

Open RAN-empowered V2X Architecture: Challenges, Opportunities, and Research Directions

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Abstract—Advances in the automotive industry and the ever-increasing demand for Connected and Autonomous Vehicles (CAVs) are pushing for a new epoch of networked wireless systems. Vehicular communications, or Vehicle-to-Everything (V2X), are expected to be among the main actors of the future beyond 5G and 6G networks. However, the challenging application requirements, the fast variability of the vehicular environment, and the harsh propagation conditions of high frequencies call for sophisticated control mechanisms to ensure the success of such a disruptive technology. While traditional Radio Access Networks (RAN) lack the flexibility to support the required control primitives, the emergent concept of Open RAN (O-RAN) appears as an ideal enabler of V2X communication orchestration. However, effectively integrating the two ecosystems is still an open issue. This paper discusses possible integration strategies, highlighting the challenges and opportunities of leveraging O-RAN to enable real-time V2X control. Additionally, we enrich our discussion with potential research directions stemming from the current state-of-the-art, and we provide preliminary simulation results that validate the effectiveness of the proposed integration.

Index Terms—Open RAN, V2X, 6G, mmWaves/sub-THz, dynamic control.

I. INTRODUCTION

Connected and autonomous vehicles (CAVs) will revolutionize transportation systems. CAVs will guarantee safer travel, less pollution, and optimized solutions in terms of time and costs with respect to the old branded cars. In this context, connectivity plays a crucial role, providing enablers such as network infrastructure, network distribution, cloud-to-edge resources, localization, data technologies, and governance. The research community is focusing on new directions that may be relevant in future beyond 5G (B5G) and 6G wireless networks, including applications for the automotive sectors, as 5G moves closer to being widely deployed around the world [1].

Currently, dedicated short-range communications (DSRC) and cellular vehicle-to-everything (C-V2X) are the two main V2X communication strategies. The former is supported by the IEEE 802.11p standard, whereas the latter is promoted by the Long Term Evolution (LTE) or New Radio (NR) standards. As suggested by the latest 3rd Generation Partnership Project (3GPP) recommendations, vehicular communications at high frequencies, e.g., millimetre-waves (mmWaves) or sub-THz, are the key 6G technology that will make V2X systems possible [2], [3]. However, those frequencies are not very reliable, particularly in dynamic and prone to link line-of-sight (LoS) blockage environments [4].

Owing to highly dynamic environments, V2X communications experience rapidly varying link conditions, which can greatly affect communication performance. Moreover, the issue of maintaining large-scale connectivity in a highly dynamic environment is the most challenging aspect to address in 6G V2X systems. The high dimensionality of the data, high data rate, stringent latency requirements, challenges with data harvesting and user privacy protection, the dynamic nature of numerous operator parameters and vendor-proprietary data, as well as irrational bandwidth requirements for training, are a few of them [1]. The 6G V2X is an extremely challenging context that calls for sophisticated orchestration, control, and optimization solutions to ensure seamless service provisioning in V2X. However, the required data collection and control primitives go beyond what is currently possible in traditional Radio Access Network (RAN) deployments.

Open RAN (O-RAN) is an emerging architectural overhaul for mobile radio networks that have recently gained extreme popularity, both in the academic and industrial contexts [5], [6]. Through open interfaces, Base Station (BS) disaggregation, and centralized control loop, O-RAN promises to introduce flexibility and programmatic control in the current and future generations of cellular networks. As such, it represents the ideal candidate to unlock the potential of V2X through large-scale data collection and dynamic control.

O-RAN concepts have been applied to optimize several endeavors of traditional RANs deployments [7], with some solutions being also tested in vehicular communication scenarios [8]. However, the research effort concerning the potential synergies of O-RAN and V2X is still unexplored. As such, the challenges of successfully integrating the two technologies are still open, and the opportunities are still to be fully exploited.

In this visionary paper, we discuss the opportunity of leveraging on O-RAN as an open platform to enable dynamic control of vehicular communications. In Sec. II, we will first focus on the challenges of integrating the two architectures by proposing possible strategies. Then, we give a series of research directions to harness the large-scale control capabilities enabled by the aforementioned integration. In Sec. III, we provide some simulation results to show the benefits O-RAN-empowered V2X solutions. Lastly, Sec. IV concludes the work.

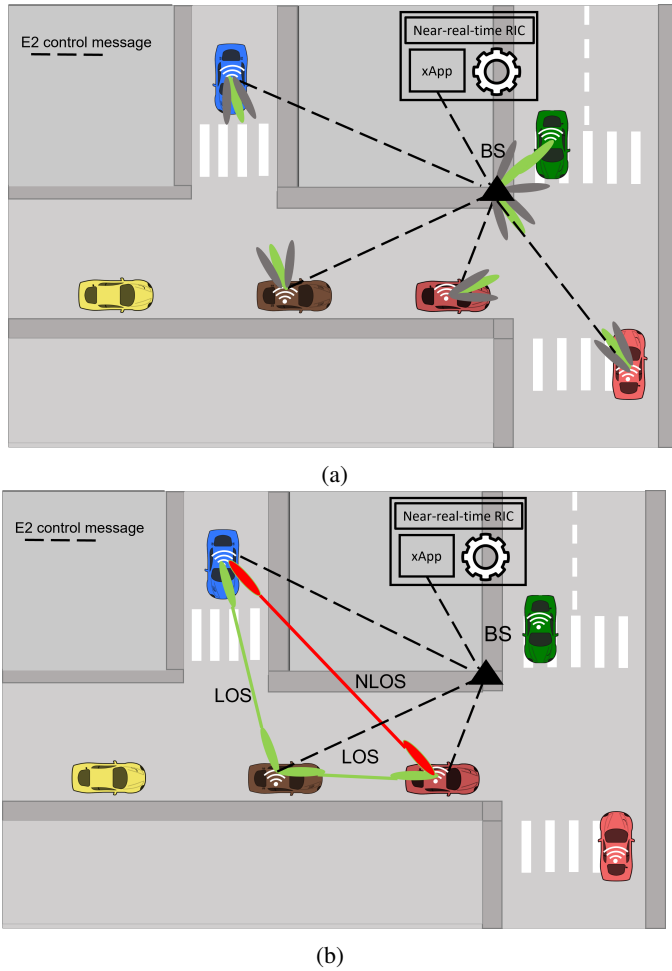


Figure 1: ORAN-empowered (a) beam selection and (b) relay allocation

II. INTEGRATION CHALLENGES AND OPPORTUNITIES

The O-RAN architecture features the possibility of applying centralized control to the RAN through the so-called RAN Intelligent Controllers (RICs). These functional components can implement arbitrary data collection and control logic by communicating with the network infrastructure (i.e. BSs) thanks to open and standardized interfaces. In particular, O-RAN introduced a Near Real-time RAN Intelligent Controller (near-RT RIC), which operates on a 1 ms to 1 s time scale and is capable of operating under stringent latency requirements. Arbitrary data collection and control mechanisms are then implemented through the so-called xApps: network applications that run on the primitives exposed by the near-RT RIC. Additionally, O-RAN has also standardized the Non-Real-Time RIC (non-RT RIC): a centralized control loop operating on a slower time scale but with broader network visibility. As such, it enables large-scale orchestration and policing mechanisms implemented as network applications called rApps. When applied to V2X, these two control loops can potentially unlock significant optimization and orchestration gains with respect to the current architecture.

A. V2X and O-RAN Integration

Due to the peculiarities of the V2X system, some modifications to the O-RAN architecture are required. The RICs communicate with the network infrastructure through open interfaces: the E2 interface for the non-RT RIC and the O1 and O2 interfaces for the near-RT RIC. The E2 interface is functionally split into two protocols: E2 Application Protocol (E2AP) - enabling communication between the RAN component and the near-RT RIC - and E2 Service Model (E2SM) - which defines the control semantics as Service Models (SMs). By standard, a BS is equipped with E2 terminations to enable data collection and control. In V2X systems, an E2 termination could also be included in Road Side Units (RSUs), both to enable their dynamic control and to tap into the wealth of CAV-related information that they make available. E2 messages can thus be multiplexed together with the other communications in the RSU control plane. Additionally, there is a case to be made for including an E2 termination in the CAVs themselves, as it will be motivated in the following paragraphs and showed in Figure 1. However, E2AP does not currently support mobility and proper modifications to the protocol are needed before the CAV can be directly accessed by the xApps deployed on the near-RT RIC. In both cases, new SM definitions will also be required to support data collection and control applied to V2X.

The non-RT RIC employs the O1 interface to apply Service Management and Orchestration (SMO) functions over the entire network infrastructure and the O2 interface to control the life-cycle of network components. These interfaces will require modifications that are naturally similar to the E2 case. In particular, the O1 interface will require the definition of dedicated V2X Management Services or at least the modification of existing ones. Furthermore, inserting O2 terminations in the RSUs could enable adaptive network deployment strategies that can selectively activate/deactivate all the network components of V2X systems to scale the system performance when required and decrease energy consumption and interference when it is possible.

B. Research Directions

In the following, we describe four fundamental open challenges of V2X, highlighting how these can be successfully addressed through O-RAN-based solutions. At the same time, we discuss the key architectural modifications required in each case.

Resources Allocation. Efficient radio resource allocation mechanisms in V2X are required to guarantee robustness against the harsh V2X propagation conditions [9]. This is especially relevant for direct vehicle-to-vehicle (V2V) connections, also known as sidelink. In this case, there is the need to choose the optimal time-frequency resource to be allocated to allow direct communication between the CAVs. According to the standard, a central entity (i.e., a BS or a RSU) is expected to allocate the radio resources. This mechanism is hindered by the limited perception of the central entity with respect to each V2V link condition and traffic requirement

[9]. In this context, an xApp could gather data about the vehicle's position and mobility, as well as channel status and interference profile. This information can be processed to adapt the allocation strategies to the fast-varying V2V environment. As previously mentioned, the O-RAN architecture could be extended to include E2 terminations directly in the CAVs. In this case, the data collection and control procedures could happen directly to the vehicles involved in the communication, unlocking the possibility of extremely fine and precise tuning of the allocation mechanism.

Beam selection and management. Beam-based communications are necessary for the high frequencies employed in V2X. Due to the high vehicular mobility, traditional beam selection and management mechanisms are considered inadequate, and sophisticated solutions are required instead. Data-driven approaches are effective in providing fast beam alignment, and O-RAN represents an ideal enabler for these solutions. For instance, an xApp could process relevant information coming from the urban layout, vehicle positioning, and past successful beam alignment to produce an up-to-date probabilistic codebook and deploy them to the base stations [10]. The same information can be used to train machine learning-based beam steering mechanisms [11]. O-RAN has been specifically designed to facilitate such data-driven control loops. However, currently, standardized SM do not specifically support the collection of the required data types.

Relay Assignment. Propagation at high frequencies is subject to severe attenuation and mostly requires direct link visibility conditions. This is a key issue in dynamic environments such as vehicular ones, where frequent link misalignment and blockage occasions can easily occur. The resulting non-LoS (NLoS) condition leads to severe system performance degradation and, consequently, intermittent connectivity. Link blockage can be mitigated by relaying and multi-hop mechanisms, for example, exploiting nearby CAVs, RSU, or smart environments technologies as Intelligent Reflecting Surfaces (IRS) [12]. However, the limited relaying resources capabilities and the fast changes in the network make the relay assignment a significant challenge in the current V2X systems. In this context, an O-RAN-based solution is capable of determining optimal relay assignment by leveraging on the data collection and information fusion capabilities of the near-RT RIC. Similarly to what has been discussed before, this context makes a case for integrating an E2 termination in the CAVs. As a result of this integration, the relay assignment choices are delivered directly to the involved CAVs, speeding up the process and reducing the signaling overhead. An introductory case study on this challenge will be presented in the next section.

V2X Network Digital Twin. The 6G V2X communications will exploit the cooperation among CAVs to augment environment perception and to enable the creation of a digital replica of the surrounding environments [13]. To obtain an accurate real-time digital reproduction of the physical environment, the envisioned digital twin-enabled V2X system has to use high-definition 3D maps and combine multi-modal sensory data

Table I: Simulation variables

Simulation parameters	
Central Frequency	28 GHz
Max EIRP	23 dBm
Simulation time	300 s
Urban Pathloss model	3GPP and ITU [4]
Vehicular traffic density	50-70 veh/km
Max hops number	4

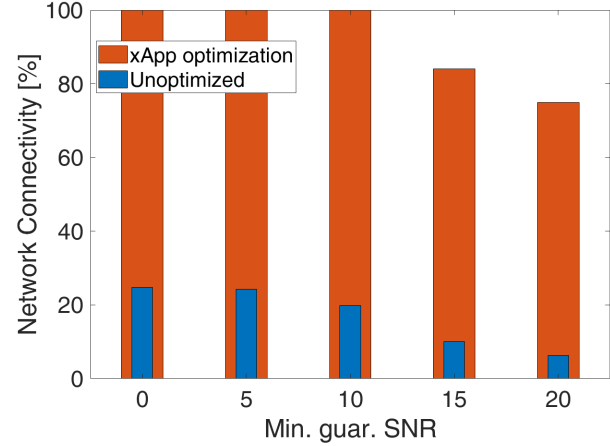


Figure 2: Network connectivity versus different SNR thresholds.

from several vehicles' onboard sensor data. The acquisition of data from the global navigation satellite system (GNSS), cameras, lidars, and radars distributed over multiple road entities must be appropriately orchestrated over a fast 6G V2X RAN. Once again, the O-RAN architecture is well-positioned to take on this orchestration role. Thanks to the fast processing capabilities of the near-RT RIC, the large data volume involved can be gathered, filtered, and pre-processed in parallel over separate network sections. The separated data streams can then be aggregated into the non-RT RIC, where the digital twin is built and kept up-to-date with the fast-changing state of the physical infrastructure. rApps deployed on the non-RT RIC can access the digital twin to produce tightly optimized policies based on a complete and precise vision of the entire physical system.

III. A FIRST SIMULATION ANALYSIS

In this section, we conduct a preliminary case study based on a typical vehicular communication scenario to demonstrate the effectiveness of the proposed system. We simulated multiple CAVs traversing an urban intersection. However, Vehicle-to-Vehicle (V2V) links can be blocked by other moving road users or buildings. RSUs and other Connected and Autonomous Vehicleless (CAVs) can act as relays when Line of Sight (LoS) is obstructed.

We replicated a V2X urban scenario using a vehicular channel simulator [4] with the parameters in Tab. I. We emulated the xApp's behaviour by calculating alternative routes between vehicle pairs using a minimum Signal-to-Noise Ration (SNR)

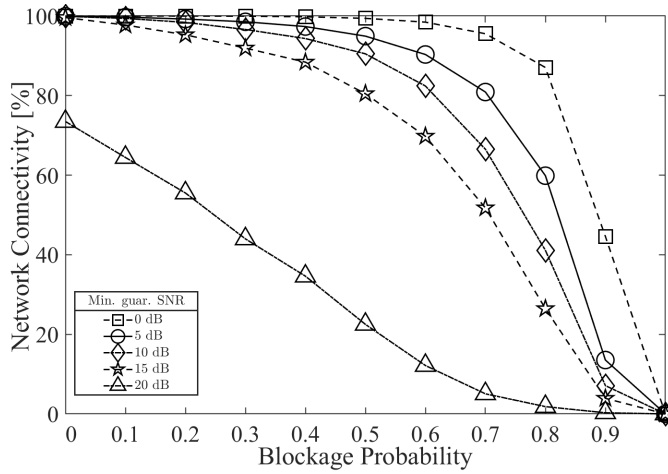


Figure 3: Network connectivity versus blockage probability for different SNR thresholds.

as a constraint. Such a constraint stands for the minimum Quality of Service (QoS) required for different V2V use cases [14].

We use the network connectivity as a performance evaluation metric for assessing the robustness of the V2X network. It is intricately linked to the density of CAVs and the reliability of the vehicle mesh configuration. A robust V2V network connectivity is required to exchange safety-critical information throughout the entire navigation area.

Results in Figure 2 demonstrate that the proposed xApp-empowered system has the potential of guaranteeing high vehicular connectivity even for high levels of minimum guaranteed Signal-to-Noise-Ratio (SNR). The unoptimized baseline approach, which considers only the direct links, shows that no more than 25% of the vehicles can establish a connection throughout the simulation time window. The slight degradation observed at high SNR thresholds primarily stems from the limited availability of links that meet the required criteria.

Figure 3 shows the impact of vehicular blockage on the V2X network and how the xApp reacts to different SNR conditions. We conducted multiple experiments by forcing the higher number of blockers and the minimum SNR to assess the xApp's ability to choose a path according to predefined communication performance criteria, even in very challenging conditions. Indeed, a higher number of blockers corresponds to an increased probability of encountering NLOS links, characterized by lower SNR values. Consequently, the presence of blockers limits the available relay options due to the reduced signal quality, complicating relay selection processes. In environments with dense blocker distributions, the challenges in identifying suitable relays become pronounced, necessitating effective relay selection methods capable of operating effectively under adverse propagation conditions.

IV. CONCLUDING REMARKS

As the world moves towards a more connected and automated future, the need for reliable and efficient communica-

tion between vehicles and network infrastructure has become increasingly important. This paper focused on using Open Radio Access Network (O-RAN) architecture for V2X communication. We debated how the O-RAN architecture has the potential to provide a more flexible, scalable, and efficient solution compared to current V2X systems. Moreover, we discussed novel research directions and justified them through introductory results, which will be subject to further analysis and validation.

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