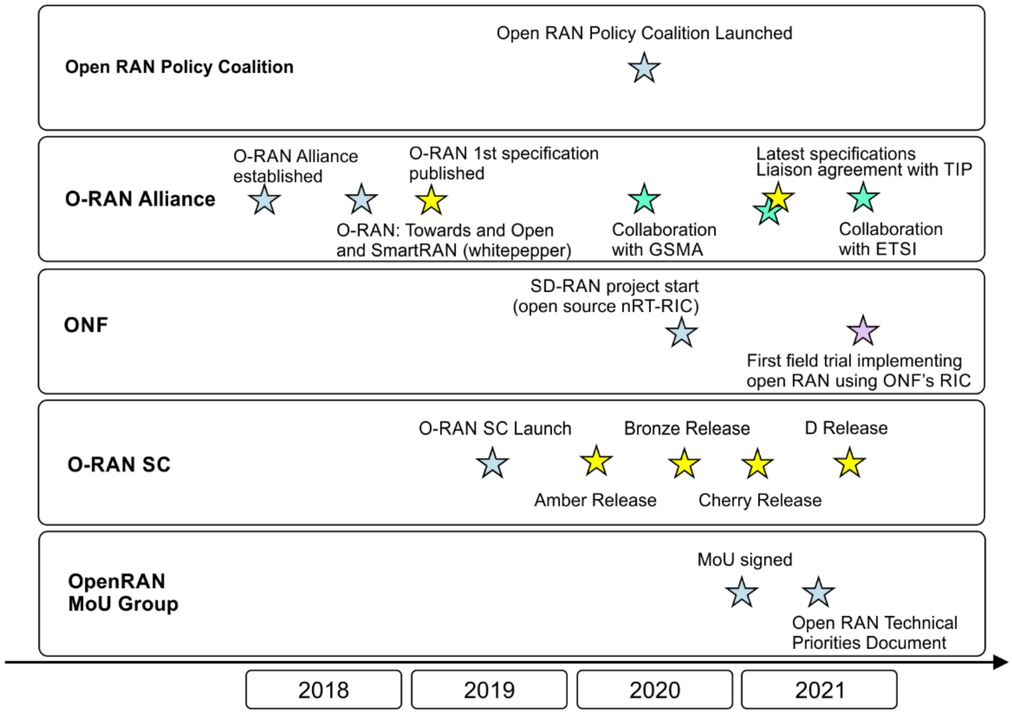

Figure 4. Timeline of selected actions and events related to Open RAN development.

3.1. O-RAN Architecture

The Open RAN vision of interface openness, disaggregation, and intelligent radio access networks was materialized by the O-RAN Alliance in its specifications of the O-RAN standard [40]. The O-RAN reference architecture is based on enhanced 3GPP nodes, functions, layers, and interfaces [41]. In Figure 5, we present a general view of the O-RAN architecture that is composed, among others, of the following functional blocks and interfaces:

1. Near-Real-Time and Non-Real-Time RAN Intelligent Controller (near-RT RIC/non-RT RIC) functions;
2. service management and orchestration (SMO) framework;
3. interfaces A1, E1, O1, O2;
4. 3GPP extended nodes O-CU, O-DU, O-RU;
5. open FH interfaces together with Open FH Management plane (M-plane).

Native 3GPP interfaces (X2, Xn, XG) enabling connection towards other eNB/gNB elements are not shown in Figure 5. O-RAN specifications are published as outcomes of the official established Working Groups (WGs), each of which covers selected RAN aspect listed above. Apart from WGs, the O-RAN Alliance constitutes dedicated Focus Groups that cover topics related to whole organization aspects.

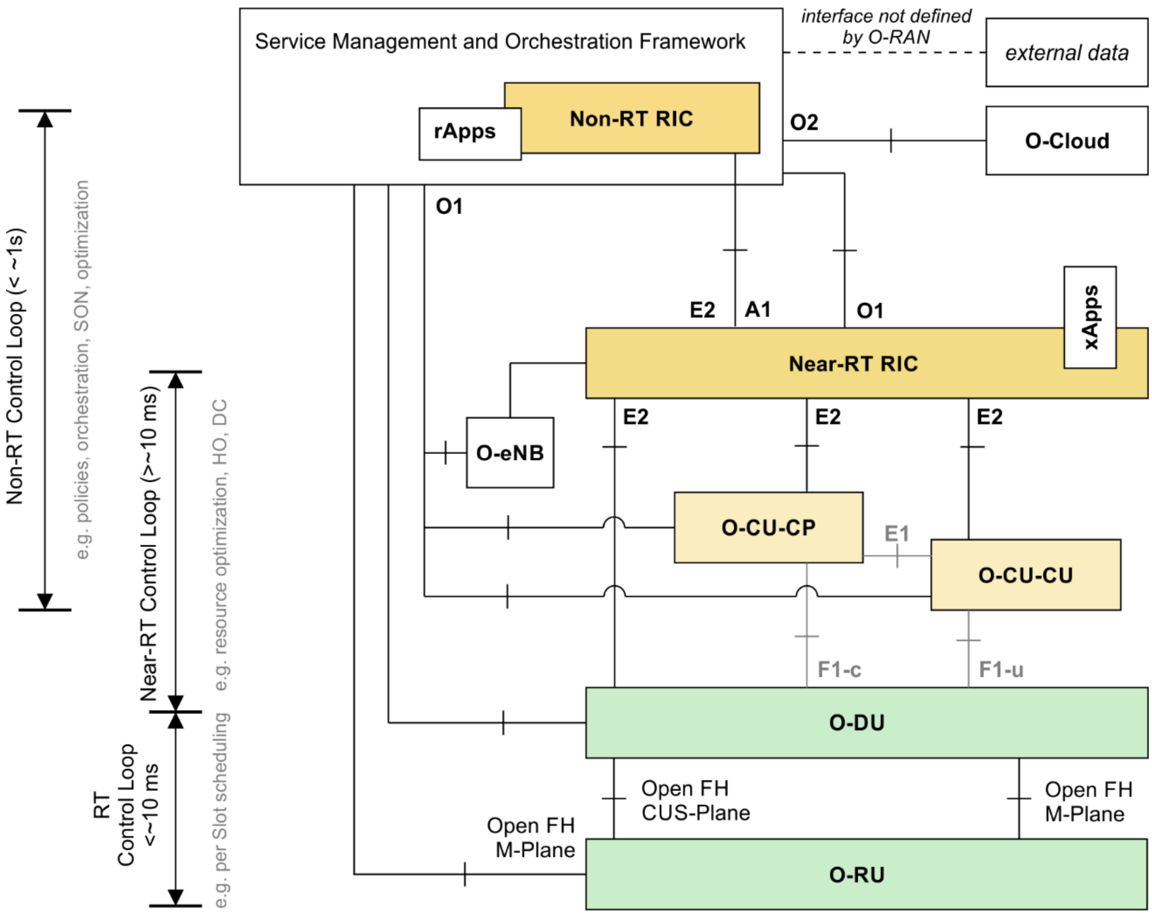

Figure 5. O-RAN reference architecture (adapted from [42]).

Non-RT RIC is placed within SMO outside RAN. Such an approach enables to feed the RIC with external/contextual data and use it for RAN optimization purposes [43]. This component contains non-RT RIC Applications (rApps) and frameworks. By means of the A1 interface, non-RT RIC may send policy update information to steer RAN performance and receive feedback from near-RT RIC, e.g., traffic patterns or user mobility behaviour. Concurrently, via the O1 interface, it receives information concerning network status. The goal of rApps is to support the control and optimization of RAN elements and resources (via R1 interface) in use cases based on a control loop greater than 1 s. The decision process may be supported by machine learning models implemented in RIC that make use of collected data. In Figure 5, the control loops timing is presented to show the time range of decision process.

Near-RT RIC is the logical function, perceived by the market as beneficial, enables Radio Resource Management (RRM) optimization based on fine-grained data collection and actions. Near-RT RIC hosts one or more xApps-dedicated applications (delivered also by the third parties) as microservices. xApps use cases encompass optimization of those areas which have been defined by 3GPP as well as internal proprietary features related to RRM, quality of experience (QoE), mMIMO, mobility, energy efficiency, self-organized network (SON), interference mitigation, etc. [44]. The control loop for xApps is greater than 10 ms. Near-RT RIC is connected via the E2 interface with E2 nodes i.e., O-CU-CP, O-CU-UP, O-DU in NR and O-eNB in Evolved Universal Mobile Telecommunications System.

The other main elements of the O-RAN architecture are as follows.

1. O-RAN Central Unit—Control Plane (O-CU-CP), which is an enhanced CU-CP defined by 3GPP that hosts RRC (3GPP TS 38.331 specification) and PDCP (control part, 3GPP TS 38.323 specification) protocol;

2. O-RAN Central Unit—User Plane (O-CU-UP), which is an enhanced CU-UP defined by 3GPP hosting SDAP (3GPP TS 37.324 specification) and PDCP (user part) protocols;
3. O-RAN Distributed Unit (O-DU), which is a logical node hosting RLC (3GPP TS 38.322 specification), MAC (3GPP TS 38.321 specification) protocols and High-PHY layer (3GPP TS 38.201 specification);
4. O-RAN Radio Unit (O-RU), which is a logical node hosting Low-PHY and RF processing;
5. Open Fronthaul—O-DU and O-RU are connected via open FH interface implementing Option 7.2x split. As mentioned in Section 2, two version of the 7.2x split are defined in which a precoding function is placed either in O-DU (Category A) or O-RU (Category B). More details of Open FH are presented in Sections 2 and 4;
6. Eventually, O-Cloud is a cloud computing platform hosting O-RAN and operations, administration, and maintenance (OAM) functions as well as third party software.

3.2. Software Development for Open RAN

O-RAN Software Community (O-RAN SC)—which is placed close to the O-RAN Alliance—was established in 2019 under Linux Foundation and its goal is to deliver open-source RAN software. The software developed within the project is distributed via Standard Apache 2 license of open source software contributions. The main tasks of O-RAN SC encompass development, maintaining documentations, testing, integration and specification alignment. The software is released in versions (see Table 2) and includes the outcomes of projects related to the reference architecture. The software is compliant with the O-RAN specification or xApps. Currently, release E of the software is under development, and its new functionalities include xAPP RAN Control, RAN Slicing, and new use cases, among others.

Table 2. O-RAN SC releases (according to-O-RAN SC Wiki [30]).

Release Name	Current Phase	Next Phase	Release Date
E Release	Development	Test and Deploy	Planned for 12.2021
D Release	Current Release	End of Life	30 June 2021
Cherry	End of Life	End of Life	12 December 2020
Bronze	End of Life	End of Life	21 June 2020
Amber	End of Life	End of Life	30 November 2019

Regarding software development, in 2020, the Open Networking Foundation (ONF) formed the Software Defined Radio Access Network (SD-RAN) project, aimed at developing open source SW platforms for multi-vendor 4G/5G RAN solutions. The initial focus of the project was on O-RAN nRT-RIC functionality, referred to as µONOS-RIC [35]. In October 2021, ONF tougher with Deutsche Telekom launched an SD-RAN field trial based on disaggregated Open RAN and ONF-based RIC [36]. Before the O-RAN Alliance was established, at least two other groups were active in the area of network openness and disaggregation, namely, Telecom Infra Project (TIP) and Small Cell Forum. TIP was founded in 2016 and currently has hundreds of members (service providers, system integrators, and others). Its goal is to test, develop, and deploy standards-based solutions related to open and disaggregated RAN [31]. TIP does not develop its own specifications; however, it takes part in both lab and field interfaces interoperability and end-to-end testing. Within TIP, an OpenRAN project group was established to support productization of solutions from 2G to 5G RAT [32]. The second organization—Cell Forum—releases specifications of Functional Application Platform Interface (FAPI/nFAPI) related to Open RAN in small cells multi-vendor deployments, which enable network densification. nFAPI defines its own open functional split between DU and RU (called S-DU and S-CU).

Next to the standardization oriented organizations and the others related to technical issues, there is an Open RAN Policy Coalition established in USA that focuses on policy moving towards adoption of Open RAN and interoperable solutions [37]. Conversely, in January 2021, Deutsche Telekom, Orange, Telefonica, Vodafone Group signed a memorandum of understanding (MoU) on the implementation of open RAN-based networks in Europe [45]. Following this initiative, in June 2021, the MoU published a document defining technical priorities for Open RAN [46].

4. Open Xhaul Transport Network—Requirements and Solutions

The support for a new range of 5G mobile services, in addition to conventional 4G services, poses high and diversified requirements on the transport network infrastructure connecting the Open RAN components. Enhanced Mobile Broadband (eMBB) services have high capacity demands, Ultra Reliable Low Latency Communications (URLLC) applications are sensitive to latencies and require increased reliability, whereas massive Machine Type Communications (mMTC) services involve a huge number of devices which should be managed efficiently in the network. At the same time, the introduction of new radio access technologies in 5G, the use of higher frequency bands, and the densification of installed antennas and access points, requires scalable, flexible, and cost-effective transport solutions. The disaggregation and distributed placement of 5G RAN functions (discussed in Section 3), depending on operator's deployment needs and in accordance with particular service requirements, results in multiple user, control, synchronization, and management data flows that differ in terms of bandwidth and latency requirements. It is expected that these flows related to the fronthaul (FH, between O-RU and O-DU), midhaul (MH, between O-DU and O-CU), and backhaul (BH, between O-CU and CN) segments of the network will be accommodated using a convergent and flexible Open Xhaul transport network, namely, it could be carried in the same portion of the physical transport infrastructure [40].

To meet the above mentioned requirements, in particular, to assure convergence of services with low-cost connectivity, the adaptation of a well-known packet-based Ethernet technology has been proposed for the underlying Open Xhaul transport network [40]. Ethernet enables statistical multiplexing of data flows and, hence, increased utilization of link bandwidth. In addition, the use of Ethernet in Xhaul allows to support other services not related to 5G, such as legacy 2G/3G/4G wireless services, enterprise services, residential broadband services, and data centre interconnections. The multi-service support is one of the capabilities identified by ITU-T in [47] that is expected from the transport infrastructure.

The convergence of services with provisioning of adequate quality of service (QoS) guarantees in the Ethernet-based Open Xhaul transport network is achieved among others with the aim of the following technologies:

1. Enhanced CPRI (eCPRI) protocol [8] that supports the transport of radio data with different functional splits options, including Options 7.2x and 2 considered, respectively, for fronthaul and midhaul in O-RAN;
2. Radio over Ethernet (RoE) protocol specified in the IEEE P1914.3 standard [48], which defines the encapsulation and mapping of CPRI data transmitted between RRH and BBU in legacy 4G services (Option 8 split) in a form of Ethernet frames;
3. Time-sensitive network (TSN) features proposed for a fronthaul network in the IEEE 802.1CM standard [49] that enable prioritized transmission of latency-sensitive Ethernet frames.

The specification of Open Xhaul [40] is also consistent with the next generation fronthaul interface (NGFI) architecture, presented in the IEEE P1914.1 standard [48], which defines a packet-based fronthaul transport network connecting distributed RUs, DUs, and CUs. The frame loss ratio and latency requirements for particular classes of services (CoS) are assumed to be in accordance with the eCPRI Transport Requirements V1.2. The estimation of bandwidth demands for dimensioning of the transport network that takes into account a statistical multiplexing gain from packet-based transmission has been discussed in the technical specification concerning Xhaul Transport Requirements [40].

The end-to-end Open Xhaul transport covers the access network—at which the cell site is located— the aggregation network, and core network (see Figure 6). Within these network segments, it is assumed that the packet switches are connected by means of high capacity and low delay point-to-point Ethernet links, which are realized using either fibre optic, wireless, or cable technologies. Below, we briefly discuss the main technologies considered for the underlying physical network.

1. Wavelength division multiplexing (WDM) allows to significantly increase the capacity of an optical fibre due to multiplexing of signals transmitted on different wavelengths using either passive or active WDM equipment installed at the link ends [50]. Passive WDM reduces about 4–6 times the cost of active WDM since it does not use signal amplification and dispersion compensation components as well as it involves a less expensive WDM equipment. In addition, its installation at a cell site is simplified due to reduced power supply requirements. However, passive WDM has some drawbacks related to limited management, fault detection, configuration, and maintenance capabilities. A trade-off solution for a large-scale deployment of 5G fronthaul networks connecting a huge number of sites is a semi-active WDM network, which uses a passive WDM equipment at the remote (cell) side and active WDM at the hub site. This solution has the advantages of both passive and active WDM, whereas it mitigates their drawbacks such as the cost of active WDM equipment and limited protection and management capabilities of passive WDM. Currently, depending on the spectral grids used, up to 6/12-channel (in MWDM) and 40-channel (in DWDM) systems are considered for O-RAN [40] with a transmission distance of 10–20 km (passive solutions) and transmission rates of 10–25 Gbps in access and 100 Gbps (per wavelength) in aggregation/core networks. The demand for fibre resources can be further reduced by means of bi-directional transceivers and the allocation of different wavelengths in opposite directions, which enables the transmission in a single optical fibre.
2. Passive optical networks (PONs) are point-to-multipoint access networks, widely used in "fibre-to-the x" (FTTX) applications, which make use of the optical fibre as a transmission media. PONs are based on a central optical line termination (OLT) equipment connected with remote optical network units (ONUs), which are installed at the client side. The access of PON clients to the transmission resources is achieved either using time-division multiplexing (TDM) techniques and/or by means of passive WDM technologies. The application of PONs for transport of 5G Xhaul traffic has been broadly discussed in the literature [50,51], and is considered in the O-RAN specification [40]. Since PONs are multi-service systems, they allow to carry mobile traffic (e.g., backhaul) along with non-mobile traffic (e.g., fixed access services). In fronthaul use cases, special attention should be placed on a latency vs. bandwidth efficiency issue arising in TDM-PON solutions that relay on a dynamic bandwidth assignment (DBA) mechanism. As WDM-PONs realize dedicated point-to-point links, they have advantageous features, such as high capacity, low latency, and operational simplicity [51], which make them a suitable solution for Xhaul networks.
3. Microwave (MW) and mmwave (mmW) radio transport technologies have been the primary solution for provisioning backhaul connectivity in previous generations of mobile networks, providing transmission capacities of a few Gbps in MW systems and up to 10 Gbps in E-band (70/80 GHz) systems, with transmission distances of up to 3–4 km in point-to-point and line-of-sight (LoS) configurations [52]. To cope with high bandwidth demands of centralized 5G RANs, radio transport technologies are evolving in several directions. Among them, we can discern [40]:
    ○ exploration of higher frequency bands, such as W-band (100 GHz) and D-band (150 GHz) enabling up to 100 Gbps radio links;
    ○ expansion of capacity in traditional (lower) frequency bands;
    ○ increasing spectral efficiency by application of higher order modulation formats and by utilization of LoS MIMO systems;
    ○ introduction of new signal multiplexing mechanisms such as orbital angular momentum;
    ○ aggregation of bands and carriers;

- ○ introduction of higher class antennas enabling reuse of channels in a given geographical area by reducing the minimum angle between two links using the same channel.

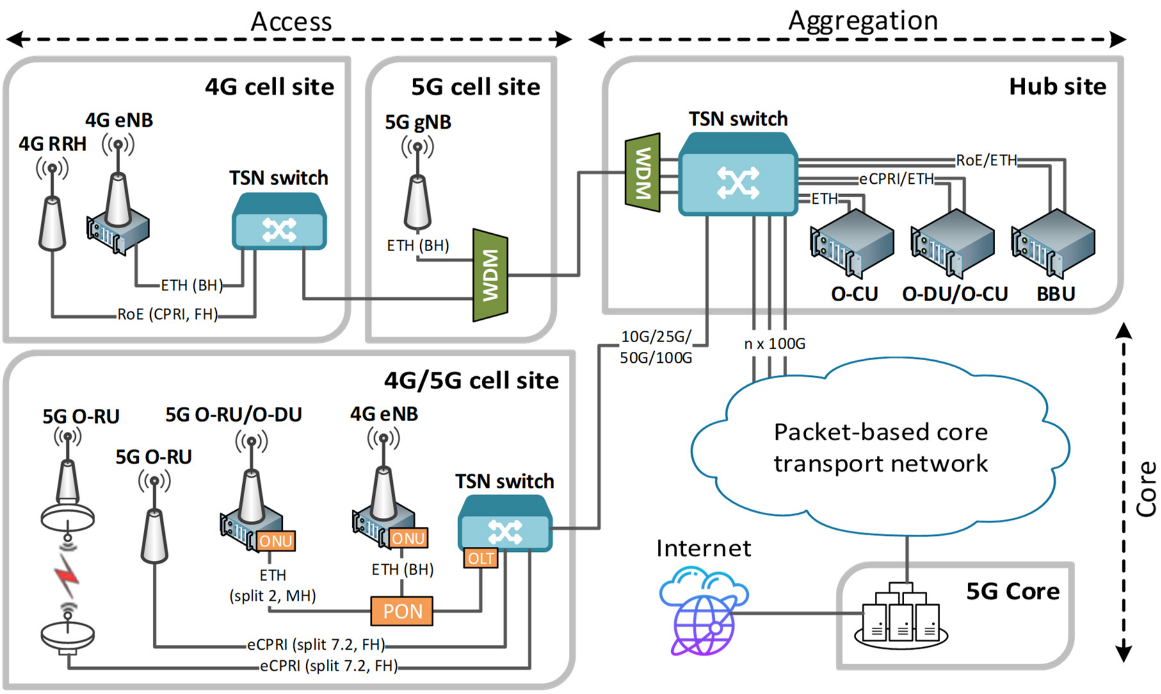

Figure 6. Example of Open Xhaul transport network.

5. Market Expectations, Requirements and Open RAN Benefits

Open RAN is an awaited technology described by industry as a solution which brings a set of benefits from both operators and end-user perspectives. It is a specific RAN-related framework enhancing commercial-proofed 3GPP solutions by introducing new interfaces and nodes from a scratch. From a mobile network operator (MNO) perspective, there are certain requirements towards Open RAN which need to be specified, implemented, and deployed to meet the MNO expectations. In the latest published technical specification [53] signed by selected European operators, there is a detailed prepared guidance for Open RAN indicated area and use cases which O-RAN should cover. The authors has stated that it is expected that from 2022 a wide Open RAN network roll-out should start. It is a strong expectation that Open RAN products will achieve a proper quality and security level as well as they will support standalone (SA) and non-standalone (NSA) modes, both 4G and 5G RAT also for legacy bands. The functionalities related to intelligent and programmable operation are perceived with minor priority, i.e., are expected to be deployed later. In [54], the operators under the open RAN MoU have defined in detail some priority levels (must have, nice to have) and priority types (how many operators have the corresponding priority) for Open RAN scenarios, infrastructure requirement, Open FH, RIC, RAN features, etc. Finally, an Open RAN architecture together with a wide radio access network decomposition may introduce many benefits, which will finally be evaluated after commercial deployment. In Table 3, a subjective extract of features perceived as benefits, gains, and game changers are presented based on common available resources.

Table 3. Review of expected Open RAN benefits.

Overall (Potential) Benefits	Source
Multivendor ecosystem	[25,37,55,56]
Reduce cost	[25,55–57]
Interoperability	[25,37,41,57]
Open Interfaces	[25,41,56,57]
Hardware and Software Disaggregation	[25,37,41,55,56]
Open Software	[25,41,56]
Open Hardware (e.g., x86, ARM CPUs)	[25,41,56]
COTS Hardware	[25,41,55]
Programmable interfaces for SMO	[25]
Support compute-heavy scenarios on COTS HW	[25]
Native AI/ML support	[25,41,43,44,56]
Support Virtualization of RAN	[41,55–57]
Additional types of network deployments	[45,57]
Operational simplification	[37,55]
More flexible scaling	[25,37,45,56]
3rd RAN programmability	[25,44]
Improving user performance	[43,44]
Time to deploy	[55]
Enabling or speed up innovation	[25,43,45,56,57]
Gain for specialized company to deliver products	[57]
Consolidation of various radio generation	[55]
More energy efficient	[55]
Uses standardized 19” racks	[25]
Security enhanced	[55]

6. Research Activities

Parallel to Open RAN standardization works, academic and other research and development (R&D) centres are conducting research mainly based on the O-RAN Alliance reference architecture proposed that is expected to be the first commercial deployed solution in the field. In this section, an overview of the latest addressed research topics is presented. In Table 4, the research topic are assigned to proposed features area groups together with indication whether those research activities are related to theoretical studies or laboratory/PoC (proof-of-concept) experiments.

The authors of [58] focus on exploiting the capabilities of Non-RT and RT RIC in optimization of 5G FH and BH services in a dynamic optical transport network. The solution proposed consists of an off-line optimization scheme based on integer linear programming that is run at the Non-RT RIC and a machine learning scheme that is executed at the RT RIC. In [59], the authors present a novel machine learning solution to resource orchestration in energy constrained vRANs that addresses a challenging problem of predicting the power consumption and performance of software stack processing. The authors of [60] propose a reinforcement learning-based scheme for improving overall transmission throughput and minimizing the number of handovers (HOs). In [61], the authors perform a simulation study based on a reinforcement learning technique applied in dynamic functional split selection (among DUs and CU) for minimization of energy consumption. The author of [22] proposes a method for the placement of CNF in different network segments, i.e., local, regional, and core, for scalable service provisioning. In [62], the authors develop a machine learning workflow based on the O-RAN specification and open-source software implementation (O-RAN SC, Acumos, ONAP). The authors of [63] and [64] discuss a possible path for future 5G network slicing integration with multi-access edge computing (MEC). In [65], a new approach based on automatic neighbour relation (ANR) is proposed for minimization of handover failures in an O-RAN based on open interfaces. The authors of [66] make use of a convolutional neural network and propose a physical layer authentication method in 5G Open RAN based on a specific emitter detection (RF fingerprint), which is evaluated on the Software Defined Radio (SDR) platform. In [20], the authors review the FH compression techniques proposed in 3GPP and O-RAN and assess the impact of capacity reduction in fronthaul on air interface performance. The authors of [67] and [68] propose a reference design of the M-Plane for 5G open FH and a network management system for 5G Open RAN according to O-RAN Alliance specifications. In [69], the authors present the O-RAN Alliance RAN architecture together with some practical use cases utilizing the AI/ML techniques. The authors of [70] focus on intelligent connection management with the aim to optimize user load balancing using deep reinforcement learning and graph neural networks techniques. In [71], the authors focus on orchestrated slicing of network resources in 5G RAN and core network. Finally, the authors of [72] propose a network outage-oriented model of virtualized O-RAN nodes in an O-cloud deployment.

Table 4. Open RAN features area covered by research activity.

Features Area	Theoretical Study	Lab/PoC
ML	[58,60,61,65,66,69,70]	[59,62]
Energy-efficiency	[61]	[59]
RRM	[60,65]	[59]
vRAN	[61]	[59]
Traffic steering	[60,70]	
Throughput	[20,60]	
Deployment	[22,63,67,68,72]	
Security		[66]

7. Conclusions—Challenges and Open Issues

Open RAN may be treated as a wide list of features and use cases which have to be first specified and then implemented within multi-vendor networks to deliver expected value. Thus, unpredictability of how the process of real commercial deployment will look in next few years is recognized. Conversely, there are up-to-date market predications showing that Open RAN is going to bring measurable revenues in the global RAN market. According to report [73], total cumulative Open RAN revenues are projected to USD 10–15 B between 2020 and 2025 and Open RAN revenues get 10% percent of RAN market by 2025. Moreover, according to [74], Open RAN solutions are predicted to grow to USD 11.2 bn in 2026. However, most of the revenue is expected to go to incumbent vendors instead of new challengers and multi-vendor deployments. The authors of [75] predict that around 2027–2028, Open RAN will first time outrun the legacy RAN market as is perceived as quickly expanding. In [76], it is estimated that O-RAN market will attain overall (hardware, software, services) revenue of USD 21.371 B in 2028 by growing at a CAGR 83.1% (in the forecast period 2020–2028). Additionally, factors which may bring Open RAN closer to market success is the support of some countries in developing cutting-edge domestic technologies, positive impact of vertical market deployment, and new use cases. Developing of mature Open RAN solutions will take several years. According to the proposed use cases [77] and market expectations [46], future works will cover QoE, performance and energy efficiency aspects in first phase. Then, in the second phase, it is expected that Open RAN will support novel scenarios, namely, Radio Resource Allocation for Unmanned Aircraft Vehicle Applications, RAN Slice Service Level Agreement Assurance, Machine Learning and contend based radio resource optimization and mobility.

To achieve the pointed out technical objectives and benefits, the recognized challenges and open issues need to be clarified and solved. First, it is not clear on the scale of future swapping legacy networks by Open RAN based solutions. Possible scenarios encompass alternative update legacy eNB/gNB to support O-RAN or new cells deploying next to those already run in field. It is not easy for greenfield suppliers to implement all advances features which are currently developed by brownfield vendors; thus, it is not sure that coverage or capacity of the cells will be kept in an easy way in case of swapping to Open RAN. Open RAN solutions are strongly 4G and 5G oriented—which may lead to keep at least to separate platforms to enable connections also with legacy networks (i.e., 2G, 3G)—such deployment is not a desirable approach from operational, maintenance and cost reduction perspectives. Certainly, before introducing a new technology, mobile network operators need to test and verify it in labs and wide-scale trials. In case of a multi-vendor RAN stack, it is crucial to conduct interoperability tests based on adopted evaluation criteria and then run the process dedicated to integrating and maintaining networks, taking also into account risk ownership. As O-RAN allows to implement ML-assisted algorithms for radio resource management, another set of tests needs to be prepared to be confident that models are trained in a proper way and that selected KPI goals are achieved. In a multi-player environment, which is established by Open RAN, security concerns need to be evaluated and addressed. Finally, it should be said that there are high expectation towards Open RAN. Nonetheless, despite of a wide set of identified benefits, currently, there is no established uniform approach to deployment of Open RAN across the market, which is mainly oriented to evolution towards well-known, mature and proved 5G/NR solutions.

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