Empowering Smart Factories with O-RAN

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***Abstract*—It is envisioned that 6G mobile networks will enhance and majorly empower the Industry 4.0 paradigm, evolving towards smart factories with optimized and customized services. Especially the smart factory scenario with high-capacity data communication, which requires the usage of new portions of the electromagnetic spectrum (mmWave/sub-THz), is presenting us with new challenges, both in communications and networking. This article discusses the new challenges arising from high-capacity data communications in smart factories. It proposes extensions to the current Open Radio Access Network (O-RAN) standards for 6G networks to enable further evolution of Industry 4.0 and beyond. We motivate the need for real-time functionalities in O-RAN and an extended interface to the user equipment (UE) to allow for its fine-granular control.**

I. Introduction

One of the most prominent use cases for 6G is mobile networks for smart factories. In this scenario, radio coverage, bandwidth, and dependability/security have different requirements and opportunities than traditional cellular networks. Smart factory automation typically has stringent requirements for determinism, low latency, and reliability. Moreover, some applications, such as manufacturing and industrial IoT, require support for multiple concurrent connections between machines and sensors. The newly defined smart factory services are embracing all service classes foreseen in the fifth-generation (5G) mobile networks, such as Enhanced Mobile Broadband (eMBB), Massive Machine Type Communication (mMTC), and Ultra Reliable Low Latency Communication (URLLC) [1]. Currently, 3GPP defines the usage of the millimeter wave (mmWave) band for 5G. Especially for the smart factory scenarios, the sub-terahertz (sub-THz) bands are considered the next frontier to be explored in 6G networks [2]. These new high-frequency regimes challenge the design of the Radio Access Network (RAN) control plane by demanding real-time control loops to be executed at the distributed unit (DU) and Radio Unit (RU) function levels.

With the primary challenge in real-time control and operation, efforts are underway in the Open Radio Access Network (O-RAN) standards specification by O-RAN Alliance, where it is considered that a near-real-time action needs to be completed in a time frame from 10 milliseconds up to 1 second. Anything below that time is considered real-time, and above that, non-real-time. On the other hand, O-RAN does not specify a real-time controller in its current version. In the literature, efforts are already made towards implementing real-time control in O-RAN [3], [4] to support demanding 6G network use cases, such as for smart factories. This is facilitated by the architectural component referred to as RAN Intelligent Controller (RIC). This new architectural component provides a centralized network abstraction, allowing operators to implement and deploy custom control loops in the RAN. The real-time RIC, considering the challenges of the new high-frequency bands in smart factories, can be identified as the key component for real-time control of future smart factories.

This article discusses the new challenges arising from high-capacity data communications in smart factories. It proposes extensions to the current O-RAN standards for 6G networks to enable further evolution of Industry 4.0 and beyond. We motivate the need for real-time functionalities in O-RAN and an extended interface to the user equipment (UE) to allow for its fine-granular control. We also present the opportunity of interfacing with novel technology solutions such as Reconfigurable Intelligent Surfaces (RISs) to provide reliability to the communication system in a smart factory. Our analysis considers two main principles and their extensions needed to empower smart factories with O-RAN: functional disaggregation and centralized intelligent control. In the first, we discuss virtualized functionalities across multiple network nodes: centralized unit (CU), DU, and RU and their role in building smart factories. The second principle is the RIC and the opportunities and challenges it presents for smart factories. This work summarizes a broader tutorial by the same authors available as a preprint [5].

II. Evolution of Mobile Networks for Smart Factories

Increasing bandwidth has historically driven mobile network generation (4G/5G/B5G). In the 5G evolution, smart factories were identified as promising user candidates, as they consist of a dense concentration of intelligent mobile robots requiring low latency and high reliability for control. Moreover, high data rates for transmitting high-definition images or maps are already processed by advanced Artificial Intelligence and Machine Learning (AI/ML) algorithms. As consolidated by the 5G Alliance for Connected Industries and Automation

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(5G-ACIA)[1], several future industrial use cases will have hard real-time requirements, demanding decision-making within milliseconds or even microseconds.

In the further evolution of mobile networks towards 6G, there are predictions of peak data rates of 1 Tbps and guaranteed rates of up to 1 Gbps for 95% of User Equipments (UEs), where yet more new service classes and Key Performance Indicators (KPIs) are arising from smart factories. Non-public (private or campus) networks deployed in smart factories consist of a dense concentration of intelligent mobile robots requiring low latency, high reliability, and high data rates. A mix of characteristics of URLLC and mMTC was also found to be suitable for some factory applications, originating the Massive URLLC (mURLLC) [6] class of service. This new class of service would be necessary to support, for example, a dense concentration of remote-controlled intelligent mobile robots operating on the factory floor. We envision this new service to deliver user-experienced data rates up to 1 Gbps while meeting latency requirements of sub-10 ms in the RAN. It is worth noting that the reliability KPI of URLLC services is envisioned to rise by at least one order of magnitude (99.99999%).

A recent survey from the O-RAN next Generation Research Group (nGRG), where major technology companies were inquired about 6G use cases and potential technology gaps, confirmed a significant interest in specialized vertical industries, such as smart factories (Report RR-2023-01). Following a similar trend, both the Next G Alliance [7] and the ITU-T Focus Group FG-NET2030 [8] published reports on 6G use cases and applications. From the listed reports, it is clear that smart factories will continue to evolve in the context of next-generation mobile networks, such as 6G.

Figure 1 illustrates the state-of-the-art O-RAN architecture as it fits the services in smart factories. Two critical components are to be noted, namely the non-real-time (non-RT) RIC, inside the Service Management and Orchestration (SMO), and the near-RT RIC. The SMO framework connects to RAN nodes of the network through the A1 and O1 open interfaces. The Non-RT RIC focuses on RAN policy management, updates/upgrades, and radio resource management. Moreover, it guides the near-RT RIC via the A1 interface. The policies and higher-layer procedures to be applied on the RAN are handled with the help of rApps running on the non-RT RIC. The near-RT RIC component is located on the network's edge, connecting to the O-CU and O-DU through the E2 open interface, and runs xApps. Intelligent network orchestration can be achieved by deploying AI/ML algorithms on rApps/xApps.

Figure 1 also illustrates a simplified view of the RAN control protocol stack with its distribution among the disaggregated units, as proposed by O-RAN. This protocol stack includes physical and link layer functions that are used for three categories of radio management: (i) short-term radio resource management, which deals with decisions that must be taken within the channel coherence time (such as in multi-antenna processing) and strict latency constraints (such as dynamic

[1]https://5g-acia.org/

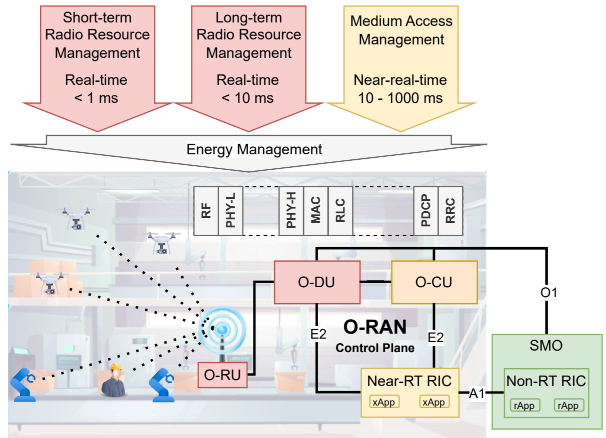

Fig. 1. RAN Management requirements (top), the smart factory network (left), and the O-RAN control plane (right).

scheduling of URLLC traffic). This includes robots/human proximity detection for human safety assurance; (ii) long-term radio resource management, which deals with decisions that can be taken based on large-scale channel variations (such as power control and beam management) and looser latency constraints (such as dynamic scheduling of eMBB traffic), which is employed in Autonomous Guided Vehicle (AGV) tracking and control; and (iii) medium access management which controls the channel multiplexing, RAN slicing, etc., which ensures data security and privacy in the network. The lower the function (closer to the O-RU), the faster its execution needs to be. For higher functions (closer to the O-CU), there is more time flexibility, thus entering the domain of the near-real-time RIC. Currently, O-RAN focuses on offering AI-based control to the higher layers of the protocol stack, with limited flexibility for the lower layers hosted at O-DUs/O-RUs, which is relevant to smart factories. 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 should be made in real-time or within temporal windows shorter than the 10 ms supported by near-RT control loops, which is necessary for several smart factory use cases [9].

III. Technology for O-RAN in Smart Factories

The control of the radio access networks for future smart factories brings RIC closer to the radio interface (O-RU/UE). This is necessary to allow for real-time data-driven decisions. It requires efficient control-data exchange (telemetry and monitoring) among UE, RAN functions (O-RU, O-DU, and O-CU), and RIC. An efficient access/transport network (X-haul) is also required. We dedicate this section to discussing technology and the related features in O-RAN that will be addressed in smart factories. Table I summarizes the enabling technologies discussed along with these features, as also discussed in this section.

TABLE I
O-RAN CHALLENGES FOR ENABLING SMART FACTORY DEPLOYMENT

RAN target	Smart factory requirements	Enabling technology	O-RAN features to be addressed
Radio interface	High capacity + Low complexity	Sub-THz	Specification needed of real-time controllers and interfaces.
	High reliability	RIS	
Monitoring	High data rate + High granularity	Telemetry	More flexible interfaces required and finer-grained data.
X-haul	High data rate + Low latency	Fiber-to-the-Edge	Better definition of interfaces on different RAN functional splits.

A. *Sub-THz communication*

The primary motivation for using communications technologies in the sub-THz spectrum in smart factories is this technology's ability to deliver exceptionally high data rates. While high network capacity can also be achieved at lower frequencies using advanced Multiple Input Multiple Output (MIMO) technologies, the system typically needs to include a large number of relatively low-rate UEs due to practical limitations of the propagation channel and of the hardware, which limits the maximum per-UE data rate. On the other hand, smart factory UEs will require high data rates, with high expectations for video quality and other demanding applications. Thus, sub-Thz makes a strong case for a candidate for communication technology in smart factories.

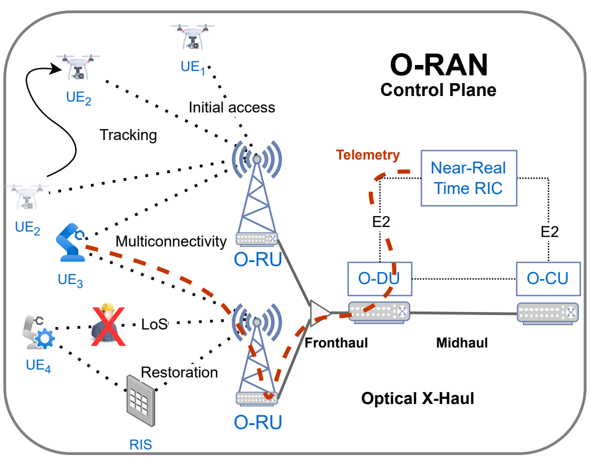

Fig. 2. Smart factory sub-THz networks with O-RAN control plane, and X-Haul network.

Figure 2 illustrates a smart factory network based on sub-THz communications and an O-RAN control plane. By transitioning to sub-THz communication systems and away from the traditional sub-6GHz frequency range, the communication systems migrate from an omnidirectional model of communications to a directional beamformed transmission regime; this is necessary to provide sufficient signal strength. This requires a beam alignment phase during the initial access of a UE (e.g., UE_1), a procedure that increases complexity in higher frequency ranges and with narrower beams. Moreover, as UE moves (e.g., UE_2), it is necessary to maintain the beam alignment condition between the UE and the O-RU, thus requiring fast beam-tracking procedures. Furthermore, due to the physical characteristics of high-frequency beams, they can be easily absorbed by obstacles, thus being susceptible to line of sight (LoS) blocking, which will require multi-connectivity solutions (e.g., UE_3). Alternatively, another new technology can be considered, i.e., RIS (e.g., UE_4).Finally, given the extremely high power consumption at these frequencies, fine-grained energy management may be beneficial in efficiently controlling such devices' activation. From a physical layer perspective, sub-THz smart factory networks are expected to operate under the following conditions:

- highly directional beamforming along unobstructed propagation paths;
- dense network deployments;
- low complexity hardware and signal processing.

While this beam alignment procedure could be theoretically carried at the physical layer using sophisticated hardware (e.g., fully digital beamforming architectures) and signal processing techniques, in practice, due to the need for low-complexity hardware and signal processing, beamforming is typically implemented in 5G mmWave systems using so-called "beam management" protocols that select the best beams from a predefined list of available ones instead of calculating a beam ad-hoc. This list is commonly referred to as a codebook. However, to enable communications at a reasonable range, i.e., in the order of meters, sub-THz systems are expected to use much larger codebooks of much narrower beams than in current mmWave systems. Therefore, classical beam management protocols based on beam sweeping mechanisms quickly become inefficient or impractical. In summary (Table I), the need for high bandwidth capacity with low complexity signal processing pushes the need for sub-THz bands, but O-RAN does not provide in its current specification means for the required customized real-time control.

B. *Reconfigurable Intelligent Surfaces*

As illustrated in Figure 2 (e.g., UE_4), RIS can be a promising technology to support 6G networks in many smart factories to address connectivity issues by providing a *virtual LoS*, i.e., when the direct line of sight is lost between the UE and the RIS [10]. RISs enables novel ways of manipulating and extending the wireless channel to establish the desired communication link, thus increasing communications reliability. When integrating RIS into smart factories, the following features need to be considered: (i) RIS is an external element, not a part of the O-RU, and deserves special consideration; (ii) RIS can be shared among different O-RUs, so an entity needs to decide which surface should be allocated to which

UE/O-RU and (iii) RIS lacks the computational capacities of O-RUs and thus needs to be controlled entirely by the previously mentioned entity. Thus, novel concepts will be required to offload the computations while keeping the tight latency requirements for mechanisms such as beam steering.

Which information needs to be collected to control RIS is still an open issue, such as the user's location and channel conditions. When deploying RIS different channel qualities result from different connections, a trade-off between delay and channel quality needs to be considered. It is also critical to mitigate unintentional interference. Unlike with O-RUs, RISs themselves are not capable of collecting such metrics. Instead, they rely on data gathered by the O-RU and evaluated by another entity to be configured appropriately, which too is an open challenge.

For example, initial access requires new approaches when RIS is involved. Commonly, O-RU performs beam sweeping to find new UEs and determine the best beam for each. If a new user instead appears inside the area only covered by RIS, the RIS side has to perform the beam sweeping. How this is controlled and managed is still an open challenge.Finally, efficient control algorithms will be required to manage real-time interactions between O-RUs, RIS, and UEs, as stated in Table I.

C. RAN Telemetry

Network telemetry solutions are critical to all domains of mobile networks, including mobile RAN, transport, and cloud network infrastructure to enable smart factories. To this end, O-RAN Alliance proposed standards for E2 interface and the near-RT RIC module to enable telemetry for control and management [11]. E2 interface enables self-optimizing networks, anomaly detection, and allocation of radio resources at a coarse-grained level. These telemetry events are expected to occur relatively infrequently, ranging from tens to hundreds per second. The relatively slower pace enables xApps, applications running on the Near-RT RIC, to gather telemetry data, make inferences, and adjust RAN functions based on predefined control policies. For instance, in Fig. 2, telemetry stream flows between UE_3 and the Near-RT RIC. The O-RAN Alliance has defined different ways for the Near-RT RIC to interact with E2 nodes, so-called *E2 interface service models* (E2SMs).

Telemetry technologies in O-RAN face several significant challenges that also need to be addressed in the context of smart factories. One notable challenge is transporting all necessary uplink signals from the physical layer (PHY) to the RIC because RAN generates significant volumes of data at a high frequency. Developing a single API that collects information for different purposes is inefficient. Service models are specialized static APIs integrated into the RAN functions and designed based on specific use cases to capture only the essential information. This service model specifies the particular data that can be collected and the level of granularity at which it is collected. Whenever an xApp developer aims to introduce a new telemetry system, they must create a dedicated service model. However, this kind of data collection architecture cannot scale as the number of xApps increases and evolves. Hence, in the smart factory context, the scope of telemetry needs to be well-designed.

Real-time requirements are exacerbating this problem. Many critical RAN control loops impose strict time constraints that range from tens of microseconds to milliseconds. Applications that require real-time control loops can use a set of pre-defined policies offered by service models, which can run inside the RAN functions to eliminate control plane intervention latency. However, the current approach requires implementing control policies on a use-case basis and has scalability issues. The current E2 interface architecture does not provide the required flexibility for smart factories, as noted in Table I.

D. X-haul Challenges

In future 6G smart factories, optical fiber will serve as the primary transmission medium for wired manufacturing and production components, delivering high bandwidth, low latency, and reliability through Fiber-to-the-Edge (FTTE) technology, as depicted in Fig. 2. The main X-haul-related features that need to be considered in smart factories are from the current optical standards and interfaces that need to be considered in O-RAN architecture, as summarized in Table I. In particular, open X-haul (O-X-haul) interfaces need to be defined and established, depending on the chosen O-RAN functional split. In other words, the way RAN functions are split among O-RU, O-DU, and O-CU determines whether the front- or midhaul protocols and traffic traverse the optical transport network or remain local, defining the latency and throughput requirements towards the underlying optical X-haul. In addition, integrating any optical transport X-haul technology with the O-RAN may also require an adaptation and extension of O-RAN's native interfaces and protocols to seamlessly integrate the optical transport while preserving a cohesive overall performance and functionality of the O-RAN system.

IV. O-RAN Evolution towards 6G Smart Factories

Driven by the technology evolution of O-RAN, smart factories are expected to introduce new components, features, and interfaces to O-RAN. These will include the components required to provide real-time control and proper control data. This section presents a possible evolution of the O-RAN standard towards smart factories and discusses the main components of interest, most notably the evolution of real-time RIC and U1 interface. We finish this section with a short discussion of other technologies and their embedding in smart factories.

Figure 3 presents a schematic based on the O-RAN standard [12] that introduces the Real Time RIC and RIS components, their companion interfaces A1* and E2*, and the novel U1 interface between the UE and the Near-RT RIC (dashed lines). It additionally shows the F1 and Open Fronthaul interfaces, connecting the O-CU to the O-DU, the O-DU to the O-RU, and the Uu interface that connects the UE to the radio base station (composite of O-RU, O-DU, and O-CU).

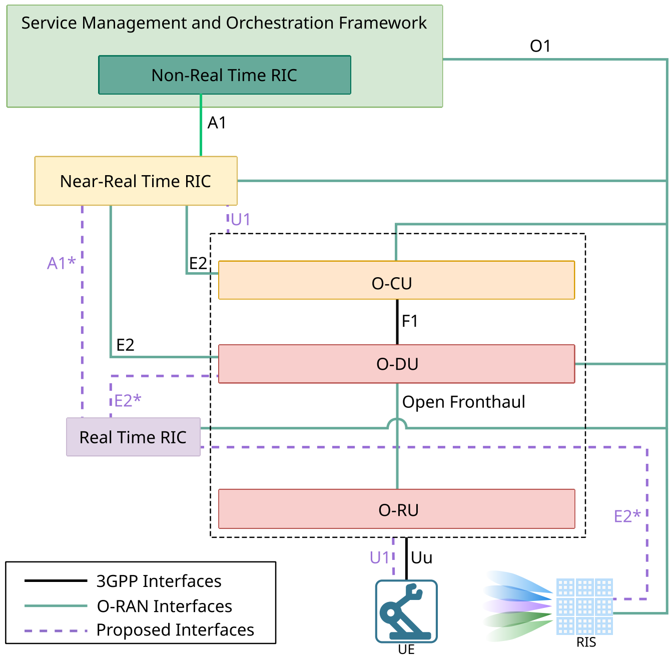

Fig. 3. Proposed extensions to O-RAN.

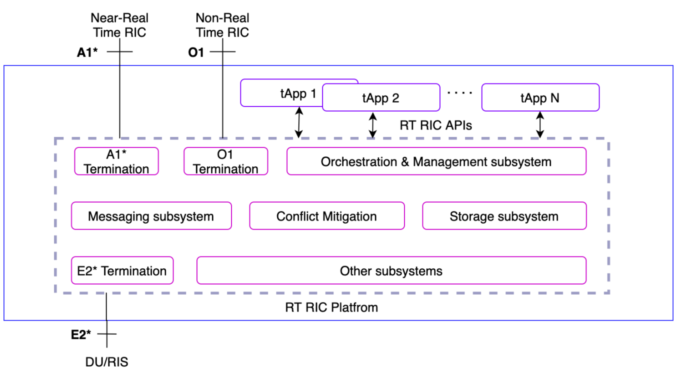

Fig. 4. Real Time RIC architecture.

A. Real Time RIC

We describe the architecture of Real time RIC in Fig. 4. This architecture is intended to be high-level and not exhaustive. At its core, Real time RIC has the RT RIC platform, which enables time-critical applications (tApps) via the RT RIC APIs. It consists of various subsystems like a messaging subsystem for internal messaging, a storage subsystem for storing various kinds of data, and an orchestration and management subsystem for tApps management. The RT RIC Platform also hosts terminations for A1*, O1, and E2* interfaces (Fig. 3).

1) A1 Interface:* This interface is similar to the A1 interface. It will enable a bidirectional flow of enrichment information between near-RT RIC and RT RIC. This information may include policies, intents, predictions, etc.

2) E2 Interface:* The E2* interface is an extension of the current E2 interface that allows RT RIC to communicate with O-DU and RIS with very low latency. It supports new service models that enable real-time data collection and control operations from the O-DU to RT RIC. The E2* interface enables RT RIC to (i) access data like signals sampling data, which is critical for low latency applications but is not available over the regular E2 interface, and (ii) to control operations like beam forming at lower latency than that offered by the regular E2 interface. However, the tight latency constraints on the E2* interface mean that its implementation needs to be significantly faster than the regular E2 interface [3].

B. U1 Interface

Unlike in public networks, UEs in smart factories tend to be not just communication devices with a human interface but platforms with diverse capabilities. These UEs may have their local controllers to manage these functionalities. They might run their apps (uApps) like xApps on the near-RT RIC. Allowing these controllers to exchange enrichment information with near-RT RIC is essential for better control decisions, joint optimizations, etc. Currently, UEs have two control interfaces- Non Access Stratum (NAS) for the core network and Radio Resource control (RRC) for the RAN. NAS is used for procedures like registration, authentication, session management, etc., while the RRC interface is used for bearer management, cell selection, power control, etc. Neither of these interfaces allows UE to communicate to near-RT RIC. Therefore, we propose a new interface named U1.

U1 provides a channel for sharing enrichment information between the UE controller and near-RT RIC (Fig. 3). This interface starts on near-RT RIC and terminates at the UE. U1 messages are tunneled from UE to the O-CU and, from there, sent through another tunnel to Near-RT RIC (using the same logical connection as E2). U1 is a RESTful interface that uses HTTP2 and JSON to transfer the enrichment information. In the future, this could also be used to share AI models between Near-RT RIC and UE [13]. Moreover, U1 provides enrichment information in both directions—from UE to near-RT RIC and near-RT RIC to UE.

C. Further technology evolution

Further technology evolution will be driven by ever-evolving softwarization and virtualization of upcoming 6G smart factory networks. Take an example of In-band Network Telemetry approaches, such as In situ Operations, Administration, and Maintenance (IOAM) or In-band Network Telemetry (INT), that can be included in the O-RAN specification to monitor and verify the correct operation of the network [14]. For instance, INT enables realizing AI/ML-based self-driving mobile networks by collecting fine-grained and real-time telemetry data for use cases beyond 5G.

Over the years, the concept of data collection in networking equipment has evolved significantly. Although packet-sampling-based techniques such as sFlow, Netflow, and IPFIX have been proposed in recent decades, they have struggled to keep up with the need for real-time, accurate, and fine-grained measurements. While various methods have been proposed for in-band network measurement, adopting P4-based in-band network telemetry architecture has gained significant momentum due to the advent of programmable data planes.

In-band telemetry is a promising concept for O-RAN architecture to adapt 6G smart factories, providing end-to-end QoS measurements and visibility in the network.

X-haul evolution will also mark the smart factory network architectures. For instance, the fronthaul control and user plane interfaces between O-RU and O-DU are expected to require Ethernet encapsulation as a prerequisite, with IP encapsulation as optional. At the same time, the payload is defined by one or multiple eCPRI transport headers with the corresponding application data [15]. With Software Defined Networks (SDN) becoming an integral part of the control and optimization of current and future optical transport networks, APIs and protocols such as RESTful APIs or OpenFlow might be needed and adapted to facilitate communication between SDN controllers and O-RAN components. Additionally, the O-RAN dependency on IP/NETCONF for network management tasks, as well as the lack of fully open YANG models covering the full spectrum of initialization, configuration, and management functions of the O-RU and O-DU, as well as of the optical components interconnecting these, make the management interface still heavily dependent on proprietary vendor solutions.

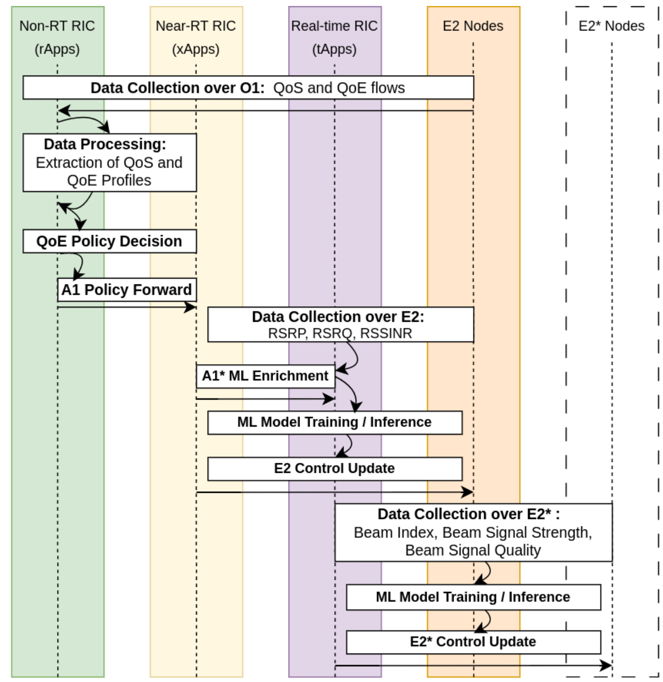

Fig. 5. Information flow of multi-level control loops.

V. Case Study: Multi-level Control

A case study of multi-level control in smart factories exemplifies several of the proposed technology features and standard extensions to the O-RAN. We discuss the communication among AGVs and Autonomous Mobile Robots (AMRs) operating in a time-critical smart factory environment.

Figure 5 presents the main components of the robots' control process. Three control loops define iterations at different levels of the RAN, including data gathering from the network, decision-making, and signaling back to the controlled devices. Decision-making is made on the RICs, and control data is sent and received to/from the E2 and E2* nodes, i.e., O-CU, O-DU, and RIS.

Starting from the first control loop, from the bottom up, as shown in Fig. 5, UE-specific telemetry will be obtained through DL/RL-Assisted Beam Mobility Management tApps running on RT RIC. Real-time tApps will consider Beam Index, Beam Signal Strength, Beam Signal Quality (Signal-to-Noise Ratio and Signal-to-Interference-plus-Noise Ratio), and Beam direction metrics in Beamforming. UE mobility and handover telemetry data such as Speed, Acceleration, and Connection history will provide predictive mobility management. The E2* interface will benefit the O-RAN architecture at the physical layer. Through tApps running on real-time RIC, incoming AGV or AMR localization data will be used in RIS configuration.

In the second control loop, signal data can be fed to the near-RT RIC via the A1* interface, and the second loop can be triggered there. Extended applications such as anomaly detection or traffic steering xApps are designed for different purposes and work on near-RT RIC to detect UEs containing anomalies and take action. However, in the current O-RAN architecture, low-latency data communication cannot be provided for these applications to operate with high reliability and precision. UE-telemetry coming through our proposed A1* interface will allow xApps to work much more efficiently. Signal power information and Physical Resource Block (PRB) data from the UE must be transmitted to anomaly detection or traffic steering xApps with high precision. Collecting this data through RT RIC will fulfill this requirement and increase the learning ability of the AI/ML models running in the second control loop during the offline training phase.

The third and last control loop is Quality of Experience (QoE) rApps running on non-RT RIC via R1 open APIs. Designing QoE rApps for 6G smart factory networks on top of the RIC requires a thorough understanding of the lower control loops, network architecture, the specific requirements of the use case, and the expected user experience. Thus, overall network optimization is achieved through three multi-level control loops.

Proposed A1*, E2*, and U1 interfaces are necessary for real-time communication and robust and efficient operation of multi-level control loops. Resource allocation management based on QoS demand and RAN Slicing competency will become more optimized through tApps, xApps, and rApps, which will communicate through the mentioned interfaces. While ensuring that offline and online training and classification are sufficient through xApps developed on Near-RT RIC, UE-Centric operations are handled with RT-RIC and tApps.

VI. Summary and Final Remarks

This paper focused on the challenges of implementing next-generation mobile networks in smart factory scenarios. To this end, it proposed extensions to the current O-RAN standards. Especially the notion and standardization of a Real-Time RIC module were proposed, as the related interfaces, including the support for various novel technology solutions, such as RISs.

In addition, we proposed a novel interface between the Near-Real Time RIC and the UE and discussed ways to enable tighter coordination of the O-RAN control and the underlying optical transport X-haul control plane. We showed that the roadmap to proposing, standardizing, and implementing an architecture supporting the future smart factory mobile networks is still an open challenge but full of opportunities for technology innovation in both sectors.

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