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Open Radio Access Networks in Multi-Vendor Environments: A Survey of Interoperability Solutions and Best Practices

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Abstract: The quick advancement of Open Radio Access Networks (O-RAN) has largely transformed the deployment and management of 5G networks by adopting open, flexible, and interoperable structures. This paper delves into O-RAN, covering its essential features, design concepts, and deployment obstacles. It also outlines the architecture of O-RAN while pointing at openness and multi-vendor integration as the main principles. The paper also discusses the main challenges faced in O-RAN implementation, including interoperability, latency, scalability, and network optimization. Additionally, optimization strategies for improving system performance and addressing these challenges are presented, with a particular focus on the role of cloud-based data migration in O-RAN. The study also reviews security measures necessary to protect an integrity and confidentiality of data in O-RAN deployments. Consequently, the results of this study contribute to the extensive body of research on O-RAN and its practical applications, which will aid in the development and deployment of next-generation communication networks in the future.

Keywords: *Open Radio Access Networks (O-RAN), Radio Access Network (RAN), Multi-vendor Environment, Network Function Virtualization (NFV).*

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I. INTRODUCTION

The evolution of mobile cellular networks has been going on nonstop since the 1970s. There have been many published and released standards for such systems throughout the years. The 1980s witnessed a shift from analog to digital technology then the third generation (3G), at the end part of the 1990s, introduced packet-switched communication. Despite advancements, all legacy generations up to 5G shared common characteristics: it primarily targeted the consumer market, aimed to deliver higher throughput, leveraged wider bandwidths and new frequency bands, and was predominantly used for voice communication and internet connectivity. However, the advent of 5G brought about a paradigm shift, introducing new requirements and objectives to address emerging technological and industrial needs[1].

A key innovation within 5G and a foundational element for future 6G systems is the concept of Open RAN [2]. Unlike traditional RANs—built as monolithic, proprietary solutions by single vendors—Open RAN promotes disaggregation and virtualization of RAN components. This approach enables Mobile Network Operators (MNOs) to utilize standardized open interfaces to interconnect diverse components, fostering flexibility and innovation. Open RAN provides MNOs with two primary advantages: the ability to adopt innovative products from a diverse vendor ecosystem, thereby mitigating vendor lock-in, and the capacity to optimize network performance by leveraging measurement data from disaggregated RAN nodes for joint optimization and dynamic configuration adjustments[3][4].

Despite its advantages, Open RAN faces critical challenges, particularly in integration and interoperability. The OpenRAN system testing requires a lot of teamwork and effort. Meta said that in order to realize Open RAN's full potential, a standardized development environment, optimization metrics, and testing and validation procedures are necessary[5]. In this regard, the Open RAN standard organizations such as TIP and O-RAN Alliance are crucial in assisting with the mitigation of this difficulty. As previously said, E2E infrastructure vendors have established testing procedures, testing centers, WGs, and plugfests to address the fact that no one vendor can excel in every area. To fulfill the needs of their novel use cases, the network operators of the future will want a more varied ecosystem of suppliers [6].

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A. Motivation and Contributions of the Study

This study is motivated by the potential of Open RAN to transform wireless networks by enabling vendor-neutral, interoperable, and flexible architectures. Unlike traditional proprietary RAN systems, Open RAN fosters innovation and reduces costs through disaggregation and open interfaces. However, achieving seamless integration in multi-vendor environments poses challenges, driving the need for robust solutions and best practices to unlock its full potential for 5G and beyond. The key contributions include:

- Provides an in-depth exploration of O-RAN architecture, highlighting its modular and open-source approach for 5G networks.
- Identifies key technical and operational challenges in implementing O-RAN, such as interoperability, latency, and scalability.
- Discusses potential strategies to address the identified challenges, emphasizing innovative approaches and best practices.
- Examines optimization techniques to improve the performance and efficiency of O-RAN systems.
- Reviews security measures specific to cloud-based O-RAN data migration, ensuring system resilience against cyber threats.

B. Organization of the Study

The paper is structured as follows: Section I introduces the study. Section II covers O-RAN architecture. Section III discusses challenges. Section IV explores solutions. Section V examines optimization. Section VI reviews security. Future directions are discussed at the end of Section VII.

II. OVERVIEW OF OPEN RADIO ACCESS NETWORKS (O-RAN)

Figure 1 shows that the RAN is the most important component of a wireless communication system because it establishes a connection between the user equipment (UE) and the core network. One of RAN's primary functions is to oversee the allocation of radio resources [7]. Figure 1 shows the two main units of a typical RAN: the Radio Unit (RU) and the Processing Unit (PU).

- ❖ Radio Unit: The RU is in charge of both sending and receiving signals; it has transceiver antennas.

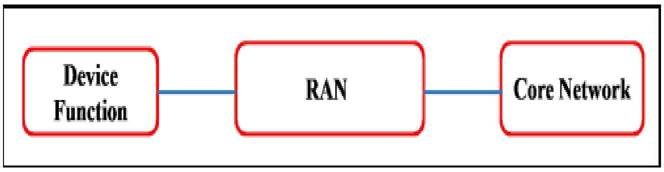

Fig. 1.An illustration of basic RAN.

- ❖ Processing Unit: The RAN processing unit is in charge of radio management, resource utilization and sharing, and a few more tasks, including pre-coding and encryption. Increased network adaptability is a result of each unit's ability to carry out its designated tasks[8]. The fundamental operation of these components is best described as:

A. Radio Functions at RU

Transceiver antennae and specialized radio hardware are housed in RU and are responsible for physical layer functions like modulation, digital-to-analog conversion, filtering, and so on. Signal amplification and regeneration are additional functions it performs [9].

B. Baseband Processing Function

This section handles actions at the higher layers, such as controlling radio links and medium access, which include carrier aggregation, soft combining, fast radio scheduling, COMP, and more [10]. Furthermore, it is in charge of choosing the MIMO scheme, beam creation, and antennas [11].

C. Radio Control Functions

The goal of this section is to manage the sharing of system resources and the workload between various applications and parts of the system.

With its virtualization and radio resource management capabilities, it is a crucial RAN unit. In essence, it regulates the total RAN performance using radio control techniques. [12].

D. Packet Switching Functions

This layer is essential in virtualization, just like the radio control function. In particular, it manages two connections, encrypts data, handles several paths, and executes packet processing activities [13].

Figure 2 displays the historical development of RAN. At first, there weren't many users, and the data rate needed was minimal. A relatively modest number of BSs were adequate to meet this demand because certain data-restricted cellular services were available, such as voice calls, text messaging, etc. Conventional RANs, as seen in Figure 2(a), have the RU and PU combined[14]. There was more than enough BS to cover the enormous area. Adopting the frequency reuse paradigm meant that interference avoidance computation was minimal at best. In subsequent iterations, as illustrated in Figure 2(b), RU and DU were partitioned. Traditional placement of RUs involved mounting them high up, typically on top of a tower, to support expansive areas, while DUs were housed in a room under the BS. To link the two devices, fibre optic cable was used[15]. Additionally, the data-hungry apps' introduction and the subsequent growth in the number of UEs drove up the requirement for extra densification. However, an enormous demand for data rates could not be met by densification alone[16]. Therefore, the framework is now at a state where frequency reuse-1 is possible.

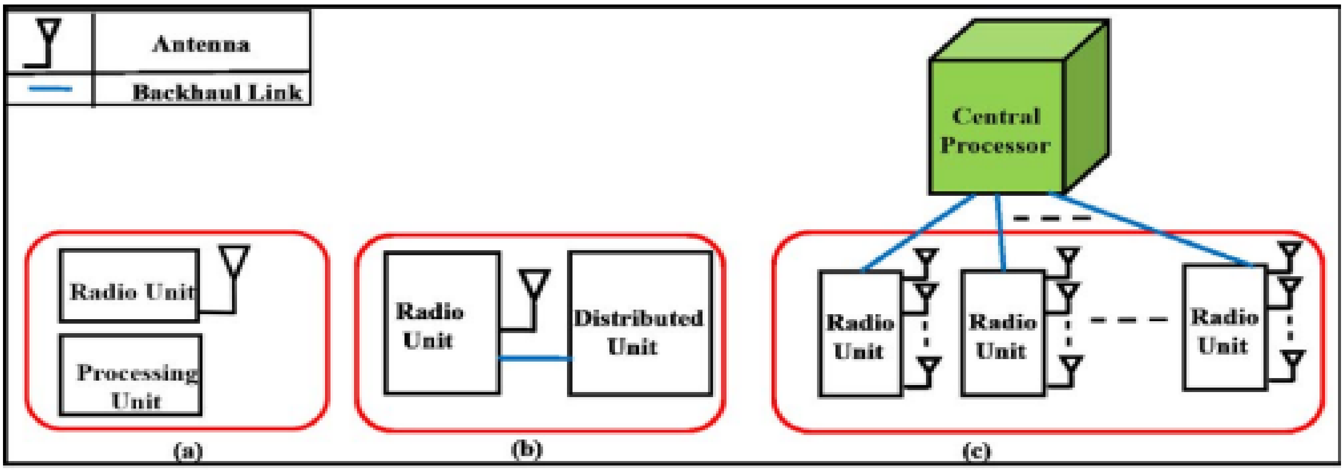

Fig. 2.Different Generations of RAN Condition.

Figure 2(c) shows that demand for the linked framework has also grown as millimeter wave (mm-wave) demand has started to rise. Figure 2(c) depicts a CRAN, where a single CP, technically termed a cloud processor, is used to integrate all of the PUs of the BSs [17][18].

➢ *Key Advancement in RAN*

The following are examples of significant improvements made to the previous/existing RAN:

- BS centric to UE centric: The dominated-selected BS would be associated with a UE in traditional RAN based on the received signal strengths from other BSs. One problem with this BS selection method is that the interference power that cell edge users experience is often the same as the power that serving BS users experience[19].
- Mm-Wave and beamforming: The ever-increasing data rate requirement could not be adequately met by BS densification alone, as was previously discussed. Moreover, high data rates require additional bandwidth. The greatest option would be to use the mm-wave spectrum, which is quite vacant [20][21].
- Single point to multi-point transmission: Each user was connected using a BS-centric strategy in traditional networks. As a result, there was significant inter-cell interference for the edge user. The CRAN approach has been superseded by the UE-centric strategy, which uses several BSs to reduce interference from nearby cells [22]. Consequently, the CP controls a group of BSs or radio heads that service each UE.
- Coordinated Transmission: A number of frequency bands were formerly employed to orthogonalize the nearby cell users. This led to a particularly inefficient method of using available resources. CRAN takes advantage of numerous transmitting points to provide service to every user. Coordinated multipoint transmission describes this type of transmission[23]. CoMP algorithms are executed within CP to facilitate coordination among the BSs within a cluster. Notable CoMP approaches include coordinated beamforming, distributed transmission, and joint transmission [24][25].

➢ *Advantages of O-RAN*

Through a number of innovations and the separation of hardware and software, O-RAN develops a distinctive architecture and offers a number of advantages (like network slicing and reduced latency) [26]. Aside from making network automation easier, O-RAN offers a number of advantages, like:

- Agility: The network is ideal for current, previous, and future generations because of the unified software-enabled design.
- Deployment Flexibility: The network becomes adaptable for installation, upgrades, and extensions through disaggregation and software association.
- Real-time responsiveness: Software-driven service-specific networks, such as O-RAN, prioritize mission-critical, real-time services above less important ones based on their intended use[27].
- Operating Cost Reduction: The maintenance cost might be cut by as much as 80% using O-RAN's plug-and-play functionality in conjunction with modern learning approaches. Operators can consolidate the connection improvements from different generations by making software the core of the network. This will result in millions of dollars in savings for the operators[28].

III. CHALLENGES IN MULTI-VENDOR O-RAN ENVIRONMENTS

Achieving flawless interoperability among components from multiple suppliers is the primary problem of constructing a multi-vendor O-RAN network. There are still a number of operational and technological challenges that must be resolved, even though the O-RAN Alliance has established open interfaces and protocols to enable this interoperability.

A. Standardization and Interface Compatibility

The absence of completely standardized interfaces across vendors is one of the biggest obstacles in the multi-vendor O-RAN ecosystem. There has been a lot of effort in developing open interfaces among RAN components thanks to the O-RAN Alliance, although various companies may apply their own interpretations of these standards or add proprietary modifications [29]. This can present problems

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with compatibility when integrating components from different suppliers, as small variations in implementation can lead to performance concerns or even system failures.

Achieving interoperability requires that all vendors follow the O-RAN requirements to the letter. Nonetheless, suppliers might be motivated to include exclusive features that set their goods apart from rivals[30].

B. Performance Optimization

Maintaining uniform performance across various components in an O-RAN network supported by several vendors is no easy feat. Because of potential differences in performance between vendors' hardware and software, it can be challenging to optimise the network such that all components provide the same level of service [31]. Many variables, including the manufacturer of the radio unit and the distribution unit it is connected with, may affect the latency, throughput, and stability of a network [32].

The optimisation of speed is already a challenging task before adding sophisticated technologies like AI and ML to the RAN.

C. Security Concerns

There are additional security concerns due to the openness of the O-RAN design. The vendor in a classic single-vendor RAN would have been mostly responsible for security, as it would have been able to guarantee that all components were built and tested to fulfill particular security standards. It becomes more challenging to guarantee that all components in a multi-vendor O-RAN satisfy the required security standards because the duty for security is divided across numerous vendors [33].

Furthermore, malevolent actors may execute cyberattacks by taking advantage of the open interfaces defined by O-RAN[34]. For instance, an attacker can easily exploit the deficient security in the hardware and software of a manufacturer to infiltrate the entire network.

D. Network Management and Orchestration

It is more difficult to manage and orchestrate an O-RAN network that uses more than one vendor than a more conventional, single-vendor network. Equipment from many manufacturers, each with its own configuration and administration tools, must be managed and monitored by operators in a multi-vendor environment [35]. This may lead to operational complexity and, therefore, require the network operators to undergo special training.

Advanced network management systems are also necessary to make sure that every component is correctly organized to function as a whole [36]. These systems must be able to handle different versions of the software, settings and performance parameters when operating in a multiple vendors environment, among other challenges [37].

E. Collaboration and Future Directions

The interworking challenges of the multi-vendor O-RAN network require a collective approach from vendors, network operators, and Standards organizations. It is imperative that vendors collaborate to guarantee that their products are completely compatible with one another's components and that comply rigidly to the O-RAN requirements [38]. To effectively appreciate the complexities of a network that has adopted the use of several vendors, the operators need to secure the correct tools and education.

In addition, the 3GPP and the O-RAN Alliance's next standardization organizations will also be charged with the vital responsibility of defining and managing these open standards through which equipment can interconnect across various vendors [39].

The O-RAN is a revolutionary model in the telecom sector; it encourages multi-supplier structures that have the prospect of offering more solutions, cheap solutions and a more malleable solution.

To fully utilize O-RAN, however, the difficulties of integrating components from various manufacturers must be overcome[40]. Addressing standardized processes, performance improvement, security, and networks should remain in constant interest and be managed collectively. If vendors, operators, and standardization organizations come together, they can remove these barriers to achieve the full potential of 5G O-RAN networks[41].

IV. INTEROPERABILITY SOLUTIONS AND BEST PRACTICES FOR O-RAN

Interoperability of O-RAN is accomplished through openness, openness of those rational interfaces, and community standards that can be adapted into a modular software system that allows integration of components from different vendors [42]. Open RAN promotes collaboration with several suppliers because it separates software and hardware, which makes it easier to change and does not rely on proprietary systems.

A. Standardization Efforts by O-RAN Alliance

With the goal of improving RAN and related technologies for future generations, the O-RAN Alliance was established in 2018 [43]. A scalable and agile RAN is envisioned by an openness of O-RAN. Furthermore, open interfaces permit a multi-vendor, more competitive, and lively ecosystem, which in turn allows smaller vendors and operators to implement or personalize their own solutions[44]. Intelligence is also crucial to the O-RAN Alliance's mission. Automating operational network operations and reducing OPEX requires networks to be self-driving through the use of learning technologies[45]. They have also included use cases that demonstrate how the O-RAN design could be beneficial. Their guiding beliefs comprise:

- Taking the lead in guiding the industry towards smart RAN powered by big data and AI, RAN virtualization, and open, interoperable interfaces.

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- Reducing reliance on proprietary hardware and increasing use of COTS and merchant silicon [46].
- Outlining APIs and interfaces, promoting standards for their adoption where necessary, and, when suitable, investigating open source [47].

B. Open Interfaces and APIs: Enabling Interoperability Through Key Specifications and Protocols.

- Open RAN architecture emphasizes open interfaces and protocols, enabling seamless interoperability between hardware and software components from different vendors[48].
- This ensures that network elements, such as radios and RAN applications, from diverse suppliers can integrate effectively.

➢ *Flexibility and Vendor Neutrality:*

- The focus on vendor-neutral hardware and software ensures flexibility in choosing suppliers and promotes interoperability through standardized, open interfaces[32].
- The use of community-developed standards enables CSPs to mix and match components, reducing vendor lock-in[49].

➢ *Support for Cloud-Native Solutions:*

- Open interfaces facilitate the adoption of cloud-native approaches in RAN deployments, particularly crucial for 5G networks[50].
- These interfaces enable better scalability, virtualization, and cost efficiency[51].

➢ *rApps and SMO Platform:*

- Significant progress has been made in defining how rApps (radio applications) interact via the SMO (Service Management and Orchestration) platform using R1 interfaces.
- The R1 interface enables rApps to access and share data and services securely, promoting a collaborative ecosystem.

➢ *Advancing R1 Specifications:*

- The evolving R1 specifications will simplify rApp development further by introducing services such as AI/ML model management, RAN KPI calculation, and policy engine support[52].
- These enhancements will encourage rapid development and deployment of portable rApps by a global community.

C. Cellular Network Testing Standards and Research

➢ *Cellular Network Testing Standards*

Cellular Network Testing Standards: The 3GPP, the O-RAN Alliance, and the ETSI are among the standardization organizations that are trying to provide standards for testing Next-G cellular networks.

- 3GPP: In addition to outlining functional, performance, and compliance testing, the 3GPP standards also provide RF transmission masks, signaling criteria, and anticipated performance statistics. Manufacturers of networks and devices carry out these processes with the use of specialist testing tools and UEs. By following these steps, third parties like the O-RANAlliance may extend the 3GPP protocols with their own features and services.
- O-RAN Alliance: One group working on open cellular network standards is the O-RAN Alliance. Combining forces with a xRAN Forum, it is the product of the C-RAN Alliance. The goal of this project is to make next-generation RANs more open, intelligent, virtualized, and interoperable by expanding existing RAN standards [4].

✓ **ETSI:** A document pertaining to AI in system testing and AI model testing was released by ETSI [7]. It debuted in their 5G PoC and is now accessible to the public. All the way from AI model validation to network optimization, this specifies a general framework for testing AI models and systems and is part of ETSI's general Autonomic Network Architecture program[53].

➢ *RAN Testing Research, Methods, and Technologies*

The 4G and 5G wireless protocols through the use of novel and unconventional testing methods in regulated laboratory settings. For instance, software-defined radios (SDRs) have been used to conduct eavesdropping, jamming, spoofing, and other systematic assaults on network modules or interfaces, which have revealed security weaknesses in 4G and 5G networks. Demonstrating particular wireless protocol vulnerabilities, putting solutions in place, and assessing their effectiveness are made easier by SDR hardware and open-source software [54]. Investigations of a commercial 4G RAN that supports mission-critical applications have shown indications of systematic radio assaults [55]. The software-implemented and SDR-sent targeted radio interference degrades system performance. Additionally, it suggests ML methods for processing the network's performance measurement counters and KPIs in order to identify and categorize assaults[56].

V. LITERATURE REVIEW

Provide an overview of the literature in this section that focuses on Open RAN in multi-vendor settings with frameworks and developments. Also, provide summary in Table I:

Krasniqi, Hajrizi and Qehaja (2023) take a look at the major obstacles and takeaways from actual installations of private 5G Open RAN networks in both academic and commercial settings. Up until recently, the RAN system was kept under wraps and considered private. If it weren't for the mobile operators' efforts to redefine their needs for the network architecture and foster a more varied ecosystem of vendors, RAN would likely remain closed and proprietary for the foreseeable future[57].

Cao et al. (2022) suggest using deep reinforcement learning (DRL) to implement a smart user access management strategy. A federated DRL-based system is suggested to enhance the performance of distributed DQNs taught by UEs. This scheme would enable a global model server to change the DQN parameters through the RIC. An upper confidence bound (UCB) technique for selecting the best set of UEs and a dueling structure for decomposing the DQN parameters are

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created so that a global DQN can be predictively trained with reasonable signaling overheads. EachUE is able to maximize long-term throughput and minimize frequent handovers under the suggested design[58].

Mehran, Turyagyenda and Kaleshi (2024) presents the recent endeavors from Smart RAN Open Network Interoperability Centre (SONIC) Labs to integrate and assess the interoperability and functionality of O-RAN-based multi-vendor Open RAN solutions on SONIC Labs commercially-neutral, multi-tenancy open network testbed. The viability of creating multi-vendor Open RANs is assessed according to the O-RAN-compliant Interoperability Testing (IOT) and End-to-End (E2E) test suite. The test campaigns confirm the E2E integration and successful IOT between pairs of Open RAN components for 22 multi-vendor Open RANs[59].

Marinova and Leon-Garcia (2024) the purpose of this paper is to lay out some ground rules for AI/ML frameworks and approaches that work well in an O-RAN setting. It also takes into account the kinds of applications (xApps and rApps) that can be built to run the network through the RICs programmatically and autonomously, which is useful for very demanding service types like V2X and Industry 5.0. They also show that O-RAN is suitable for the needs of the service kinds to be accomplished, and they give the E2E network slice orchestration architecture [60].

By launching the first 8-node network of the NVIDIA Aerial RAN CoLab (ARC), the X5G testbed at Northeastern University has succeeded in overcoming these challenges. To improve performance on GPUs, the Aerial SDK for PHY layer has been fine-tuned. The X5G testbed has also connected to the OAI open-source project's upper levels via the SCF FAPI. Using a digital twin concept, they cover the IT infrastructure, software integration, and radio frequency planning[61].

Table 1 Provides An Overview Of The Literature Review On Open RAN In Multi-Vendor Settings

References	**Focus On**	**Key Findings**	**Objectives**	**Challenges and Limitations**	**Future Work**
[57]	Real deployments of private 5G Open RAN networks by academia and industry.	The RAN system has been traditionally closed and proprietary; however, mobile operators are pushing for a more diverse vendor ecosystem.	To analyze challenges and lessons learned during the deployment of private 5G Open RAN networks.	Resistance from established proprietary RAN vendors; limited openness in current RAN ecosystems.	Explore further deployment strategies and overcome proprietary constraints in RAN systems.
[58]	Intelligent user access control using Deep Reinforcement Learning (DRL).	Proposed a federated DRL-based scheme with global DQN training to optimize user equipment throughput and reduce handovers.	To develop an intelligent access control scheme using DRL for enhanced throughput and minimized signaling overhead.	High computational requirements; signaling overhead during training.	Optimize DRL algorithms for scalability and efficiency in real-world scenarios.
[59]	Integration and assessment of multi-vendor Open RAN solutions at SONIC Labs.	Successful interoperability and end-to-end integration between Open RAN components for 22 multi-vendor setups.	To evaluate the viability of multi-vendor Open RAN solutions using O-RAN-compliant IOT and E2E test suites.	Complexity in integrating multi-vendor components; limited standardization in testing.	Expand test campaigns to include more vendors and refine testing frameworks.
[60]	AI/ML frameworks and applications (xApps and rApps) for O-RAN optimization.	Demonstrated E2E network slice orchestration and suitability of O-RAN for demanding service types like V2X and Industry 5.0.	To provide guidelines on AI/ML frameworks for autonomous network control and optimization.	Complexity in AI/ML model integration; scalability for diverse service types.	Enhance AI/ML frameworks and develop new applications for emerging service requirements.
[61]	Deployment of an 8-node network using NVIDIA Aerial RAN CoLab and OAI integration.	Demonstrated software integration, network infrastructure setup, and a digital twin framework for RF planning.	To address deployment challenges using GPU-accelerated PHY layers and open-source integration.	Integration complexities; limited scalability of the testbed.	Expand the testbed to larger-scale deployments and refine digital twin frameworks for RF planning.

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VI. CONCLUSION AND FUTURE WORK

To achieve the intended outcomes in multi-vendor networks, a wide variety of features and use cases known as "open RAN" must be specified and then implemented. This paper aims to analyze whether O-RAN can bring innovation to the 5G networks by being open, flexible, and interoperable. It defines main features, issues, and best practices, especially in the case of cloud data migration and protection. Although, the O-RAN Alliance comes with enhanced benefits, it still poses some important hurdles such as interoperability, latency and scalability which require enhancement for its wider adoption.

Further studies should be devoted to the methods of solving or overcoming some issues that require improvements in the way of network performances, underlining latency and multi-vendor integration. A better understanding of machine learning for enhancing network optimization and also, new trends in security protocols will improve the operational capability of O-RAN. Conversely, the real world applies applications' scalable patterns have room for even more research and growth.

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