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5G NR-V2X: Towards Connected and Cooperative Autonomous Driving

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***Abstract*—5G New Radio (NR) is touted as a pivotal enabling technology for the genuine realization of connected and cooperative autonomous driving. Despite numerous research efforts in recent years, a systematic overview on the role of 5G NR in future connected autonomous communication networks is missing. To fill this gap and to spark more future research, this paper introduces the technology components of 5G NR and discusses the evolution from existing cellular vehicle-to-everything (V2X) technology towards NR-V2X. We primarily focus on the key features and functionalities of physical layer, Sidelink communication and its resource allocation, architecture flexibility, security and privacy mechanisms, and precise positioning techniques. Moreover, we envisage and highlight the potential of machine learning for further performance enhancement in NR-V2X services. Lastly, we show how 5G NR can be configured to support advanced V2X use cases.**

I. INTRODUCTION

The fifth generation (5G) mobile communication networks, aiming for highly scalable, converged, and ubiquitous connectivity, will be a game changer in opening the door to new opportunities, services, applications, and a wide range of use cases. One of the most promising 5G use cases, expected to shape and revolutionize future transportation, is vehicle-to-everything (V2X) communication, which is seen as a key enabler for connected and autonomous driving. V2X communications, as defined by the 3rd generation partnership project (3GPP), consists four types of connectivity: vehicle-to-vehicle (V2V), vehicle-to-pedestrian (V2P), vehicle-to-infrastructure (V2I), and vehicle-to-network (V2N).

To fully support autonomous, next generation vehicles will be equipped with a wide range of embedded sensors including cameras, radar, global navigation satellite system (GNSS) and others. However, the functionality of these sensors may be compromised due to the highly complex vehicular environment. For example, in-car cameras and radar sensing may not perform well in many non-line-of-sight scenarios where nearby vehicles are occluded. By equipping vehicles with cellular V2X (C-V2X) technology to complement embedded sensor functions and to interact with external vehicles and infrastructure, a higher level of situational awareness can be achieved enhancing autonomy for connected vehicles [1]. This paper introduces 5G New Radio (NR), which is a promising technology to realize C-V2X communications and autonomous driving. To support this, the 5G network will provide lower latency, higher throughput, improved robustness in mobility, and higher energy efficiency. There are three major communication service categories of 5G: enhanced mobile broadband (eMBB), massive machine-type communications (mMTC) and ultra-reliable low-latency communications (URLLC). eMBB aims to provide data rates of at least 10 Gbps for uplink and 20 Gbps for downlink, plays a pivotal role for multimedia services and high-precision map downloading. mMTC will allow future driverless vehicles to constantly sense and learn environment changes using embedded sensors. URLLC targets 1 ms over-the-air round trip time (RTT) and 99.999% reliability for a single transmission, which are critical for autonomous driving. A wide range of advanced NR-V2X use cases have been illustrated in Fig. 1.

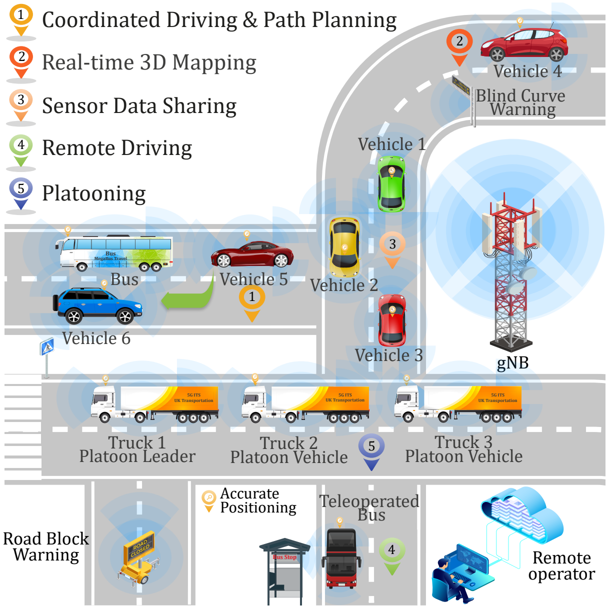

Fig. 1: Advanced use cases and services of NR-V2X.

With the aim of realizing connected and cooperative autonomous driving with the aid of NR-V2X, we first discuss the 3GPP standardization roadmap, focusing on key features of NR-V2X communications. Next, we present the design considerations, technology components, functionalities, and

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key enhancements of NR-V2X. We provide an insight into novel and powerful attributes of the NR physical layer (PHY). We discuss NR Sidelink (SL) resource allocation and highlight its enhanced functionalities for broadcasting and multicasting. We briefly outline 5G NR architecture deployment options focusing on flexible mobility and dual connectivity. We explain security and privacy issues of NR-V2X communications. In addition, we discuss how machine learning can be exploited to improve the performance of V2X communications. Finally, we discuss advanced use cases for tangible applications of NR-V2X.

II. 5G NR: 3GPP ROADMAP

The first C-V2X specifications, incorporating long-term evolution (LTE) communication technology into vehicular networks (denoted LTE-V2X) were introduced in 3GPP Rel. 14 [1]. LTE-V2X supports two operation modes: 1) Network-based mode, which uses the LTE-Uu interface as the logical interface between a vehicle and network infrastructure; 2) Direct mode, which is based on device-to-device (D2D) communication defined in 3GPP Rel. 13 [2], allowing devices to communicate directly (e.g., V2V, V2P, V2I) via the PC5 interface, known as LTE SL, without involving network infrastructure. Despite all the advantages of LTE-V2X, it does not address the stringent requirements for autonomous driving, specifically those required by the URLLC service. 3GPP has introduced 5G NR with the ambition to fulfill the 5G requirements and defined the standardization roadmap in two consecutive phases. Phase 1, Rel. 15, the first step of the 5G NR standardization roadmap, focused on eMBB and an initial study of URLLC [3]. Phase 2, coming in 3GPP Rel. 16 and beyond, focuses on expanding and optimizing the features developed in Phase 1. The key targets of Phase 2 are to enhance URLLC and network performance [4]. NR-V2X, in addition to broadcast transmissions, will support both unicast and multicast transmissions. 3GPP Rel. 17 will target 5G NR SL resource allocation mechanisms for power-efficient operation, coverage extension, mobility and latency improvement in V2X communications. Fig. 2 illustrates the 3GPP roadmap towards NR-V2X.

III. KEY FEATURES OF 5G NEW RADIO

This section summarizes NR key features that will fulfill the diverse and stringent requirements of autonomous driving from the network, user, applications and use cases perspectives.

A. The NR-V2X Physical Layer (PHY) Design

The 5G NR PHY design needs to deal with harsh V2X channel conditions and diverse data service requirements, specifically: 1) Highly dynamic mobility from low-speed vehicles (e.g., less than 60 km/h) to high-speed cars/trains (e.g., 500 km/h or higher). The air interface design for high mobility communication requires more time-frequency resources to deal with the impairments incurred by Doppler spread and multipath channels. 2) Wide range of data services (e.g., in-car multimedia entertainment, video conferencing, high-precision map downloading, etc) with different quality-of-service (QoS) requirements in terms of reliability, latency, and data rates. Some requirements (e.g., high data throughput against ultra-reliability) may be contradictory and hence it may be difficult to support them simultaneously.

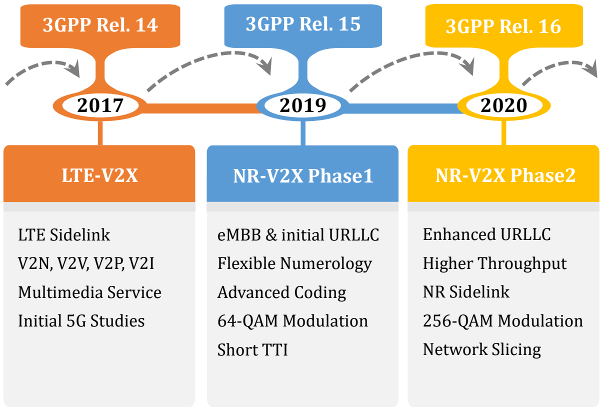

Fig. 2: 3GPP roadmap towards 5G NR-V2X.

Against this background, the frame structure of 5G NR [5] allows flexible configurations to enable support for a majority of C-V2X use cases. Similar to LTE, 5G NR uses orthogonal frequency-division multiplexing (OFDM) whose performance is sensitive to inter-carrier interference (ICI) incurred by carrier frequency offsets and Doppler spreads/shifts. The maximum channel bandwidth per NR Carrier is 400 MHz compared to 20 MHz in LTE. Identical to LTE, the frame length is fixed to 10 ms, the length of a subframe is 1 ms, the number of subcarriers per resource block (RB) is 12, and each slot comprises 14 OFDM symbols (12 symbols for extended cyclic-prefix mode). Compared to the LTE numerology with subcarrier spacing of 15 kHz, the NR frame structure supports multiple subcarrier spacings including 15, 30, 60, 120, or 240 kHz. A small subcarrier spacing can be configured for C-V2X use cases requiring high data rates but with low/modest mobility, while a large subcarrier spacing is of particular interest for the suppression of ICI in high mobility channels.

Channel coding plays a fundamental role in C-V2X PHY to accommodate a diverse range of requirements in terms of data throughput, packet length, decoding latency, mobility, rate compatibility, and capability of supporting efficient hybrid automatic repeat request (HARQ). Unlike LTE, which uses convolutional and Turbo Coding, two capacity-approaching channel codes have been adopted in 5G NR [6]: low-density parity-check (LDPC) codes and polar codes. While the former is used to protect user data, the latter is for control channels in eMBB and URLLC which require ultra-low decoding latency. Excellent quasi-cyclic LDPC (QC-LDPC) codes have been designed for 5G NR. The unique structure of QC-LDPC allows parallel decoding in the hardware implementation (i.e., lower decoding latency).

C-V2X services in 5G NR are expected to share and compete with other vertical applications for system resources (e.g., spectrum/network bandwidth, storage and computing, etc.) within a common physical infrastructure. A central question is how to design an efficient network to provide guaranteed

QoS for V2X while balancing data services to other vertical applications. Network slicing (NS), the paradigm to create multiple logical networks tailored to different types of data services and business operators [7], offers a mechanism to meet the requirements of all use cases and enables individual design, deployment, customization, and optimization of different network slices on a common infrastructure. Although initially proposed for the partition of core networks using techniques such as network function virtualization (NFV) and software-defined networking (SDN), the concept of NS has been extended to provide efficient end-to-end data services by slicing PHY resources in radio access networks (RANs). The slicing of PHY resources mainly involves the dynamic allocation of time and frequency resources by providing multiple numerologies, each of which constitutes a set of data frame parameters such as multi-carrier waveforms, sub-carrier spacings, sampling rates, frame and symbol durations.

B. NR SL Features and Resource Allocation

Through SL protocols, each vehicle can directly exchange its own status information, such as location, speed, trajectory and intended local route, with other vehicles, pedestrians, and road infrastructure. The basic functionalities of the NR SL are the same as those in the LTE SL. However, NR SL introduces major enhancements in functionality that enable advanced 5G use cases and could enhance autonomous driving. The key enhancements in the NR SL protocols are as follows: i) SL feedback channel for higher reliability and lower latency, ii) carrier aggregation with support for up to 16 carriers, iii) modulation scheme supporting up to 256-QAM for increased throughput per single carrier, iv) power control mechanism for QoS management, and v) modified resource scheduling for reduced resource selection time. Moreover, NR-V2X, along with traditional broadcast communication, supports unicast and groupcast communications, where one vehicle can transmit different types of messages with different QoS requirements. For instance, a vehicle can transmit some periodic messages by broadcasting and aperiodic messages through unicast or groupcast. The reliability of unicast and groupcast communications can be improved via a re-transmission mechanism. It is noted that the re-transmission in LTE-V2X is carried out in a blind manner, i.e., when the source vehicle uses re-transmissions, it re-transmits regardless whether the initial transmission was successful or not. In the case of successful transmission however, such blind re-transmission leads to resource wastage. When several transmissions are required, blind re-transmission may be highly inefficient. In NR-V2X, a new feedback channel, called physical sidelink feedback channel (PSFCH), is introduced to enable feedback-based re-transmission and channel state information acquisition [8]. Detailed operations and procedures of PSFCH feedback transmissions is presented in [9].

In NR-V2X, the available resources for direct communication between vehicles can be either dedicated or shared by cellular users. To manage the resources, two SL modes are defined for NR-V2X, Mode-1 and Mode-2. In SL Mode-1, it is assumed that the vehicles are fully covered by one or more base stations (BSs). The BSs allocate resources to vehicles based on configured and dynamic scheduling. Configured scheduling adopts a pre-defined bitmap-based resource allocation, while dynamic scheduling allocates or reallocates resources every millisecond based on the varying channel conditions. In SL Mode-2, resources need to be allocated in a distributed manner without cellular coverage. There are four sub-modes, sub-mode 2(a)-2(d) for Mode-2. In 2(a), each vehicle can select its resources autonomously through a sensing based semi-persistent transmission mechanism. 2(b) is a cooperative distributed scheduling approach, where vehicles can assist each other in determining the most suitable transmission resources. In 2(c), a vehicle selects the resources based on preconfigured scheduling. In 2(d), a vehicle schedules the SL transmissions for its neighbouring vehicles.

C. Dual Connectivity and Mobility Robustness

3GPP has defined multiple options for 5G NR deployment, which can be broadly categorized into two modes, non-standalone (NSA) and standalone (SA). In order to accelerate the deployment of 5G networks, the initial phase of NR will be aided by existing 4G infrastructure and deployed in NSA operation mode. In contrast, the full version of NR will be implemented and deployed in SA mode.

The NSA mode supports interworking between 4G and 5G networks. The NSA architecture is comprised of LTE BS (eNB), LTE evolved packet core (EPC), 5G BS (gNBs) and 5G core (5GC) network. NSA has the salient advantage of shorter implementation time as it leverages an existing 4G network with only minor modification. It can support both legacy 4G and 5G devices. Essentially, NSA mode implies multi radio access technologies (RATs) and dual connectivity for end-users [10]. Among all the NSA deployment options, 3, 4 and 7 are the most common options supporting dual connectivity and mobility robustness, as illustrated in Fig. 3.

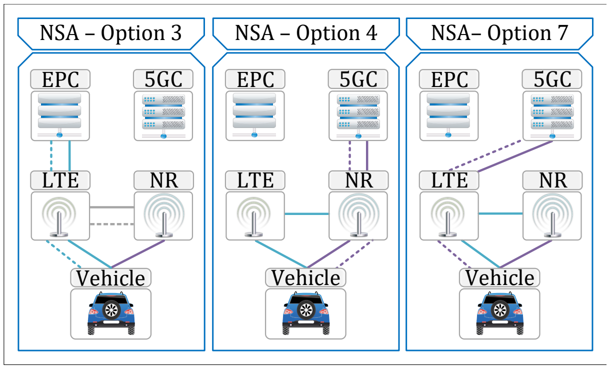

Fig. 3: NSA deployment options for 5G NR.

The SA mode consists of only one technology generation, LTE or NR. The SA operation in NR is envisaged to have an entirely new end-to-end architecture and a 5GC network. In fact, gNBs, directly connected to 5GC, utilizing 5G cells for both control and user plane transfer. The SA mode is designed to enhance URLLC, whilst fulfilling the requirements of eMBB and mMTC. The key advantages of SA mode are easy deployment and improved RAT and architecture performance.

That said, it requires the 5G RAT to be rebuilt and a cloud native 5G core to fully realize all the potential benefits of a 5G network. In addition, the SA mode facilitates a wider range of new use cases and supports advanced NS functions.

D. Security Aspects of 5G NR-V2X

5G is an evolution of 4G and inherits some of its basic security mechanisms. However, the 5G architecture is fundamentally different from a 4G network and supports cloud-native core, virtualization, SDN, NFV, disaggregated RAN, user and control separation, edge computing, and NS. These radical changes might bring new type of threats and vulnerabilities, hence, new mechanisms need to be adopted to address the 5G security requirements, particularly for NR-V2X. Notwithstanding, the required functionalities and security enhancement for 5G networks are largely dependent on NSA or SA deployment strategy. The scope of security enhancements in NSA is relatively limited, as it is dependent on the underlying 4G deployment to facilitate the requirements of 5G communications. In contrast, the scope with SA is wide and requires novel security features and mechanisms to be developed from scratch to tackle security challenges.

From an architectural perspective, the security and privacy issues in 5G networks can be broadly categorized into three tiers, namely, end users or nodes (e.g., vehicles), access network, and core network. In 5G, the core network security consists of a range of functions. The authentication function (AUSF) is a core entity introduced to perform authentication of a UE. The security anchor function (SEAF), defined in Rel. 15, is a new function which is used to enhance security at network level and to provide flexible authentication and authorization schemes. SEAF can provide more flexible deployment of access and mobility management function (AMF) and session management function (SMF) entities. With this feature, device access authentication is separated from data session setup and management, which provides secure mobility and authorized access to V2X services for vehicles and users. Moreover, 5G enhances authentication by exploiting the extensible authentication protocol (EAP) thus increasing the flexibility of authentication to support both 3GPP and non-3GPP access networks (e.g., Wi-Fi). In a 5G access network, a gNB is logically split into central unit (CU) and distributed unit (DU). These modules interact via a secure interface. The security provided with this interface can prevent an attacker from breaching the operator's network, even in the case of successful access to the radio module [11].

As long as NS is concerned, each slice could accommodate a particular service and thereby may require differentiated security capabilities. It is vital to develop slice-level security, user authentication, and privacy protection mechanisms. The access to a NS should be granted only to authenticated subscribers. 5G introduces the concepts of slice isolation, robust slice access, and slice security management to ensure that an attack mounted on one a slice does not increase the risk of attack on another slice.

The general principle of user equipment (UE) authorization is similar to that in LTE systems. The only difference is that authorization in 5G is provided by the policy control function (PCF). Autonomous driving demands a real-time and reliable authentication process while keeping the overhead introduced by security protocols as low as possible.

In terms of privacy protection, the major concern is related to encryption schemes for concealing the subscriber permanent identifier (SUPI) to protect user data leakage through initial messages. In 5G, subscriber/device privacy is provided by SUPI which is a major change from LTE with international mobile subscriber identity (IMSI). While IMSI is typically transmitted in plain text over the air, SUPI travels in ciphertext over the radio link to be protected against spoofing and tracking. The second major issue is related to user data privacy over PC5, as vehicles may need to share private information (e.g., user identity). While restrictions are required with regard to the sharing of private data, some of them may need to be accessible to trusted authorities (e.g., police, rescue team) to detect malicious attackers or to ensure timely handling of emergencies such as accidents.

E. Precise positioning

Satellite-based positioning systems are unable to provide sufficiently accurate positioning needed for autonomous driving. LTE-V2X has been exploiting several radio signal-based mechanisms to improve the positioning accuracy, namely: downlink-based observed time difference of arrival (OTDOA), uplink time difference of arrival (UTDOA), and enhanced cell ID (E-CID). NR-V2X combines the existing positioning technologies with new positioning methods such as multicell round trip time (Multi-RTT), uplink angle of arrival (UL-AoA), downlink angle of departure (DL-AoD), and time of arrival (TOA) triangulation to provide more precise vehicle positioning [12]. Moreover, NR-V2X can also use real-time kinematic (RTK) positioning, which is an accurate satellite-based relative positioning measurement technique, to provide a centimetre-level positioning accuracy in some outdoor scenarios. By using wider bandwidth, flexible massive antenna systems, and beamforming, NR-V2X will provide more precise timing and accurate measurement of equivalent signal techniques in LTE-V2X. Note that no single approach may be able to reliably provide the positioning accuracy required for autonomous driving in all environmental conditions. Hence, hybrid solutions that optimally combine advanced NR-assisted positioning techniques with satellite and sensor systems into next generation vehicles, are the most promising approaches to achieve vehicle positioning accuracy for autonomous driving. Table I summarizes a comparison between NR-V2X and LTE-V2X in respect to the aforementioned features.

IV. APPLICATIONS OF MACHINE LEARNING FOR NR-V2X

Rapidly varying vehicular environments due to vehicle mobility, frequent changes of network topology and wireless channel, as well as stringent requirements of URLLC, increase the system design complexity for a end-to-end V2X network. In such a dynamic environment, machine learning (ML) can be an effective tool to address operational challenges compared to

TABLE I: Comparison between LTE-V2X and NR-V2X.

Features	LTE-V2X	NR-V2X
Subcarrier Spacing	15 kHz	15,30,60,120, 240 kHz
Carrier Aggregation	Up to 32	Up to 16
Channel Bandwidth	20 MHz	400 MHz
Latency	< 10 ms	< 1 ms
Reliability	95-99%	99.9-99.999%
Channel coding	Turbo	LDPC, Polar
Network Slicing	No	Yes
Modulation	64-QAM	256-QAM
Communication Type	Broadcast only	Broadcast, Multicast, Unicast
Retransmission	Blind	PSFCH
Security and Privacy	Basic	Advanced
Positioning Accuracy	> 1 m	0.1 m

traditional network management approaches which are more suitable for relatively low mobility scenarios. As aforementioned, vehicles are envisioned to be equipped with many on-board advanced sensors which will generate a high volume of data. In this regard, ML can efficiently analyse large volumes of data, find unique patterns and underlying structures, and finally make proper decisions by adapting to changes and uncertainties in the environment [13]. That is, ML is applicable to various operational aspects of vehicular networks by using vehicle kinetics (e.g., speed, direction, acceleration), road conditions, traffic flow, and wireless environments for adaptive data-driven decisions. In addition, as ML can be implemented in a distributed manner, it can help to manage network issues for reduced complexity and signalling overhead.

The adoption of ML has been considered particularly for vehicle trajectory prediction to support driver safety features such as collision avoidance and road hazard warning [14]. Based on previously observed trajectories, a motion model of a vehicle can be learned and its future locations can be predicted via ML using observed mobility traces and movement patterns. In addition, unexpected factors which could affect trajectories such as a driver's intention, traffic patterns, and road structures, may also be implicitly learned from historical data. Such vehicle trajectory prediction can be utilized for handoff control, link scheduling, and routing. For instance, the most promising relay node can be chosen for message forwarding and seamless handoff between V2V and V2I in an effective routing scheme using vehicle trajectory prediction.

ML based approaches can also enhance radio resource management (RRM). When conventional optimization based approaches are used in the highly dynamic V2X network, a small change in the vehicular environment may require a re-run of the whole optimization, leading to prohibitively high overhead and inefficiency. For example, considering NR SL transmission, vehicles are expected to reach a more sophisticated level of coordinated driving through intent sharing. In this case, ML based transmission mode selection and resource allocation would be of interest in view of the stringent timing requirements.

More specifically, with a decentralized ML based approach, each vehicle can observe the environments (i.e., channel qualities, interference levels, and traffic loads) and learn the mode and channel selection strategy to guarantee reliability requirements. In case the V2V link becomes unstable, a vehicle could choose the V2I mode with the least overhead to obtain the global network information. Since multiple vehicles could be involved, a multi-agent learning approach where vehicles can cooperate may be a useful approach.

From the PHY perspective, in high-mobility channels, synchronization and channel estimation are challenging tasks for V2X communication system design. The V2X system may experience frequent loss of synchronization and has to deal with short-lived channel state information (CSI) estimates due to very short channel coherence times. In addition, the use of the mmWave band requires fast and efficient beam tracking and switching to establish and maintain reliable links in rapidly changing environments. Here, ML can be useful in learning, tracking and predicting relevant information (i.e., the synchronization points and CSI in highly volatile channels, and beamforming directions) by exploiting historical information (i.e., user location, received power, previous beam settings, context information covering network status, and so on.).

While ML is expected to take an important role to lead data-driven intelligence and edge/UE-based intelligence (beyond network-side intelligence), there are also challenges in adopting ML in vehicular networks. Firstly, ML may produce undesired results. While minor errors could lead to huge impacts for safety-sensitive services, significant efforts need to be made to improve the robustness and security of an ML-based approach [13]. Additionally, the on-board computational resources in each vehicle may be limited. Due to stringent end-to-end delay constraints, the use of cloud-based computing resources may not be feasible. For such cases, techniques such as model reduction or compression should be considered in designing ML-based approaches to alleviate the computation resource limitation without degradation in the performance of V2X communication.

V. 5G NR-V2X USE CASES IN COOPERATIVE AND AUTONOMOUS DRIVING

The success of 5G NR, in practice, is largely related to the question of how well 5G NR can fulfill the requirements of designated services and advanced use cases. One of the main objectives for the NR-V2X standard is to support use cases with stringent requirements of ultra-high reliability, ultra-low latency, very accurate positioning and high throughput, which may not be achieved by LTE-V2X. NR-V2X is not intended to replace LTE-V2X services but to complement them with advanced services. While LTE-V2X targets the basic safety services, NR-V2X can be used for advanced safety services as well as cooperative and connected autonomous driving. The following use cases [15] are among the target services that may be supported by NR-V2X:

- Trajectory sharing and coordinated driving: Intention/trajectory of each vehicle will be shared to enable fast, yet safe maneuvers by knowing the planned movements of surrounding vehicles. Exchange of intention and sensor data will ensure more predictable, coordinated autonomous driving, as they know the intended movements of other vehicles.
- Vehicle platooning: This is an application of cooperative driving which refers to a group of vehicles, traveling

together in the same direction and at short inter-vehicle distances. To dynamically form and maintain platoon operations, all the vehicles need to receive periodic data (i.e., direction, speed and intentions) from the leading vehicle.

- Extended sensors sharing: Enables the exchange of raw or processed data gathered through local sensors or live video images among vehicles, roadside units, devices of pedestrian and V2X application servers. The vehicles can increase the perception of their environment beyond what their own sensors can detect and have a broader and more holistic view of the local situation.
- Remote driving: A remote driver or a cloud-based V2X application take control of the vehicle. Examples of remote driving/teleoperated applications are for incapacitated persons, public transportation, remote parking, logistics, or driving vehicles in dangerous environments (e.g., Mines).

The end-to-end latency and reliability requirements for the aforementioned use cases are presented in Fig. 4. As can be seen, three zones are identified. In LTE-V2X zone services which require less than 90% reliability and latency between 10-100 ms can be supported. In the second zone, service which requires 99% reliability and latency between 5-10 ms may be supported by LTE-V2X but surely are supported by NR-V2X. The services in the NR-V2X zone, which require less than 5 ms latency and above 99% reliability are only supported by NR-V2X.

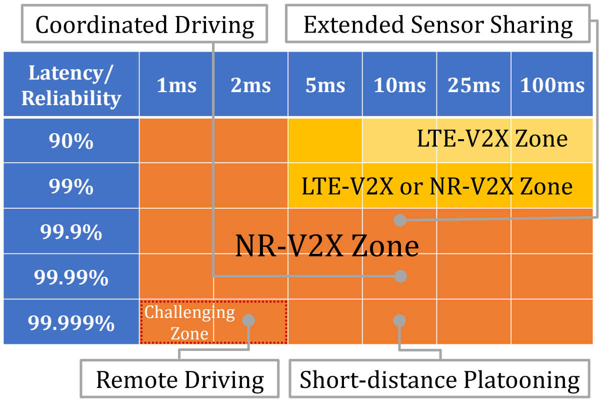

Fig. 4: End-to-end latency and reliability requirements for advanced NR-V2X use cases.

VI. CONCLUSIONS

In this paper, we have presented the design considerations, technology components, functionalities, and key features of NR-V2X towards connected and cooperative autonomous driving. We have discussed how NR-V2X is designed and configured to fulfill a number of stringent QoS requirements associated with autonomous driving in terms of throughput, latency, reliability, security, and positioning. We have also shown that ML can be exploited to significantly improve the performances of V2X communications. With its enormous potential, 5G NR is expected to be the transformative technology for highly connected and cooperative vehicular networks.

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VII. BIOGRAPHY

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