Guest Editorial
Open RAN: A New Paradigm for Open, Virtualized, Programmable, and Intelligent Cellular Networks

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I. Introduction

THE Open Radio Access Network (Open RAN) vision is based on the three principles of (i) open interfaces; (ii) cloudification; and (iii) automation through closed-loop control. It is a network architecture paradigm embodied and augmented through technical reference specifications of the 3GPP and the O-RAN Alliance. At the centre of Open RAN are open, programmable, and virtualized components, connected to each other through open interfaces that enable closed-loop, data-driven, and intelligent control. For instance, the O-RAN Alliance introduced two RAN Intelligent Controllers (or RICs) that connect through open interfaces to the disaggregated components of the RAN, and implement control loops that run at different time scales.

The goal of this Special Issue is to provide a comprehensive overview of fundamental research on algorithmic, architectural, and system issues, as well as on experimental aspects that substantially advance the state-of-the-art on the design of Open RAN systems. Indeed, while Open RAN networks are being deployed in trials around the world, there are still several open issues for both standardization and research, related to the design of data-driven intelligent solutions, efficient control loops, extension of open interfaces and testing, security, and use cases related to private cellular networks, non-terrestrial deployments, spectrum sharing, commercial 5G/6G networks, and evaluation and assessment of fundamental trade-offs, among others.

This Special Issue received 62 submissions, with more than 250 reviewers over two rounds of reviews. The process has resulted in 16 papers which are briefly summarized in the next paragraphs. The main topics discussed revolve around:

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1) RAN slicing and management of the spectrum resources, where Open RAN architecture and interfaces are used to manage and optimize how classes of traffic, users, and applications split and/or share the limited spectrum resources with data-driven closed-loop control.
2) Multiple Input Multiple Output (MIMO) systems optimization, where Open RAN is seen as an architectural enabler of cell-free massive MIMO deployments and an enabler of multi-cell coordination.
3) RAN control use cases associated to traffic steering, flow control, and security.
4) Orchestration and virtualization, using the Open RAN programmable components to manage virtualized network function and enable streamlined operations for network operators.
5) Lessons learnt from validation of multiple xApps and trials.

II. Network Slicing and Spectrum Management

Apostolakis et al. [A1] introduce ATHENA, a machine-learning-based radio resource scheduler for virtualized RAN systems. ATHENA takes into account the limitations of cloud-computing environments and outperforms the conventional ML-based solution. The authors also explore the potential for further re-orchestration of actions based on the analysis of scheduling decisions and past learning.

Zangooei et al. [A2] consider network slicing to provide bespoke services. They propose a new cooperative multi-agent RL algorithm for RAN slicing in Open RAN, designed to adapt to changing slice numbers while maintaining SLA compliance. It outperforms state-of-the-art RL methods for slicing by achieving 50% better SLA satisfaction in large-scale slicing with only 9% more resources, and it reduces SLA violations by 8% while consuming 19% fewer resources for a flexible number of slices.

Zhang et al. [A3] focus on a multi-scale adaptation approach to manage quality of service (QoS) in a Open RAN environment. To do this, they leverage a bandit-feedback version of the combinatorial multi-armed bandit framework, to deduce resource-specific information, and use side information on live network traffic to fine tune prediction allocations for the users. The framework improves throughput while reducing latency for various services.

Nagib et al. [A4] address the challenge of deploying deep reinforcement learning (DRL) agents in production environment, which is hindered by slow convergence and unstable performance when encountering previously unseen network conditions. The authors introduce a hybrid transfer learning approach to achieve safe and accelerated convergence in unknown scenarios, with a 64.6% reduction in reward variance.

Reus-Muns et al. [A5] consider a Citizen Broadband Radio Service (CBRS) scenario and develop a radar detection xApp to sense the presence of incumbents and vacate the spectrum. The detection is based on the application of the YOLO framework to signals received by the gNB. The authors also profile the performance on a laboratory testbed.

III. MIMO Optimization

Chen et al. [A6] propose O-M^3, a framework to coordinate scheduling across multiple cells in the same O-RAN Distributed Unit (DU). O-M^3 leverages GPU acceleration to meet the stringent scheduling constraints of 5G NR systems. The experimental results show how it can complete a coordinate scheduling allocation within 500 μs for an O-RAN system with 7 O-RAN radio units (O-RUs), 100 users, 100 RBs, and 2×8 MIMO.

Demir et al. [A7] explore the performance and power consumption of cell-free massive MIMO technology compared to traditional small-cell systems, in the context of virtualized O-RAN systems. They compare two infrastructure allocation mechanisms, which consider either only cloud resources or a combined allocation of cloud and radio resources.

Oh et al. [A8] also consider a cell-free massive MIMO scenario and propose a mechanism to suppress pilot contamition. Specifically, they introduce a multi-agent deep reinforcement learning (MA-DRL) framework in which multiple learning agents perform distributed learning over the O-RAN communication architecture to reduce overlapping allocation of the pilot transmissions.

IV. RAN Control and Security Use Cases

Nguyen et al. [A9] design a traffic steering framework based on the O-RAN architecture, considering joint control of the flow-split distribution, congestion, and scheduling. They introduce multi-layer optimization framework that provides fast convergence, long-term utility-optimality and significant delay reduction compared to the state-of-the-art and baseline RAN approaches, and provide numerical results to verify the effectiveness of the proposed framework.

Irazabal and Nikaein [A10] develop TC-RAN, a traffic control solution that combines an E2 service Model (E2SM) and a RAN Function to configure data flows with high granularity. The intelligent logic includes 6 programmable, extendable, and customizable components, i.e., a classifier, a policer, a queue, a scheduler, a shaper, and a pacer. The authors implement the system on OpenAirInterface and profile the performance with commercial smartphones.

Finally, Klement et al. [A11] analyze the security of open RAN using the MITRE ATT&CK framework, which provides a structured classification of malicious behaviors in end-to-end mobile communications. They focus on assessing specific threats in open cellular systems, using the O-Cloud as an exemplary environment.

V. Orchestration and Virtualization

Salvat et al. [A12] consider the issue of noisy neighbors in virtualized systems, i.e., multiple critical real-time tasks and non-critical workloads competing for the same resources. They propose an AI-driven Radio Intelligent Controller (AIRIC) which can orchestrate vRAN computing resources with a hybrid neural network architecture combining a relation network (RN) and a deep Q-Network (DQN).

Almeida et al. [A13] study how a disaggregated version of the Near-Real-Time (Near-RT) RIC can be optimally deployed as a set of network functions across different locations in a network. Specifically, they focus on different functionalities and their different requirements, and dynamically cluster the RAN nodes to provide a match between their needs and the RIC network functions.

Mohammadi and Nikaein [A14] present a management and orchestration framework that enables the deployment and operation of different radio technologies (multi-x) coexisting on the same infrastructure, with built-in observability and scale. The framework is compared with state-of-the-art management and orchestration solutions, with a reduction in overhead in various operations which exceeds 60%.

VI. Deployments and Lessons Learned

Hoffman et al. [A15] present an in-depth overview of the implementation and performance of multiple xApps that cover several use cases of interest within the O-RAN ecosystem, including beam management and signaling storm detection. They also present an overview of different frameworks that can be used to develop and profile xApps.

Finally, Huang et al. [A16] discuss O-RAN in the context of field trials and deployments in private and public networks. The authors present various test results related to open fronthaul, the O-RAN cloud platform, and the intelligent controllers.

Appendix: Related Articles

[A1] N. Apostolakis, M. Gramaglia, L. E. Chatzieleftheriou, T. Subramanya, A. Banchs, and H. Sanneck, "ATHENA: Machine learning and reasoning for radio resources scheduling in vRAN systems," *J. Sel. Areas Commun.*, 2023.

[A2] M. Zangooei, M. Golkarifard, M. Rouili, N. Saha, and R. Boutaba, "Flexible RAN slicing in open ran with constrained multi-agent reinforcement learning," *J. Sel. Areas Commun.*, 2023.

[A3] X. Zhang, J. Zuo, Z. Huang, Z. Zhou, X. Chen, and C. Joe-Wong, "Learning with side information: Elastic multi-resource control for the open RAN," *J. Sel. Areas Commun.*, 2023.

[A4] A. M. Nagib, H. Abou-Zeid, and H. S. Hassanein, "Safe and accelerated deep reinforcement learning-based O-RAN slicing: A hybrid transfer learning approach," *J. Sel. Areas Commun.*, 2023.

[A5] G. Reus-Muns et al., "SenseORAN: O-RAN based radar detection in the CBRS band," *J. Sel. Areas Commun.*, 2023.

[A6] Y. Chen, T. Hou, W. Lou, J. Reed, and S. Kompella, "M3: Real-time multi-cell MIMO scheduling in 5G O-RAN," *J. Sel. Areas Commun.*, 2023.

[A7] O. T. Demir, M. Masoudi, E. Bjornson, and C. Cavdar, "Cell-free massive MIMO in O-RAN: Energy-aware joint orchestration of cloud, fronthaul, and radio resources," *J. Sel. Areas Commun.*, 2023.

[A8] M. S. Oh, A. B. Das, S. Hosseinalipour, T. Kim, D. Love, and C. G. Brinton, "A decentralized pilot assignment methodology for scalable O-RAN cell-free massive MIMO," *J. Sel. Areas Commun.*, 2023.

[A9] V.-D. Nguyen et al., "Network-aided intelligent traffic steering in 6G O-RAN: A multi-layer optimization framework," *J. Sel. Areas Commun.*, 2023.
[A10] M. Irazabal and N. Nikaein, "TC-RAN: A programmable traffic control service model for 5G/6G SD-RAN," *J. Sel. Areas Commun.*, 2023.
[A11] F. Klement, W. Liu, and S. Katzenbeisser, "Towards securing the 6G transition: A comprehensive empirical method to analyze threats in O-RAN environments," *J. Sel. Areas Commun.*, 2023.
[A12] J. X. Salvat, A. Garcia-Saavedra, X. Li, and X. Costa-Perez, "AIRIC: Orchestration of virtualized radio access networks with noisy neighbours," *J. Sel. Areas Commun.*, 2023.
[A13] G. Almeida et al., "RIC-O: Efficient placement of a disaggregated and distributed RAN intelligent controller with dynamic clustering of radio nodes," *J. Sel. Areas Commun.*, 2023.
[A14] A. Mohammadi and N. Nikaein, "Athena: An intelligent multi-X cloud native network operator," *J. Sel. Areas Commun.*, 2023.
[A15] M. D. Hoffmann et al., "Open RAN xApps design and evaluation: Lessons learnt and identified challenges," *J. Sel. Areas Commun.*, 2023.
[A16] Y. Huang, Q. Sun, N. Li, Z. Chen, J. Huang, and H. Ding, "Validation of current O-RAN technologies and insights on the future evolution," *J. Sel. Areas Commun.*, 2023.

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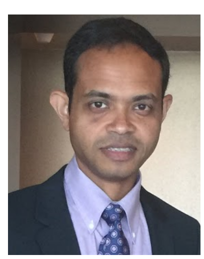

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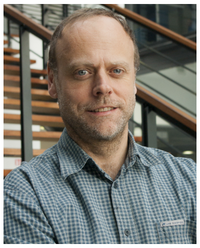

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