The Architecture of AI and Communication Integration towards 6G: An O-RAN Evolution

Zexu Li
China Telecom Research Institute
Beijing, China
lizx28@chinatelecom.cn

Qingtian Wang*
China Telecom Research Institute
Beijing, China
wangqt08@chinatelecom.cn

Yue Wang
China Telecom Research Institute
Beijing, China
yue.wang@chinatelecom.cn

Tao Chen
VTT Technical Research Centre of Finland
Espoo, Finland
tao.chen@vtt.fi

Abstract

The evolution of communication architecture shifts towards virtualization and cloud-native network functions, setting the stage for the flexibility and integration of emerging technologies. Artificial Intelligence (AI) and Machine Learning (ML) as intrinsic elements in network design are some of the crucial visions and requirements for 6G. This paper, from the perspective of O-RAN, explores how current network architectures should evolve towards the integration of communication and intelligence in 6G. It begins with a comprehensive analysis and comparison of the AI-related work conducted by various standard organizations. Building on this, an end-to-end AI integration framework is proposed, which leverages AI technologies, data services, and digital twin (DT) technologies to achieve an integrated intelligent 6G communication system. After that, the key enabling technologies for cross-domain AI, service-based RAN, programmable RAN and digital twins are discussed. At last, the paper analyzes the challenges and opportunities for O-RAN evolution.

Keywords

6G, O-RAN, AI/ML, Integrated architecture

ACM Reference Format:
Zexu Li, Qingtian Wang, Yue Wang, and Tao Chen. 2024. The Architecture of AI and Communication Integration towards 6G: An O-RAN Evolution. In *The 30th Annual International Conference on Mobile Computing and Networking (ACM MobiCom '24), November 18–22, 2024, Washington D.C., DC, USA*. ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3636534.3701550

1 Introduction

The evolution of mobile networks from 2G to 6G reflects a continuous drive towards greater connectivity, reliability, and versatility. The 6G aims to provide more flexibility and integrate Artificial Intelligence (AI) into 6G's initial architecture [1]. AI's role in 6G extends beyond enhancing network performance; it aims to enable real-time decision-making, optimize resource allocation, and support new services that require low latency, high reliability, and dynamic adaptability [2][3].

The evolution towards 6G has the collaborative efforts of key standards development organizations (SDOs) such as the 3rd Generation Partnership Project (3GPP), the International Telecommunication Union (ITU), and the Open RAN Alliance (O-RAN). Each organization plays a distinct role in defining the technical frameworks and standards. The 3GPP is primarily responsible for the technical specifications of mobile networks, including 5G-advance and the emerging 6G. It focuses on developing comprehensive standards that cover the entire network architecture, i.e., RAN and core network (CN), ensuring interoperability and global harmonization. 3GPP's approach emphasizes the integration of new technologies into a unified and scalable framework, with a strong emphasis on backward compatibility and global deployment. The ITU sets the high-level vision and requirements for telecommunications including spectrum allocation and performance criteria for 6G [4]. It defines the overall goals and benchmarks for 6G, providing a strategic roadmap that guides the development of network capabilities and use cases. Its work is crucial in aligning global efforts and setting a unified direction for 6G evolution.

In contrast, O-RAN focuses specifically on the RAN and promotes openness, flexibility, and vendor interoperability. Unlike 3GPP and ITU, which address broader network aspects, O-RAN emphasizes disaggregation of network components, open interfaces, and the integration of AI and software-driven capabilities. This approach aims to create a more dynamic and programmable RAN environment, enabling faster innovation and adaptation to new technologies such as AI. To facilitate the evolution of O-RAN towards 6G, O-RAN Alliance has set up a next Generation Research Group (nGRG) to work on prioritized 6G topics. The native AI and new architecture principles for 6G are key topics addressed by nGRG. The published research reports regarding architecture and Native AI can be found at [5–7]. The nGRG has organized six workshops that invite operators, vendors, and academia as speakers to share their views on 6G. Moreover, nGRG leads the Seed Funding Sponsorship for academic scholars to promote 6G evolution. Polese et al. [8] analyze the potential performance gains of use cases under O-RAN architecture. Abdalla et al. [9] present the critical features

*corresponding author.

ACM MobiCom '24, November 18–22, 2024, Washington D.C., DC, USA

ACM ISBN 979-8-4007-0489-5/24/11
https://doi.org/10.1145/3636534.3701550

of physical layer real-time control and AI-based RAN control based O-RAN framework. Ko et al. [10] propose an EdgeRIC to achieve real-time intelligence services for 6G. However, these studies focus on the analysis of specific use cases, yet there is currently a lack of high-level O-RAN solution for the communication and intelligence integration towards 6G.

In this paper, we primarily discuss how the O-RAN-based architecture can evolve with AI native in 6G. After analyzing the work and gaps related to AI from multiple SDOs, an end-to-end (E2E) framework integrating communication and AI is proposed. Based on the proposed framework, we further discuss key enabling technologies, including cross-domain AI collaboration, service-based RAN, programmable RAN and Digital RAN. Finally, challenges and opportunities are highlighted to provide some light for future work.

2 Gap Analysis on AI/ML Related Work

Research on the integration of AI and communication has made great progress in recent years. However, the current network architecture, interfaces and AI-integrated technology still face many challenges. This section provides a gap analysis on AI-related work between O-RAN and 3GPP and further identifies the gap towards native AI in 6G.

2.1 Gap Analysis Between O-RAN and 3GPP

With the introduction of AI technology into communication systems, various international SDOs have begun to investigate how AI technology can be used to optimize and enhance networks. 3GPP is currently considering enhancements to 5G systems to support AI features. In contrast, O-RAN has set up the nGRG to explore AI/ML support for next-generation networks in addition to considering 5G enhancements. Figure 1 provides current AI/ML related works triggered by O-RAN and 3GPP.

Firstly, the scope of AI-related work differs between 3GPP and O-RAN. The 3GPP RAN Working Group (WG) and SA WG have respectively studied use cases and solutions for AI within the RAN domain, CN domain, and network management systems. In contrast, O-RAN focuses on AI in the RAN domain, Service Management and Orchestration (SMO) and cloud. The following Table 1 lists the primary use cases discussed by 3GPP and O-RAN in the RAN domain.

	3GPP	O-RAN
Similar use cases	Load balancing (3GPP RAN3)	Traffic steering (O-RAN WG3)
	Energy saving (3GPP RAN3/5)	Energy saving (O-RAN WG2/3/6)
	RRM resource optimization for network slice instance	RAN Slice SLA assurance
Specific use cases	AI for air interface	mMIMO and QoE optimization

Table 1: AI use cases in 3GPP and O-RAN for RAN domain

Secondly, 3GPP does not introduce new network functions for AI on RAN side. Since the release 17 phase, RAN1 and RAN3 groups have explored AI use cases for the air interface and the network, respectively [11, 12]. Specifically, RAN3 has identified three use cases including network energy saving, load balancing, and mobility optimization, while RAN1 has identified use cases on CSI feedback, beam management, and positioning. 3GPP considers that model training should be deployed at the OAM or the gNB, and model inference can be deployed at the gNB. For OAM, 3GPP SA5 has defined the Management Data Analysis Function (MDAF) to provide network management data analysis services to consumers [13, 14]. In contrast, O-RAN focuses on cloudification and network capability openness. O-RAN has defined two new logical functions to achieve AI for the RAN [5, 15]. Non-Real Time (Non-RT) RAN Intelligence Controller (RIC) added in SMO enables long-time-scale control and optimization of RAN resources and AI/ML workflow. Near-RT RIC is mainly used for near-real-time control and optimization. Due to differences in functionality and architecture, O-RAN has also introduced the O1/O2/E2 interfaces to collect data from the E2 node and O-cloud and introduced the A1 interface to enable policy transmission from the Non-RT RIC to the Near-RT RIC. Additionally, O-RAN has defined the Y1 interface to expose RAN analytics information.

Recently, 3GPP has begun a study item at the SA plenary level regarding the AI/ML consistency alignment, aiming to avoid inconsistencies in AI research among RAN, CN, and network management systems. However, 3GPP has not reached an agreement on how to coordinate AI capabilities across different domains. From 2022, O-RAN nGRG has already begun research and discussions on the issue of cross-domain AI collaboration for 6G. O-RAN has published some research reports that provide a definition of cross-domain AI, use cases, technical requirements, and possible evolutionary directions for network AI collaboration [6, 16]. Since O-RAN does not involve research on the CN, this paper only analyzes the differences within the RAN domain and the management system.

2.2 Gap Analysis Towards 6G

Although a great deal of research has been conducted in academia and industry on the integration of AI and networks, there are still a number of challenges that need to be addressed for the next-generation communication system.

(1)The AI capabilities of cloud and network lack coordination: In the 5G phase, SDOs such as 3GPP are discussing how to use AI to optimize network performance for RAN, CN, and management system, respectively. However, different network domains currently consider AI use cases independently, and there is a lack of collaboration of AI capabilities across domains. Currently, data, models, and computing resources are difficult to share between different network domains, which makes it difficult to provide E2E intelligent services to users.

6G needs to collaborate different dimensions of resources in the clouds and network, such as communication, computing, data and models, through communication connectivity at AI level. In addition, with the introduction of generative AI, 6G needs to consider the collaboration between large models and small models, as well as resources deployed at the cloud, network, edge, and devices.

(2)AI services are not sufficiently real-time for edge applications: The real-time performance of AI services for edge applications remains insufficient, posing a critical challenge as we advance towards 6G. Current AI models often struggle to meet

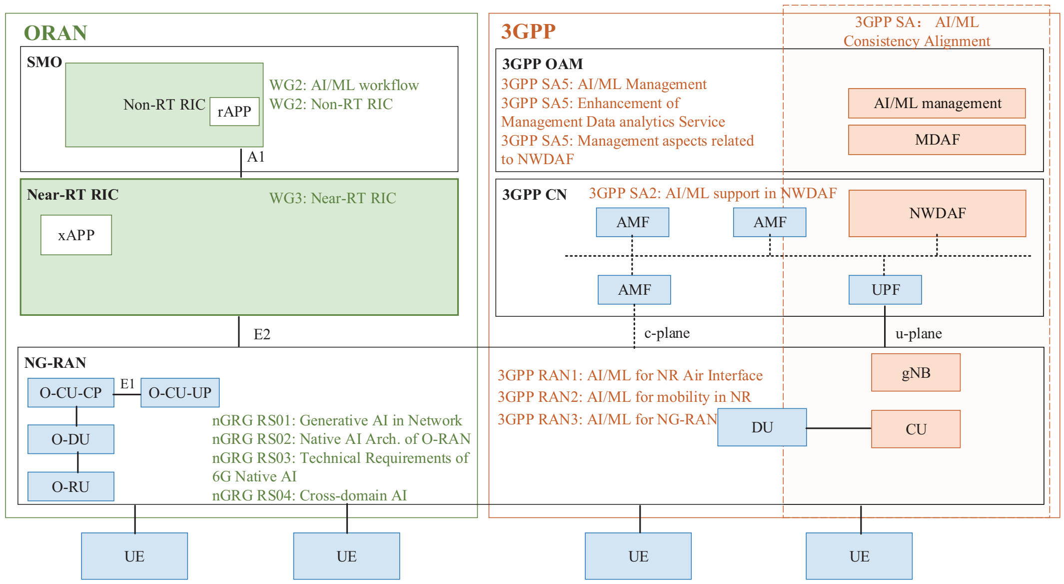


Figure 1: An illustration of gaps between O-RAN and 3GPP on AI

the stringent latency requirements demanded by edge computing scenarios, such as autonomous driving and real-time industrial control. This shortage limits the effectiveness of AI native in the network, where rapid decision-making and low-latency responses are essential.

To build a robust 6G network with native AI capabilities, it is crucial to address these real-time performance gaps. Firstly, enhancing the responsiveness of AI algorithms is necessary, requiring optimization techniques that prioritize speed without sacrificing accuracy. Secondly, the deployment of AI closer to the edge must be carefully managed, ensuring that computational resources and data flow are orchestrated to minimize delays. Without resolving these real-time challenges, the integration of AI into 6G networks may fall short of its potential, hindering the support of latency-sensitive applications and compromising the overall user experience. The dAPP [17]and EdgeRIC [10] are the perfect trail for the 6G real-time application.

(3)The reliability of AI is difficult to guarantee: Due to the weak explainability of AI, directly transferring AI technology into communication systems may introduce unforeseen security issues. Building an intrinsic AI-enabled 6G network urgently requires addressing the security and reliability issues of network AI. Firstly, it is necessary to consider data privacy and security, requiring unified orchestration and management of the data lifecycle, and establishing a secure and reliable data collection and transmission mechanism. Secondly, the security and trustworthiness of AI models and systems need to be ensured. On the one hand, it is important to research trustworthy and explainable AI algorithms; on the other hand, establishing a real-time responsive digital twin system is necessary for pre-validation and regulation of AI strategies.

3 E2E Framework for Communication and AI Integration Based on O-RAN

Based on the aforementioned gap analysis, Figure 2 presents an E2E AI-integrated network framework for 6G, evolving from the architecture of O-RAN. The proposed framework aims to leverage data management capabilities, E2E AI collaboration technologies, as well as real-time responsive digital twin systems, to create a closed-loop, autonomous network integrating communication and intelligence.

Data management capability will be a crucial driving force in integrating networks with intelligence. Through data management services, multidimensional and heterogeneous data generated by users, networks, and environments can be provided to AI and digital twin systems. Since the data required by consumers may generated from different data sources or even different network domains, data management services must possess cross-domain and cross-layer orchestration capabilities. AI and ML technologies are key enablers of network autonomy. By leveraging AI for intelligent analysis of large amounts of data, network configuration, access technologies, and network and computing resources can be flexibly optimized. In addition to deploying AI capabilities within individual domains, it is also necessary to consider the coordinated management of AI across domains to ultimately provide E2E intelligent service to users. The digital twin system serves as the reliability assurance for the integration of communication and intelligence. Using data collected from the real world, the digital twin system performs real-time dynamic mapping and modeling of the environment, services, and network performance. Network optimization or configuration strategies generated by AI can be pre-validated and tested within the digital twin system to ensure that these strategies do not adversely affect the normal operation of the actual network.

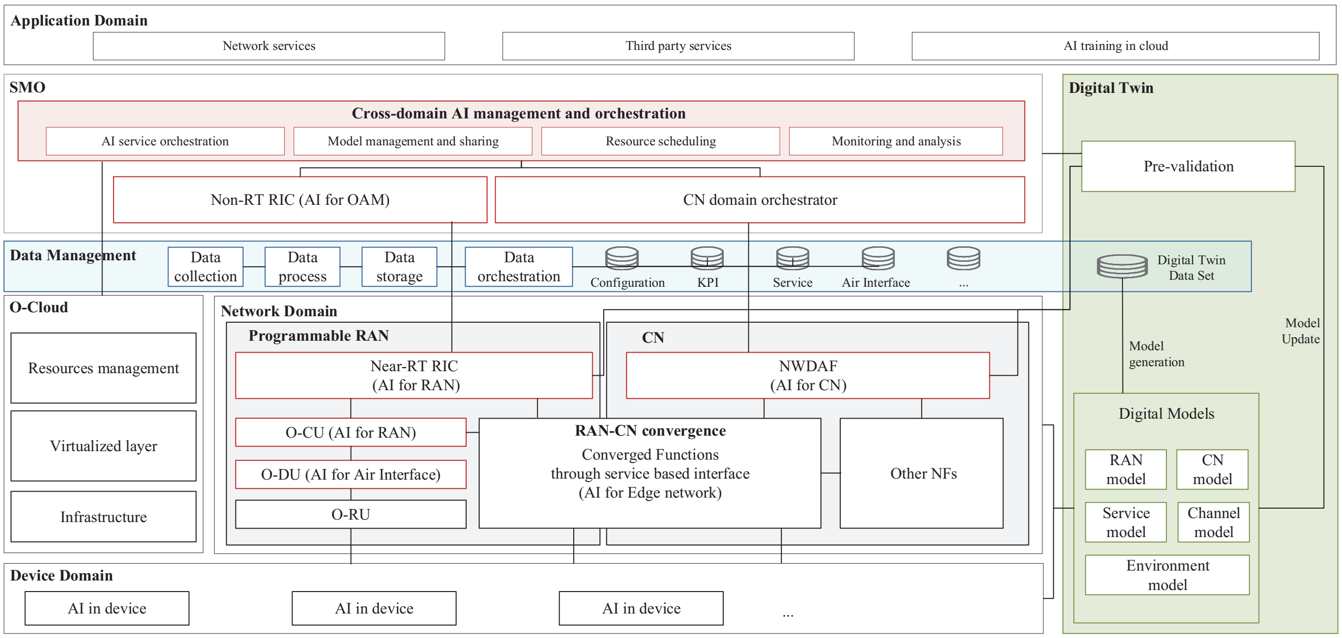


Figure 2: E2E AI framework based on O-RAN architecture

4 Key Technologies

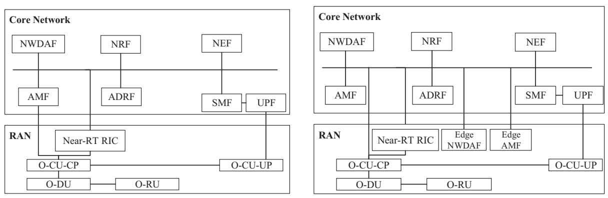
4.1 Cross-domain AI Collaboration

With the continuous enrichment of intelligent scenarios, the AI capability of the 6G network will be further embedded in the function of the network element, or even replace the original algorithms within the network function [18]. However, the computing resources and models distributed across these domains are not yet efficiently coordinated based on the current architecture, which presents many urgent challenges for the deployment and use of AI. Firstly, the computing resources in the cloud and at the edge are difficult to coordinate, resulting in low utilization of computing resources. Secondly, existing research focuses on AI use cases within a single network domain or node, making it difficult for the network to flexibly provide E2E intelligent services to users. Thirdly, since large language models (LLM) and generative AI require large amounts of data and sufficient computing resources for training, they are typically deployed at network centers or in the cloud. However, there is currently a lack of collaborative mechanisms for integrating large models with other traditional AI models. Finally, due to the strong privacy and security requirements of terminal data, user data, and some network data, when data cannot be transmitted across domains, the network needs to support distributed learning. Therefore, cross-domain AI collaboration is the necessary enabler to achieve native AI for 6G.

(1) E2E AI management and orchestration: An E2E AI management and orchestration capability should be provided so that the computing resources, models, and data distributed across various domains can be efficiently coordinated. Based on the O-RAN architecture, the non-RT RIC within the SMO can serve as the intelligent control function for the RAN domain. However, beyond the Non-RT RIC, a higher-level AI management and orchestration function is required. This function should connect with intelligent control functions within each domain, flexibly orchestrating cloud and network resources according to AI tasks. Additionally, a data and model repository should be established, responsible for coordinating the data and model requirements within each domain, thereby reducing the communication overhead caused by repeatedly exchanging data and models.

(2) Data and model collaboration across domains: Another issue that needs to be addressed is how data and models can be exchanged and used across domains. Data and models are crucial components for realizing AI functionality, and the amount of data and models transmitted in future networks will be enormous. If data and models are transmitted through current network interfaces and control signaling, it will cause unpredictable impacts on traditional communication services. As AI application scenarios are becoming more complex, the size of individual AI models may grow significantly, and whether new protocols and interfaces for model transmission need to be defined requires further study. Additionally, the types of AI models are highly diverse, and different AI service providers may use different types of algorithms and models. In the scenarios of cross-domain model transmission, it is also necessary to consider issues related to the identification and use of models across vendors.

(3) Collaboration between large models and other models: Due to the broad adaptability and accuracy of large models in natural language processing and computer vision, standardization groups are also considering how to apply large models to networks. 3GPP SA5 in Rel-19 has begun discussing the management issues of generative AI, and O-RAN nGRG RS01 has initiated a research item on the requirements of generative AI. Large models possess



(a) option 1.　(b) option 2.

Figure 3: Two potential evolution options for the serviced-based RAN

stronger adaptability and higher precision, but their training process consumes more time and computing resources, while small models offer higher execution efficiency and lower computing costs, making them suitable for real-time scenarios where quick local responses are required. Therefore, it is foreseeable that in 6G, large models and small models will collaborate to empower network intelligence. Large models will be deployed in centralized locations or the cloud where computational resources are abundant, while small models will be distributed at the network edge or even on terminals based on specific AI use cases. On the one hand, general large models can provide a foundational model that can be further fine-tuned using small models. On the other hand, large models can act as global decision-makers for multiple small models.

4.2 Serviced-based RAN

The service-based 5G CN has brought significant advancements in performance improvements and simplification of signaling procedures, however, the RAN architecture remains relatively rigid and monolithic, limiting its adaptability to diverse and evolving service requirements. This inflexibility has highlighted the need for a more dynamic and service-based approach as we move towards 6G.

A service-based RAN in 6G offers several key advantages over the traditional RAN model. By decoupling network functions and enabling them to be offered as modular services, this architecture allows for greater flexibility, scalability, and efficiency. It can better accommodate the diverse range of applications and services that 6G is expected to support, from ultra-reliable low-latency communications to massive machine-type communications. This modular approach also facilitates easier upgrades and the integration of new technologies, ensuring that the RAN can evolve with the broader 6G ecosystem.

In order to achieve a service-based RAN in 6G, it would required to re-design the traditional RAN architecture. It involves the adoption of cloud-native principles, where RAN functions are virtualized and containerized, enabling them to be deployed, scaled, and managed more dynamically. However, fully virtualization of all RAN functions in the 6G phase may be impractical. As illustrated in Figure 3, this paper presents two possible evolution options for service-based RAN. The first option involves connecting the near-RT RIC to the bus via a service-based interface, thereby simplifying the signaling overhead associated with RAN and CN coordination in AI. The second option is to connect both the RIC and Central Unit Control Plane (CU-CP) to the bus through service-based interfaces, which could further enhance the flexibility of RAN and CN coordination. In specific network edge scenarios, partially CN functions may integrate with service-based RAN functions. Furthermore, the use of open interfaces and standardized protocols will be crucial to ensuring interoperability and enabling a more open and collaborative ecosystem. This shift will also require close collaboration between industry stakeholders, including network operators, equipment vendors, and standards organizations, to define the necessary frameworks and ensure seamless integration.

4.3 Programmable RAN

The AI involves three key components: computation, data, and algorithms. Programmable RAN allows the seamless adaptation of 6G network settings through a flexible framework and standardized interfaces. This capability ensures that network configurations can be dynamically adjusted to meet changing demands.

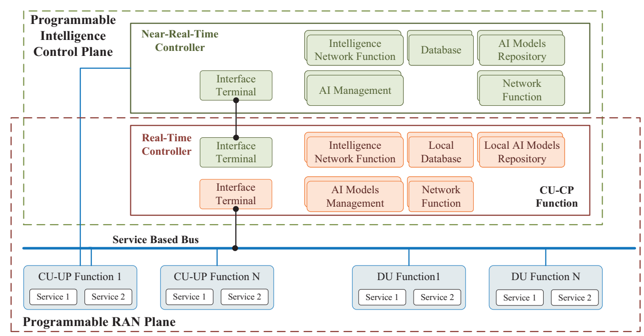


Figure 4: The framework of programmable RAN

Programmable RAN also constructs data sets for training AI algorithms and exploring data relationships within network functions. it also enables secure data sharing with third parties through appropriate methods, ensuring privacy and security. Through the programmability of RAN, the 6G can leverage data more effectively to enhance performance and innovation. Programmable RAN can embed or replace AI algorithms through a framework that ensures compliance with the specified input and output formats and includes a security check. This framework offers a set of interfaces and functional modules, enabling efficient AI deployment and management.

As shown in Fig, 4, we present an overview of the programmable service-based RAN framework, a real-time intelligence controller is designed in a CU-CP, and the functionalities are also proposed. There is an interface for the near-real-time and real-time intelligence controllers' internal communication including the trained AI model communication and data collection. The Central Unit User Plane(CU-UP) is a service-based architecture and all the functionalities are connected via a bus.

4.4 Digital Twin RAN

A Digital Twin RAN creates a virtual replica of the physical RAN environment, enabling real-time monitoring, simulation, and optimization of network performance [19, 20]. This approach allows operators to predict network behavior, test new configurations, and deploy AI-driven strategies without impacting the live network, thereby enhancing operational efficiency and reliability.

Data acquisition is fundamental to building an effective Digital Twin RAN. This involves collecting data from various sources within the network, including performance metrics, configuration parameters, and traffic patterns. Advanced sensors, network monitoring tools, and AI-based data analytics are employed to continuously update the digital twin with real-time data, ensuring that the virtual model accurately reflects the current state of the network. Secure data handling and processing are crucial to maintaining the integrity and reliability of the digital twin.

The Digital Twin RAN offers significant advantages for 6G networks. It enables predictive maintenance, allowing operators to proactively address potential issues before they impact service. The digital twin also facilitates continuous optimization of network resources, leading to improved performance and reduced operational costs. Moreover, by providing a safe environment to test and validate AI algorithms and network strategies, the Digital Twin RAN accelerates innovation and enhances the adaptability of 6G networks to evolving user demands.

5 Challenges and Opportunities

Following up on the evolution of O-RAN, the current stage of 6G is on nGRG. Based on the research findings of the Midterm (2025-2027) on nGRG, it will focus on several strategic steps to guide the evolution of O-RAN towards 6G. A primary responsibility will be to provide critical inputs to O-RAN WGs and Focus Groups (FGs) to support the preparation for 6G standards studies. This will involve translating the latest research insights into actionable recommendations that will shape the future O-RAN 6G standards. However, the challenges are also will faced in this stage as follows:

(1) Coordination with Other SDOs: Jointly O-RAN aligns with other SDOs such as 3GPP and ITU presents coordination challenges. Ensuring that O-RAN's contributions are well integrated into global 6G standards requires constant collaboration, negotiation, and alignment of technical priorities.

(2) Real-Time Performance: As 6G envisions massive connectivity and diverse use cases, ensuring the scalability and real-time performance of O-RAN solutions is critical. Balancing the flexibility of programmable RAN with the requirement for high performance in dynamic environments remains a key challenge.

There are also opportunities for O-RAN:

(1) Driving Innovation in 6G: The nGRG and O-RAN have the opportunity to drive innovation in 6G by shaping next-generation RAN technologies. By leading the development of open, intelligent, and software-defined RANs, O-RAN can redefine how networks operate, making them more adaptive and responsive to new demands.

(2) Enhanced Network Intelligence: The integration of AI and machine learning opens opportunities to enhance network intelligence, automate operations, and optimize performance in real time. The ability to deploy intelligent RAN functions can significantly improve user experiences and support advanced use cases such as autonomous networks and real-time analytics.

6 Conclusion

The integration of AI and communication is reshaping the 6G networks and evolving the communication systems from communication pipelines into providers of digital and intelligent services. This paper explores the potential evolutionary paths of network architecture towards 6G based on the O-RAN, emphasizing the deep integration of cloud and network, and the convergence of communication and intelligence. Despite significant research efforts by academia and SDOs like 3GPP and O-RAN, current network architectures still have shortcomings in meeting 6G's requirements. This study provides a foundational understanding of the role of 6G in harnessing the full potential of AI services across various applications, paving the way for a new era of intelligent communication networks.

Acknowledgments

This work was partially funded by the National Key R&D Program under Grant 2022YFB2902100, and partially supported by 6G-Cloud project which have received funding from EU Horizon Europe programme under GA No. 101139073.

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