dApps: Distributed Applications for Real-Time Inference and Control in O-RAN

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ABSTRACT

The Open Radio Access Network (Open RAN) — being standardized, among others, by the O-RAN Alliance — brings a radical transformation to the cellular ecosystem through disaggregation and RAN intelligent controllers (RICs). The latter enable closed-loop control through custom logic applications (xApps and rApps), supporting control decisions at different timescales. However, the current O-RAN specifications lack a practical approach to execute real-time control loops at timescales below 10 ms. In this article, we propose the notion of dApps, distributed applications that complement existing xApps/rApps by allowing operators to implement fine-grained data-driven management and control in real time at the central/distributed units (DUs). dApps receive real-time data from the RAN, as well as enrichment information from the near-real-time RIC, and execute inference and control of lower-layer functionalities, thus enabling use cases with stricter timing requirements than those considered by the RICs, such as beam management and user scheduling. We propose feasible ways to integrate dApps in the O-RAN architecture by leveraging and extending interfaces and components already present therein. Finally, we discuss challenges specific to dApps, and provide preliminary results that show the benefits of executing network intelligence through dApps.

INTRODUCTION

Cellular networks are undergoing a radical paradigm shift. One of the major drivers is the Open Radio Access Network (Open RAN) paradigm, which brings together concepts such as software-defined networking, disaggregation, open interfaces, and “white-box” programmable hardware to supplant traditionally closed and inflexible architectures, thus laying the foundations for more agile, multivendor, data-driven, and optimized cellular networks [1].

This revolution is primarily led by the O-RAN Alliance, a consortium of network operators, vendors, and academic partners [1]. O-RAN is standardizing the Open RAN architecture, its components, and their functionalities, as well as open interfaces to facilitate interoperability between multi-vendor components, real-time monitoring of the RAN, data collection, and interactions with the cloud. By adopting the 7.2.x split, O-RAN builds upon the disaggregated Third Generation Partnership Project (3GPP) next generation node bases (gNBs), which divides the functionalities of the base stations across central units (CUs), distributed units (DUs), and radio units (RUs) [1]. As shown in Fig. 1, O-RAN also introduces the concept of the RAN intelligent controller (RIC), an abstraction that enables near-real-time (or near-RT) and non-real-time (non-RT) control and monitoring of the RAN via software applications called xApps and rApps, respectively. In the O-RAN vision, the components of the RAN expose a set of controllable parameters and functionalities, as well as streams of data (e.g., key performance measurements [KPMs]). These are used by xApps and rApps to fine-tune the behavior of the RAN, adapting it to the operator goals, and to the network and traffic conditions through sophisticated artificial intelligence (AI) and machine learning (ML) algorithms [2]. The RICs, xApps, and rApps will eventually realize the vision of self-organizing networks autonomously detecting ongoing changes in channel, network, and traffic state, and reacting to meet minimum quality of service (QoS) requirements and to comply with service level agreements (SLAs). This includes resource allocation [3], network slicing [4], handover and mobility management [5], and spectrum coexistence [6].

However, we are still far from the vision of fully automated and intelligent cellular networks. Indeed, limiting the execution of control applications to the near-RT and non-RT RICs prevents the use of data-driven solutions where control decisions and inference must be made in real time, or within temporal windows shorter than the 10 ms supported by near-RT control loops [2, 7]. Two practical examples are user scheduling and beam management. Scheduling requires making decisions at sub-millisecond timescales (e.g., to perform puncturing and preemption to support ultra-reliable low-latency communications [URLLC] traffic with latency values as low as 1 ms). Similarly, beam management involves beam sweeping via reference signals transmitted within 5-ms-long bursts (half the duration of a 5G NR frame) [8].

Unfortunately, the near-RT RIC and xApps might struggle to accomplish these procedures because they have limited access to low-level information (e.g., transmissions queues, I/Q samples, beam directionality) and/or incur high latency to obtain it. For example, beam management would require the transmission of reference signals (or, as proposed in [8], I/Q samples) from the DU/ RU to the RIC over the E2 interface. This would result in increased overhead and delay due to
to propagation, transmission, switching, and inference latency, which might prevent real-time (i.e., < 10 ms) execution. Moreover, since I/Q samples contain sensitive user data (e.g., packet payload), they cannot be transmitted to the RIC out of privacy and security concerns and are therefore processed at the gNB directly. For these reasons, such procedures (and any procedure that requires real-time execution or handles sensitive data) are typically run directly at the DU/RU, usually via closed and proprietary implementations — referred to as the “vendor’s secret sauce.” While hardware-based implementations can satisfy the above temporal requirements and deliver high performance, they are ultimately inflexible, hard to update, and not scalable as their upgrade (e.g., after a new 3GPP release) requires hardware or (whenever possible) firmware updates.

As of today, the O-RAN architecture focuses on offering softwarized, programmatic, and AI-based control to the higher layers of the protocol stack, with limited flexibility for the lower layers hosted at DUs/RUs. However, prior work has demonstrated how running AI at the edge of the network — with a specific focus on PHY and medium access control (MAC) layers of the DUs/RUs — can provide major performance benefits. Moreover, recent works have shown that AI at the edge can significantly improve network performance by leveraging traditionally available KPMs (e.g., throughput, signal-to-interference-plus-noise ratio [SINR], channel quality information, latency) [4, 9, 10], as well as by processing in parallel (thus not affecting demodulation and decoding procedures) I/Q samples collected at the PHY layer that carry detailed information on channel conditions and spatial information of received waveforms [8, 11]. Although the O-RAN specifications have identified a few use cases that could benefit from running intelligence at gNBs directly, these use cases are left for future studies [11].

Main Contributions. The goal of this article is to foster a discussion on enabling network intelligence at the edge in the O-RAN ecosystem. As illustrated in Fig. 1, we introduce the notion of dApps, custom and distributed applications that complement xApps/rApps by implementing AI at the edges of the current RICs. dApps receive real-time data and KPMs from the RUs (e.g., frequency-domain I/Q samples), DUs (e.g., buffer size, QoS levels), and CUs (e.g., mobility, radio link state), as well as enrichment information (EI) from the near-RT RIC, and use it to execute real-time inference and control of lower-layer functionalities. We build on already available logical components and propose an extension of the O-RAN architecture to include the concept of dApps with minimal modification to the specifications. Finally, we discuss challenges specific to dApps, and provide preliminary experimental results obtained on the Colosseum testbed [2, 12] that demonstrate how dApps can enable a variety of real-time inference tasks at the edge and reduce control overhead.

Why dApps? dApps are distributed applications that complement xApps/rApps to bring intelligence at CUs/DUs and support real-time inference at tighter timescales than those of the RICs. This section identifies their advantages and discusses relevant use cases and applications.

Reduced Latency and Overhead. Moving functionalities and services to the edge is one of the most efficient ways to reduce latency. The near-RT RIC brings network control closer to the edge, but it primarily executes in cloud facilities [1]. Therefore, data still needs to travel from the DUs to the near-RT RIC, and the output of the inference needs to go back to the DUs/RUs, which causes increased latency and overhead over the E2 interface to support data collection, inference, and control. This can be mitigated by executing real-time procedures at the CUs/DUs directly via dApps, which substantially reduces both latency and overhead (later, we demonstrate a 3.57× overhead reduction).

AI at the Edge. While AI (and specifically ML) is usually associated with data centers with hundreds of GPUs, nowadays there is plenty of evidence on the feasibility of training and executing AI on resource-constrained edge nodes with a limited footprint [13]. GPUs are now smaller, more powerful, cheaper, and widely available. Technological advances in AI have resulted in procedures and techniques (e.g., pruning [13]) that make it possible to compress ML-solutions by 27× and reduce inference times by 17× while resulting in a negligible accuracy loss of 1 percent.
Controlling MAC- and PHY-Layer Functionalities. Another important aspect is related to controlling lower-layer functionalities of the MAC and PHY layers, such as procedures related to scheduling, modulation, coding, and beamforming, which all operate at sub-millisecond timescales and require real-time execution. While xApps can be used to select which scheduling policy to use at the DU (e.g., round-robin), they cannot allocate resource elements to user equipments (UEs) in real time at the sub-frame level (e.g., to perform puncturing and preemption for URLLC traffic). Moreover, many PHY-layer functionalities (e.g., beamforming, modulation recognition, channel equalization, radio frequency fingerprinting-based authentication) operate in the I/Q domain, and recent advances show how these can be executed in software with increased flexibility, reduced complexity, and higher scalability by processing the I/Q samples directly [8]. Because of these tight time constraints and security concerns, xApps and rApps — which operate far from the DUs, unlike dApps — are not suitable to make decisions on these functionalities.

Access DU/CU Data and Functionalities in Real Time. dApps make it possible to access control- and user-plane data that is either unavailable at the near-RT RIC, or available but not with sub-millisecond latency. This includes real-time access to I/Q samples, data packets, handover-related mobility information, and dual connectivity between 5G NR and 4G, among others. By executing at the DUs/CUs, dApps will be able to access UE-specific metrics and data to deliver higher-performance services tailored to individual UE requirements, and instantaneous channel and network conditions.

Extensibility and Reconfigurability. Although there are rare cases where AI has been already embedded into DUs and CUs, the majority of such solutions still leverage hardware-based implementations of MAC and PHY functionalities [1] that strongly limit their extensibility and reprogrammability. On the contrary, the integration of dApps within the O-RAN ecosystem offers the ideal platform for software-based implementations of the above functionalities, and thus facilitates their instantiation, execution, and reconfiguration in real time and on demand. In this context, the O-RAN Alliance is developing standardized interfaces to support hardware acceleration in O-RAN [1], which is a first step toward the integration of AI within DUs and RUs.

Challenges and Open Issues

Despite the above advantages, bringing intelligence to the edge comes with several challenges:

Resource Management. First, AI solutions require computational capabilities to quickly and reliably perform inference. For this reason, the DUs must be equipped with enough computational power to support the execution of several concurrent dApps sharing the same physical resources without incurring resource starvation and/or increased latency due to the instantiation and execution of many dApps on the same node. In this context, GPUs, CPUs, field programmable gate arrays (FPGAs), hardware acceleration, and efficient resource virtualization, sharing, and allocation schemes will play a vital role in the success of dApps.

Softwarized Ecosystem. Similar to the RIC, CUs/DUs will need a container-based platform to support the seamless instantiation, execution, and life cycle management of dApps. In contrast to other virtualization solutions (e.g., virtual machines), this offers a balanced trade-off between platform-independent deployment, portable and lightweight development, and rapid instantiation and execution. At the same time, dApps must not halt or delay the real-time execution of gNB functionalities. In this context, hardware acceleration will be pivotal in guaranteeing that dApps execute reliably and fast.

Standardized Interfaces for DUs/CUs. The execution of intelligence at the edge requires interfaces between DUs, CUs, and dApps that offer similar functionalities to those currently available to the RICs and other O-RAN components. This includes northbound (between DApps and the near-RT RIC) and southbound (between DApps and programmable functionalities and parameters of DUs/CUs) interfaces. In this way, DUs can expose supported control and data collection capabilities to CUs and the near-RT RIC. This is key to make sure that dApps are platform-independent and can seamlessly interact with other O-RAN components and applications.

Orchestration of Intelligence. dApps come with additional diversity and complexity. This calls for orchestration solutions that can determine which control and inference tasks are executed via dApps at CUs/DUs, and which at the near-RT RIC via xApps according to data availability, control timescales, geographical requirements, and network workload, while satisfying operator intents and SLAs. This also includes distributing network intelligence while avoiding conflicts between multiple O-RAN applications controlling RAN components.

Dataset Availability. The reliability and robustness of AI for real-time inference and control will
heavily rely on availability of diverse and heterogeneous datasets. Large-scale Open RAN test-beds such as Colosseum [12] and digital twins will play a relevant role in generating those datasets and train, test, and validate the effectiveness and generalization capabilities of dApps.

**Friction from Vendors.** Traditionally, gNB components host a large part of a vendor’s intellectual property (e.g., schedulers, beamforming, queue management). Enabling third-party applications at DUs and CUs will inevitably reduce the value of such intellectual property. Although the introduction of dApps may foster competitiveness and innovation, it might inevitably find friction from vendors. Another concern is often related to the monolithic development approach of RAN vendors, which would prevent the execution of third-party components such as dApps. Nonetheless, the xApp paradigm has already shown that it is possible to separate the RAN state machine between gNB nodes and the RICs for control in the near- or non-real-time timescales. However, we would like to point out that these two aspects are not road blockers. Indeed, these have already been overcome in the historically closed market of networking solutions for data centers where, despite early friction from manufacturers, software-defined networking (SDN) architectures and related solutions (e.g., P4, OpenFlow, Intel Tofino) have taken over the market and demonstrated how real-time reprogrammability and open hardware are not only possible but extremely effective. This shows that monolithic, inflexible approaches are not the only option, and a similar approach to that of xApps/rApps can be adopted to implement dApps.

**Proposed Architecture**

In this section, we discuss the architecture (shown in Fig. 2) necessary to support dApps while requiring minimal changes to the already existing O-RAN architecture.

**dApps as Softwareized Containers**

Similar to xApps and rApps, dApps leverage a containerized architecture to:

- Seamlessly manage the life cycle of dApps (i.e., deployment, execution, and termination)
- Facilitate the integration and use of new (or updated) functionalities included in newly released O-RAN specifications via software updates
- Provide an abstraction level where the CUs, DUs, and RUs advertise the tunable parameters and functionalities (similar to what is already envisioned for xApps and the E2 interface) to enable dApps tailored to control specific parameters
- Achieve hardware-independent implementations of dApps, which can be offered as standalone O-RAN applications in a marketplace that fosters innovation and competition via openness
- Facilitate the development and use of AI-based solutions for the lower layers of the protocol stack

This approach also requires a resource manager in place that allows containers to access and share the physical resources (e.g., CPUs, GPUs, memory) available in the RAN nodes.

**Leveraging O-RAN Interfaces**

The O-RAN interfaces currently available can be extended and used to support the deployment, execution, and management of dApps:

**Southbound Interfaces.** Currently, the O-RAN specifications do not envision data-driven control based on analysis and inference of user-plane data, including I/Q samples and data packets. However, these can be the basis for several data-driven use cases discussed later. To support these use cases, dApps require southbound interfaces to allow dApps executing at the DU to receive:

- Waveform samples in the frequency domain from the RU over the O-RAN fronthaul interface
- Transport blocks or radio link control (RLC) packets that are already locally available at the DU

Similarly, southbound interfaces must allow dApps executing at the CU to perform inference on locally available data pertaining to Packet Data Convergence Protocol (PDCP) and Service Data Adaptation Protocol (SDAP). As of today, these southbound interfaces are not yet available, but we propose to implement them by adapting and extending the service models (SMs) defined for the E2 interface. In this way, dApps can extract relevant KPMs using the southbound E2-like SM KPM adapted to support dApps within a latency of 10 ms to support real-time execution.
Northbound Interfaces. Similar to how xApps receive EI from the non-RT RIC via the A1 interface, dApps can receive EI from the near-RT RIC via the E2 interface. In this case, xApps process data from one or more gNBs and send EI to the dApps, which use it to make decisions on control operations. For example, a DU can receive traffic forecasts from the near-RT RIC and use this information to control scheduling, modulation and coding scheme (MCS), and beamforming. Similar to xApps, dApps are dispatched via the O1 interface.

Extending Conflict Mitigation to dApps
The O-RAN specifications envision conflict mitigation components to ensure that the same parameter or functionality (e.g., scheduling policy of a gNB) is controlled by at most one O-RAN application at any given time. The introduction of dApps will further emphasize the importance of conflict detection and mitigation at stricter timescales than those currently envisioned by O-RAN. Indeed, dApps require conflict mitigation to identify conflicts between rApps, xApps, and dApps. In this context, pre-action conflict resolution (e.g., those envisioned for the near-RT RIC [11]) can prevent directly observable conflicts between different applications (e.g., two applications controlling the same parameter). On the contrary, those conflicts that cannot be observed directly, but implicit conflicts where two or more applications control different parameters indirectly affecting the same set of KPMs can be mitigated through post-action verification where conflicts are detected by observing the impact and extent that control actions taken by different O-RAN applications have on the same KPMs.

Intent-Based O-RAN Apps Orchestrator
The abundance of O-RAN applications will require automated solutions capable of determining which applications should be executed and where. This task is left to the orchestration module shown in Fig. 2 residing in the non-RT RIC and executing either as an rApp or as a standalone component within the management and orchestration (SMO) domain. This module converts goals and requirements of the operator (e.g., in YAML/XML/JSON format) into a set of O-RAN applications that constitute a fabric of intelligent modules embedding the necessary AI to meet the desired intent. Then it dispatches them from the application catalog where they reside to the RAN location where they are executed, thus creating a complex ecosystem of applications that cooperate to achieve the operator intent. To achieve this, the orchestrator needs to understand the intent specified by the operator, and compute the optimal configuration and set of applications to instantiate and where [14]. This is performed by ensuring that applications are executed only at network nodes:

- Where input data can be made available within the required timescale
- That can actually control the required parameters and functionalities
- With enough physical resources (e.g., CPUs/GPUs/FPGAs) to support the required applications

For example, if an operator wants to perform real-time beam detection and traffic forecasting for a set of gNBs, the orchestrator needs to deploy a dApp that executes at the DU (where the I/Q samples are available through the Open Fronthaul interface) to perform beam detection, and an xApp at the near-RT RIC (which receives traffic-related KPMs from the CUs via the E2 interface) to perform traffic forecasting.

dApp Controller and Monitor
This component is hosted in the near-RT RIC, (Fig. 2) and is in charge of controlling and monitoring dApps executing at the gNBs. Specifically, it ensures that dApps meet the desired QoS levels and are in line with the operator intent. As a possible extension, this component can also convert an xApp into multiple atomic dApps dispatched and executed at the gNB components to provide finer control of the RAN procedures. In this case, the dispatching can be coordinated by the non-RT RIC and performed via the O1 interface.

Use Cases and Results
Now we discuss relevant use cases that would benefit from dApps and present preliminary results that demonstrate how dApps can effectively reduce overhead over O-RAN interfaces while supporting AI solutions for real-time control of the RAN.

Beam Management
dApps can be used to extend the beam management capabilities of NR gNBs. The 3GPP specifies a set of synchronization and reference signals to evaluate the quality of specific beams, and to allow the UE and RAN to use intelligent algorithms [8, 15] that select the best combination of transmit and receive beams. These techniques, however, require a dedicated implementation on RAN components that vendors offer as a black box. In this case, xApps and rApps can only embed logic to control high-level parameters, for example, select and deploy a codebook at the RU based on KPMs or coarse channel measurements. On the contrary, dApps can support custom beam management logic where the dApp itself selects the beams to use and/or explore, rather than xApps providing high-level policy guidance.

For example, in [8] we introduced DeepBeam, a beam management framework that leverages deep learning on the I/Q samples to infer the
angle of arrival (AoA) and which beam is the transmitter using a certain codebook. DeepBeam is thus an example of a data-driven algorithm that cannot be deployed at the RICs as it requires access to user-plane I/Q samples for inference. This approach is an ideal candidate for deployment in a dApp, as it requires access to information that can easily be exposed by a DU in real time (i.e., the frequency-domain waveform samples), but cannot be transferred to another component of the network without:

- Violating control latency constraints
- Exposing sensitive user data
- Increasing the traffic on the E2 or O1 interface excessively

As an example, Fig. 3 reports the data rate (and time) needed to transfer the I/Q samples required to perform inference with the DeepBeam convolutional neural networks from a DU to the near-RT RIC. DeepBeam can perform inference and classify the transmit beam and AoA using any kind of samples (e.g., from packets or sounding signals) [8]. As a reference, in this case we consider the number of samples that can be collected through 3GPP NR sounding reference signals (SRSs). We use 3GPP-based parameters and assume that each SRS uses 3300 subcarriers (i.e., the full bandwidth available to NR UEs), 2 symbols in time, and a periodicity \( t_{\text{sounding}} \) of 5, 10, or 20 slots, and that each UE monitors 3 uplink beams. The I/Q samples have 9 bits, and we assume numerology 3 (i.e., slots of 125 \( \mu \)s). The results show that it would be impractical to transfer the required amount of samples because of timing (i.e., no real-time control) and the data rate required, which can reach more than 100 Gb/s in certain configurations.

**Supporting Low-Latency Applications**

Another application of practical relevance is that of dApps to support real-time and low-latency applications by, for example, controlling RAN slicing and scheduling decisions. Indeed, the timescale at which dApps operate is appropriate to access UE-specific information from the DU in real time (e.g., buffer size, MCS profile, instantaneous SINR), and to make decisions on the RAN slicing and resource allocation strategies based on QoS requirements and network conditions.

To showcase the benefits of dApps, we trained a set of ML solutions for O-RAN applications. Specifically, we trained two deep reinforcement learning (DRL) agents that process input data from the RAN (i.e., downlink buffer occupancy, throughput, traffic demand) to control the scheduling and RAN slicing policies of the gNBs (due to space limitations, details are omitted and can be found in [2]). The gNBs are deployed on the Colosseum platform [12] and implement network slices associated with different traffic types: enhanced mobile broadband (eMBB), machine-type communications (MTC), and URLLC traffic.

The agents aim at:

- Maximizing the throughput for the eMBB slice
- Maximizing the number of transmitted packets for MTC
- Reducing the service latency for URLLC

Moreover, we also trained two forecasting models to predict the UE traffic demand and the transmission buffer occupancy.

We consider the case where the DRL agents and the forecasters can run either at the near-RT RIC as xApps or at the DUs as dApps. Both xApps and dApps have been implemented as Docker containers. In the former case, data for inference is received from the E2 interface, while in the latter, data is locally available at the dApp. We also leverage the OrchестRAN [14] framework developed in our prior work to orchestrate the network intelligence according to an operator’s intents, determine how to split and distribute intelligence among xApps and dApps, and dispatch them. Figure 4 shows the impact that running intelligence at the dApps has on the overhead over the E2 interface as a function of the total number of deployed xApps and dApps. We consider three different configurations. In one configuration, the intelligence can only run at the xApps; in the other two, the ML solutions can be executed through either xApps or dApps, with the DUs supporting at most two and eight concurrent dApps. Figure 4 shows that dApps halve the traffic over the E2 interface, with a traffic reduction up to 3.57 \( \times \) with respect to the case with only xApps. Notice that two or more xApps can share the same input data received over the E2 interface. Thus, the traffic over E2 does not linearly grow with the number of xApps.

To further demonstrate the importance of controlling RAN behavior in real time, we ran extensive data collection campaigns on Colosseum [2, 12], and demonstrated the impact of selecting different RAN slicing (i.e., the ratio of physical resource blocks [PRBs] reserved exclusively to URLLC traffic) and scheduling strategies (i.e., round-robin [RR] and proportional fair [PF]) on the application-layer latency of URLLC traffic. The results reported in Fig. 5 demonstrate the importance of joint slicing and scheduling control to support URLLC use cases. For example, when less than 30 percent of resources are reserved for the URLLC traffic, selecting the PF scheduling algorithm ensures the lowest latency. On the contrary, RR works best when more PRBs are reserved for URLLC communications, with end-to-end latency values as low as 4 ms. These results show that achieving ultra-low latency still requires decisions made at the DUs directly via dApps to ensure a tolerable end-to-end latency level despite rapidly changing channel and network conditions (e.g., buffer size, traffic load).

**Conclusions**

The availability of data-driven, custom control logic is one of the major benefits of the O-RAN architecture. In this article, we propose to extend this even further with the concept of dApp, distributed O-RAN applications executing at the DU and CU, and complementing xApps and rApps. We first discuss the benefits introduced by dApps, which include real-time control for a set of parameters that cannot otherwise be optimized with near-RT or non-RT control loops. We discuss challenges, related to standardization, the need for resources and softwareized platforms, and orchestration of the functionalities. We then provide details on an architectural extension that enables the dApp vision and illustrate two relevant use cases. Our discussion shows that while dApps are well suited to augment O-RAN control and monitoring operations, there are still a few aspects that need further...
These include integration with data factories and digital twins for reliable AI, well-defined interfaces between dApps and CU/DU functionalities, and reduced friction from vendors.

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