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Classification of C-ITS Services in Vehicular Environments

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ABSTRACT The objective of vehicular communication is to improve road safety and traffic efficiency through various cooperative intelligent transport system (C-ITS) services. These services allow information exchange between vehicles and other communication entities (e.g., vehicles, infrastructure, pedestrians). In addition, many advanced services are envisaged to support autonomous vehicles and safety applications. Therefore, the performance requirements of such services are considered highly critical for road safety. However, all these services increase the channel load, and thus, it isn't easy to differentiate which service has a higher priority for accessing communication channels. In this paper, we focus on the classification of C-ITS services, which allows the cohabitation of all services considering the strict performance requirements for some services. The aim is to classify C-ITS services based on their packet delay requirements to define higher priority for critical services to ensure their dissemination, especially under congestion conditions. Then, we present protocols and quality of service (QoS) mechanisms that can map this classification to the available vehicular networks.

INDEX TERMS Cooperative intelligent transport systems (C-ITS), vehicular and wireless technologies, Cellular-V2X, ITS-G5, vehicle-to-everything (V2X).

I. INTRODUCTION

Cooperative intelligent transport systems (C-ITSs) have been proposed in recent years to improve vehicular communication systems. These systems are studied to ensure a set of services that increase road safety, optimize traffic management and improve road user experience. The operation of these services generates data exchanges between the vehicles (vehicle-to-vehicle (V2V)), between the vehicles and a centralized infrastructure (vehicle-to-infrastructure (V2I)) and between the vehicles and other road users such as pedestrians (vehicle-to-pedestrian (V2P)). Several wireless technologies are currently available to support these vehicular network communications. Two of the most promising wireless technologies developed for ITS services are ITS-G5 and LTE-V2X. ITS-G5 is the European Standard for Vehicular Communications, proposed by the European Telecommunications Standards Institute (ETSI), and based on IEEE 802.11p (2012). LTE-V2X or C-V2X (cellular vehicle-to-everything) is proposed by 3GPP as an extension of long-term evolution cellular technology for vehicular communications.

Several ITS services are defined in the categories of road safety, traffic management and road experience. These services have different levels of criticality depending on their importance in road safety (e.g., road hazard warning service that helps to warn road accidents is considered safety critical, while service announcement (SA) services have no specified requirements). In addition, they define heterogeneous needs in terms of communication performance. The development of vehicular communications and in-vehicle sensors currently allow the emergence of more advanced services such as: dynamic lane management, automated driving, vehicle platooning, and remote driving. Such services are considered highly critical with regard to road safety. This criticality implies strict requirements in terms of network communications performance. Thus, the C-ITSs of the future will have to allow the cohabitation of all these services, taking into account their heterogeneity as shown in Fig. 1.

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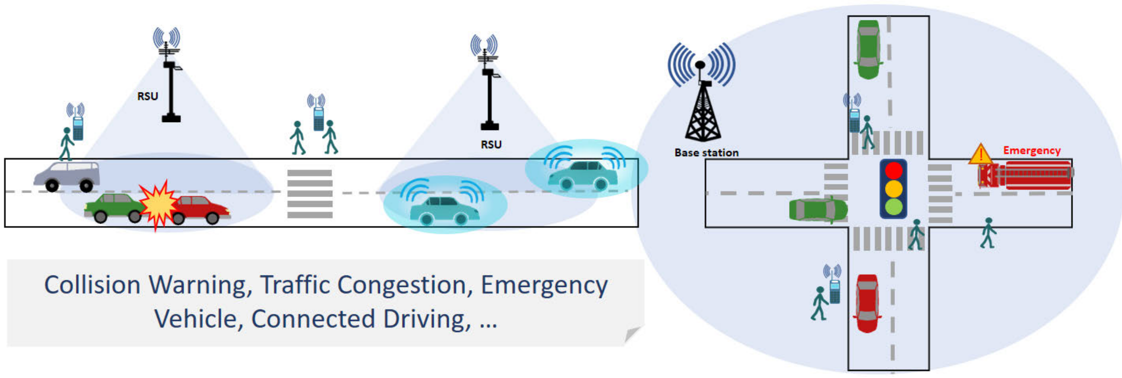

FIGURE 1. C-ITS services (Road safety, Traffic Management, Infotainment, Automated and remote driving, and others).

The communication networks part of C-ITSs should in particular take this heterogeneity into account. Indeed, these networks must be able to convey data messages of various ITS services while taking into account the heterogeneity of their performance requirements and criticality levels. This endeavour will be particularly challenging in dense vehicular environments considering the expected increase in the penetration rate of C-ITSs in vehicles, which will likely result in an overload of these networks. In this context, the main challenge of C-ITSs is to ensure appropriate allocation of communication network resources between the deployed services and to ensure a primacy of safety critical services.

The wireless communication technologies defined for vehicle communications implement mechanisms for QoS management. ITS-G5 uses the enhanced distributed channel access (EDCA) mechanism to set up queues offering differentiated access parameters to network resources according to the priorities of the data flows. LTE-V2X offers different QoS mechanisms related to the operating modes (mode 3 and mode 4) for vehicular communications. These mechanisms are also based on differentiated access to network resources based on the prioritization of data flows. QoS mechanisms can allow C-ITSs to ensure the proper functioning of their services while taking into account the limited resources offered by communication technologies. However, to exploit these resources properly, it is necessary to have a clear classification of C-ITS services that will coexist in such a system. This classification should take into account performance requirements and service criticality. Currently, there is a lack of useful classification that supports specific requirements of new use cases. The existing studies consider only two classes for safety and non-safety services, reflecting only the primary scope of C-ITS services.

In this context, we propose a study of C-ITS services and use cases specified today in the literature by standardization groups. Then, we propose a classification of these services according to their communication requirements and road safety criticality. We also present a mapping between the proposed C-ITS service classes and the traffic priorities defined by the ITS-G5 and LTE-V2X technologies.

The remainder of the paper is organized as follows. Section II presents an overview of C-ITS services and their evolution and insights gained from European projects. Then, the different communication modes with more details regarding C-ITS messages are presented. Section III provides an overview of the QoS mechanisms defined by the ITS-G5 and LTE-V2X technologies. Section IV focuses on the previous research studies that assess the performance requirements of C-ITS services. Section V details our proposal for the classification of C-ITS services that takes into account the performance requirements of critical services. Then, a mapping proposal is presented between C-ITS service classification and traffic prioritization defined by the communication technologies. Finally, section VI concludes the work with some observations.

II. C-ITS SERVICES

An overview of use cases and their evolution and insights gained from European projects related to the development and deployment of C-ITS services are presented in this section. Then, different communication modes and exchanged information or messages for intelligent transport system applications are given.

A. USE CASE: DEFINITION, EVOLUTION AND DEPLOYMENT

In a vehicular network, the connection between the different entities (e.g., infrastructure, vehicles, pedestrians) can be achieved using C-ITS systems that ensure various services. These services are distributed in the form of use cases where each use case represents an information exchange between two network entities related to potential events. The first scope of services or use cases that have been demonstrated by numerous studies are related to road safety through embedded signaling and driver information about unexpected and potential hazards (e.g., emergency vehicle approaching, alert stationary vehicle/breakdown, weather conditions). Then, the evolution of use cases progresses to reach other complementary services related to traffic efficiency and user comfort (e.g., parking location and availability, rerouting,

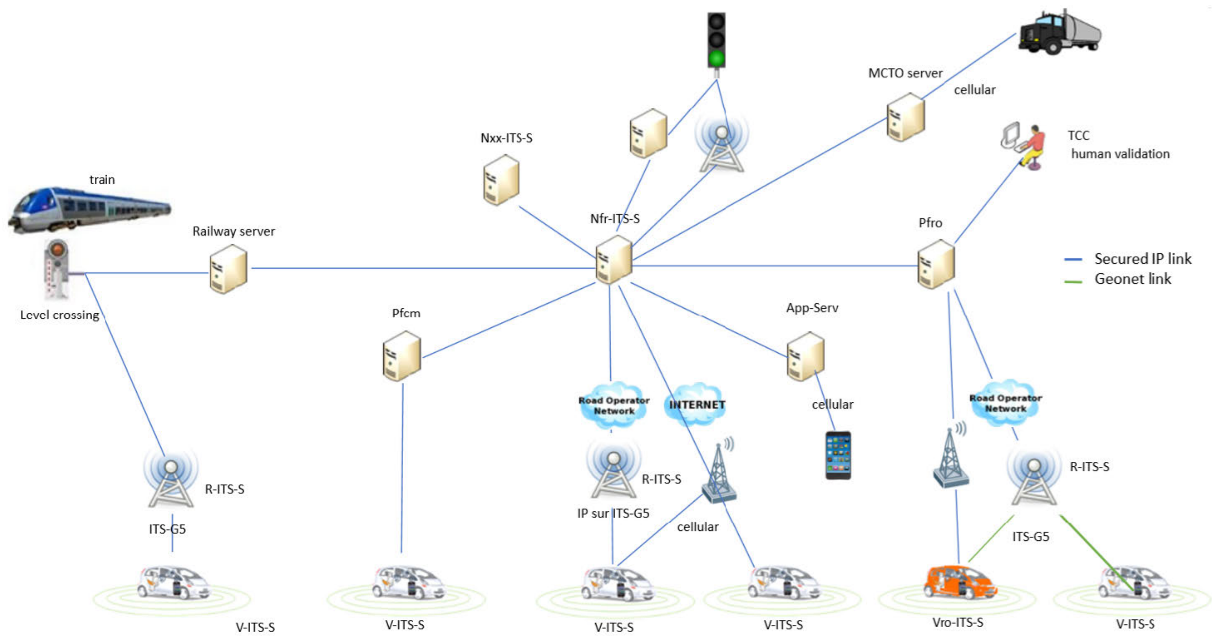

FIGURE 2. Use cases defined by Scoop [1] and C-roads [3] Projects. Nfr-ITS-S (French National ITS Station), Nxx-ITS-S (International ITS Station), PFro (Road Operator's Platform), PFcm (Car Manufacturer's Platform), R-ITS-S (Roadside ITS Station), Vro-ITS-S (ITS-S-V Road Operator), V-ITS-S (ITS-S Vehicle), TCC (Traffic Control Center), MCTO (Multimodal Cargo Transport Optimization).

traffic signal priority GLOSA (Green Light Optimal Speed Advice)). Currently, performance improvements provided by the evolution of vehicular networks have allowed development of more advanced use cases mainly related to cooperative, connected and automated mobility (CCAM) (e.g., dynamic lane management, vulnerable users, automated driving, vehicle platooning, remote driving). These other use cases can be envisaged with different levels of performance depending on the targeted level of automation (LoA): no automation, driver assistance, partial automation, conditional automation, high automation, and full automation.

Several C-ITS projects were conducted for the development and deployment of C-ITSs in Europe and worldwide. The objectives of these projects are to improve road safety in the first step and to advance toward the development of autonomous vehicles through different communication technologies. SCOOP [1], InterCor [2], C-ROADS [3] and INDID [4] are C-ITS projects supported by the European Commission for the development and deployment of C-ITS services in Europe, as illustrated in Fig. 2. Their scopes and objectives are to allow data exchange based on the V2X communications mode for various use cases related to intelligent transportation systems and to continue the development of C-ITS services. Through these projects, a catalogue of the C-ITS French use cases was defined in [5], which describes the main functions of use cases (e.g., type of road network, type of vehicle, objective, desired behaviour, expected benefits, logic of transmission, scenario).

B. COMMUNICATION MODES AND C-ITS MESSAGES

Vehicular networks are envisioned to support data exchanges through vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and infrastructure-to-vehicle (I2V) communications. These communications modes are designed for information exchanges related to driver alerts and notifications about the proximity environment in a short range. For long range, cellular networks are suitable to provide real-time services through vehicle-to-network (V2N) communications, which allow vehicular users to benefit from other services. Furthermore, more services can be added to support the ITS system by associating actors other than road managers. One can also imagine information exchanges between vehicles and pedestrians via vehicle-to-pedestrian (V2P) communications. This communication mode makes it possible to generate other use cases on user safety through a smartphone application. Therefore, in a heterogeneous architecture for vehicular networks, communication modes refer to vehicle-to-everything (V2X) communication to report the information as defined in the data dictionary [6]. Table 1 summarizes the existing messages by type of communication mode to enable ITS services. This includes the following messages:

1) Cooperative awareness message (CAM) [7]: CAM messages are broadcast periodically from the vehicle to infrastructure and vehicles in their local area and contain information about vehicle type, speed, position, and so on.
2) Decentralized Environmental Notification Message (DENM) [8]: DENM messages are sent by C-ITS stations to describe events related to different use cases, mainly for road safety and traffic efficiency.
3) Signal Phase And Timing Messages (SPATEM) / Map-Data Messages (MAPEM) [9]: These messages are transmitted by infrastructure to provide information about the traffic signal system and road topology of a roadway intersection.

TABLE 1. Data exchanged on V2X communication modes.

Communication mode	DATA Exchanges
Vehicle-to-Vehicle (V2V)	CAM/DENM messages
Infrastructure-to-Vehicle (I2V)	CAM/DENM/IVIM/SPATEM/MAPEM/ POI/ETA messages
Vehicle-to-Pedestrians (V2P)	CAM/DENM/I2I/SPATEM/MAPEM/ POI messages
Vehicle-to-Network (V2N)	Other network services

4) Infrastructure to Vehicle Information Messages (IVIM) [10]: IVIM messages are sent by infrastructure to C-ITS stations to provide road signage information such as road work warnings, road conditions, speed limitations, and so on.
5) Point of Interest (POI): POI messages are expected for additional information services (e.g., parking).
6) Estimated Time of Arrival (ETA): ETA messages are defined to give more services to vehicular users, such as multimodal cargo transport optimization (MCTO) services.

III. QoS MECHANISMS FOR C-ITS COMMUNICATIONS

A. C-ITS COMMUNICATION TECHNOLOGIES

Two of the most promising technologies for providing C-ITS services are ETSI ITS-G5 the European Standard and LTE-V2X.

ITS-G5 is an access technology based on IEEE 802.11p (2012) [11] allowing vehicles to communicate with their environment in the 5.9 GHz frequency band. This communication mode forms a distributed network between vehicles with direct communications V2V or between vehicles and roadside stations deployed by the road manager through V2V and V2I communications. The messages exchanged refer in particular to safety and non-safety services. It is specifically designed for intervehicle V2V and V2I communications. It is characterized by the integration of DCC (distributed congestion control) functionality for channel control and the use of four channel access priorities (voice, video, best effort, and background) through EDCA to guarantee QoS requirements. To provide more coverage, a traditional cellular network (4G) is used to ensure connectivity for non critical services in terms of latency, as depicted in Fig. 2. The use of a cellular network (Uu interface) with ITS-G5 forms a hybrid architecture that can greatly increase the range and coverage for some C-ITS services.

LTE is an alternative technology derived from 4G cellular networks that has been defined to support vehicular applications. LTE-V2X or C-V2X (Cellular Vehicle-to-everything) are standardized by 3GPP in its release 14 (phase 1 LTE-V2X June 2017 [12]) and release 15 (phase 2 LTE-eV2X 2018 [13]), which provide V2V, V2I, and V2P communications in the same 5.9 GHz frequency band. This technology ensures V2N communications through a related 4G network to support high data rate services without latency or reliability requirements. C-V2X defines two complementary transmission modes. The first mode is mode 3, which uses the cellular interface Uu (cellular-assisted V2V). In this mode, the cellular network allocates and manages the radio resources used by vehicles. The second mode is mode 4, which uses the PC5 (Proximity Communication 5) interface for direct communications. In this mode, vehicles can select their radio resources without the assistance of the cellular network (Cellular-unassisted V2V) through the SPS (Semipersistent Scheduling) mechanism. Mode 4 is used to ensure V2V direct communications when vehicles are out of coverage.

B. QoS MECHANISMS IN C-ITS TECHNOLOGIES

This subsection describes the protocols and mechanisms available in the existing technologies (ITS-G5 and LTE-V2X) allowing us to support QoS.

1) QoS IN ITS-G5 TECHNOLOGY

The current IEEE 802.11p was standardized in 2009 as an extension of IEEE 802.11a (Wi-Fi standard), and it is expected to support V2X communications due to Outside the Context of BSS (OCB) mode. This latter adopts OFDM at the PHY layer and the carrier sense multiple access protocol with collision avoidance (CSMA/CA) protocol at the MAC layer to manage access to the medium of communication. Based on IEEE 802.11p, two different vehicular communication standards were developed: the Wireless Access in Vehicular Environments (WAVE) in the U.S. specified by IEEE 1609 standards and the ITS-G5 in Europe specified by ETSI TC ITS.

As shown in Fig. 3, we identified the main components for MAC and the physical layer that will be adopted to support the QoS mechanism. The MAC layer is improved with the EDCA mechanism to support data traffic with different priorities. As shown in Fig. 3, the EDCA mechanism specifies four queues with different access categories (AC): (AC0) voice traffic with highest priority to access the channel (Voice), (AC1) video traffic (Video), (AC2) best effort traffic (BE), and (AC3) background traffic with lowest priority (BK). The mapping of these queues is based on the configuration of the arbitration interframe space (AIFS) and content window (CW). The main aim of the EDCA mechanism is to adopt QoS differentiation to protect the traffic queue with the highest priority and to guarantee its transmission in dense network environments.

The CSMA/CA protocol defined on IEEE 802.11p showed a significantly high probability of collisions. In this context, ITS-G5 technology addresses congestion situations through the DCC mechanism to mitigate the risk of collisions. The DCC has been introduced to control and dynamically adjust data exchange to reduce traffic loads. It operates on the different layers of ITS station (ITS-S) architecture, as depicted in Fig. 3. DCC management contains all information provided by DCC access related to the channel occupancy and the controlled parameters to adjust traffic load. The DCC can adapt

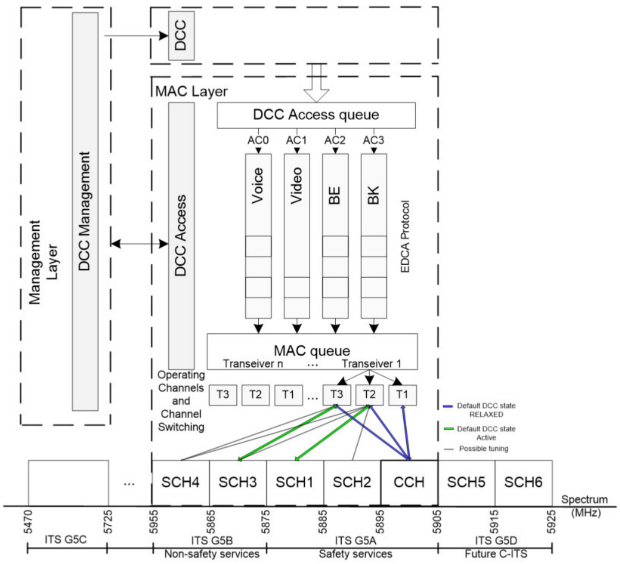

FIGURE 3. Congestion control and channel access for ITS-G5.

the traffic load through a set of algorithms such as transmit power control (TPC), transmit ratio control (TRC), and transmit data rate control (TDC). By using these algorithms, which adjust the transmit power, transfer rate, and other parameters related to control of the channel (e.g., measured channel busy ratio (CBR), receiver signal strength indicator statistics (RSSI statistics), and frame transmission indication), the DCC can better support access management in high traffic load situations. To ensure efficient traffic dissemination, the harmonized use of radio spectra for C-ITS applications in dedicated 5.9 GHz band is divided in four different bands:

- ITS G5A band: dedicated for safety applications.
- ITS G5B band: dedicated for non-safety applications.
- ITS G5C band: dedicated for Radio Local Area Network (RLAN), WLAN, etc.
- ITS G5D band: dedicated for future ITS applications.

As shown in Fig. 3, we can identify channel spacing of 10 MHz for control channels (CCHs) and service channels (SCHs) to ensure data dissemination of safety and non-safety messages. The available channels enable the use of multiple channels for different traffic communications.

As an extension of the MAC layer, multi-channel operations (MCO) have been defined to allow a multi-channel access mode under the control of management layers and DCC management. Access to the appropriate channel (CCH, SCH1, SCH2, SCH3, etc.) is related to the DCC states for each channel (congestion status: RELAXED, ACTIVE or RESTRICTIVE) and the requirements of messages through the DCC profile. The DCC profile is the set of parameters that identifies the type of traffic (e.g., CAM, DENM) and ensures its discrimination in the access, network and transport layers. DCC management is the entity responsible for managing the DCC profile and for controlling the traffic in high traffic loads.

The CCH is the default channel dedicated to the transmission of safety road messages (ITS 5GA). The transmission of any type of message using CCH is allowed only in the low traffic load (DCC state: RELAXED). In the case of the CCH channel in the DCC states of ACTIVE and RESTRICTIVE, transmission is allowed on the SCH1 channel, providing ITS services for safety and road efficiency. The use of SCH2 for traffic safety services is limited due to potential adjacent channel interference with CCH. The SCH3 and SCH4 channels located in ITS G5B are considered for non-safety services (e.g., road efficiency, other services). ITS G5C channel access is not under the control of DCC. To operate in the ITS G5A and G5B bands, the ITS-S must be equipped with single or multi ITS-G5 transceivers that support channel access under the control of DCC. Each transceiver adopts three possible configuration modes based on DCC profiles and congestion states to be connected to one or more channels. Depending on the DCC requirements of the ITS applications, the transceiver can operate in one of the following configurations [14], as depicted in Fig. 3:

- Transceiver Configuration 1 (T1): The transceiver connected exclusively to ITS G5A channels through the CCH channel.
- Transceiver Configuration 2 (T2): The transceiver can be adjusted on the SCH1 channel on demand an arbitrary ITS channel (ITS G5A safety applications) for service operation when the CCH channel is in the DCC state ACTIVE or RESTRICTIVE.
- Transceiver Configuration 3 (T3): The transceiver can be adjusted on the SCH3 channel on demand an arbitrary ITS channel (ITS G5B non-safety applications) for service operation when the CCH channel is in the DCC state ACTIVE or RESTRICTIVE.

For non-safety services, the transceiver can operate directly in configurations T2 or T3.

2) LTE-V2X TECHNOLOGY (MODE 3 AND MODE 4)

The standard LTE-V2X supports two radio interfaces: the Uu cellular interface and the PC5 interface. The PC5 interface supports direct V2V or V2I communications over the direct sidelink and includes two communication modes, namely, modes 3 and 4. The difference between these two modes lies in the management of the radio resources used by the vehicles for communications. In this context, two operating bands are designed for V2X communication: the operating band in the licensed spectrum over the Uu interface and the operating band in the nonlicensed spectrum over the PC5 interface (5.9 GHz band). For each operating band, as shown in Table 2, different channel bandwidth configurations are specified for the transmission and reception of V2X messages. This setup allows multicarrier communication (MCC), which is defined as a multicarrier V2X operation to support various V2X operating scenarios over PC5 and Uu. The available channel is divided into many subchannels to allow transmission to multiple users at the same time. This configuration is in

TABLE 2. Operating bands for C-V2X communications over Uu and PC5 [16].

	V2X Band	Uplink (UL) / UE transmit (MHz)	Downlink (DL) / UE receive (MHz)	Duplex Mode	Channel Bandwidths (MHz)
Operating band over PC5	47	5885 – 5925	5885 – 5925	-	10/20
Operating band over Uu	3	1710 – 1785	1805 – 1880	FDD	1.4/3/5/10/15/20
	7	2500 – 2570	2620 – 2690	FDD	5/10/15/20
	8	880 – 915	925 – 960	FDD	1.4/3/5/10
	39	1880 – 1920	1880 – 1920	TDD	5/10/15/20
	41	2496 – 2690	2496 – 2690	TDD	5/10/15/20

contrast to ITS-G5, where one user uses the entire bandwidth during the transmission. From a connectivity point of view, this feature together with others features related to the range and the network availability allows predicting that LTE-V2X may show better link availability than IEEE 802.11p.

In Mode 3, radio resource management (sub-channel selection) is performed under the control of the base station (eNB) through the sending of signaling control of the Uu interface (operator spectrum is used for signaling and PC5 spectrum used for the data transmission) when the vehicles are under cellular coverage. Dynamic scheduling or semipersistent scheduling (SPS) supports the programmed allocation of resources.

In mode 4, when vehicles are not under cellular coverage, the standard configures the transmission pool (radio transmission resources) according to geographic areas. Vehicles select their sub-channels using distributed algorithms with pre-configured parameters (via SPS scheduling).

When the number of neighbouring ITS-Ss increases, the channel resources are increasingly loaded; hence, there is a need for congestion control operations. Mode 3 does not implement distributed congestion control. Channel access is allocated and managed in the eNB by means of scheduling schemes to reduce the channel occupancy. This latter aspect can serve different traffic flows through their QoS requirements. For this mode, scheduling schemes are specified by the operator using its own solutions. LTE networks can support QoS handling for V2X communication via the Uu interface. For each packet, a QoS class identifier (QCI) is associated with controlling the processing of the packet in eNB (e.g., scheduling treatment, admission control) and can be delivered with guaranteed bit rate (GBR) or non-GBR requirements. The standardized QCI characteristics for V2X messages are presented in Table 3.

Mode 4 attempts to reduce channel congestion by estimating the parameters associated with the channels mainly at the PHY/MAC layer. The channel busy ratio (CBR) and channel occupancy ratio (CR) limit should be set for each transmission pool and for each packet priority as defined by the ProSe per-packet priority (PPPP). The PPPP associates one of eight priority levels for each packet (where 1 represents the highest value) when passing it to the lower layer for transmission. For each priority level, CR is calculated based on the measured CBR of the transmission pool. If the CR of the priority level complies with the CR limit, the packet can use the resource required (resource block) to be transmitted.

TABLE 3. Standardized QCI characteristics for V2X messages over LTE-Uu [17], [18].

QCI	Resource Type	Priority Level	Packet Delay Budget	Packet Error Loss Rate	Example Services
3	GBR	3	50 ms	10^{-3}	Unicast delivery of V2X messages
75	GBR	2.5	50 ms	10^{-2}	Broadcasted delivery of V2X messages
79	Non-GBR	6.5	50 ms	10^{-2}	Unicast delivery of V2X messages

TABLE 4. CR limit values [19].

CBR-based PSSCH transmission parameter configuration	PPPP1–PPPP2	PPPP3–PPPP5	PPPP6–PPPP8
CBR measured	CR limit	CR limit	CR limit
$0 \leq$ CBR measured ≤ 0.3	No limit	No limit	No limit
$0.3 <$ CBR measured ≤ 0.65	No limit	0.03	0.02
$0.65 <$ CBR measured ≤ 0.8	0.02	0.006	0.004
$0.8 <$ CBR measured ≤ 1	0.02	0.003	0.002

The CR limit values for the different PPPP priority levels are shown in Table 4. Additionally, other parameters are involved in channel congestion control and can be adapted to reduce congestion (e.g., maximum transmit rate, transmit power, MCS). These parameters are exchanged through interfaces between the congestion control management entity and access/networking/transport/facilities layers.

IV. RELATED WORKS

Many research studies have been performed to support V2X services and to enhance the C-ITS architecture. The majority of these studies focus on the performance evaluation of existing technologies through different use case requirements. In [15], the authors proposed a performance evaluation of using ITS-G5 and LTE-V2X (mode 3) in dense scenarios. They considered two scenarios: the first scenario introduces classic cellular traffic on LTE-V2X, and the second scenario evaluates the impact of handover latency on ITS services. The results showed that for LTE-V2X mode 3, the cell block utilization of eNB exceeds 40 % in the downlink in the dense scenario (E2E delay reaches 240 ms). In addition, the measured E2E delay in the handover process meets the ITS service requirement of the considered use case and depends on the channel quality indicator (CQI). It was concluded that ITS-G5 outperforms the LTE-V2X mode when LTE radio resources are allocated for additional traffic. Reference [20] reported a performance comparison between ITS-G5 and cellular-based vehicular communication systems (referred to LTE-V2X). Realistic data traffic was simulated based on CAM and DENM messages in a real road scenario (CAM depending on the vehicle movement and DENM generated by Poisson distribution to model event-driven). End-to-End Delay and Packet Inter-Reception Time were measured as the performance metrics for both technologies. It was concluded that both technologies can support vehicular communications with realistic data traffic. Centralized scheduling in the base station allows an increase in the packet reception ratio for Cellular-VCS compared to ITS-G5. Otherwise, the low signaling overhead in ITS-G5 enables it to show a higher performance for end-to-end delay than Cellular-VCS. Reference [21] proposed challenges and solutions to support ITS communications over heterogeneous vehicular NETwork (HetVNET). The authors provided an overview of communication techniques and protocols used in vehicular environments and compared the performance requirements of different use cases (for safety and non-safety services). The latter comparison is based on latency, periodicity of messages and reliability. The frequency of periodic messages varies from 1 Hz to 10 Hz, whereas the maximum latency is 100 ms for safety services and no more than 500 ms for non-safety services. Then, the HetVNET framework was proposed with relation to the proposed analysis of communication technologies and use case requirements.

In [22], the authors discussed the design approaches of a 5G V2X communication system through performance analysis of use case requirements over existing communication technologies. This analysis was conducted to identify the suitable network architecture for enabling 5G V2X communication. The authors considered use cases expected to improve automated vehicle communication in different aspects, including cooperative awareness, cooperative sensing, cooperative maneuver, vulnerable road user, traffic efficiency, and tele-operated driving. Stringent requirements of advanced use cases have been described in terms of latency, reliability, and data rate (e.g., for cooperative collision avoidance, the maximum latency is no more than 10 ms with ultra-high reliability (>99%)). The results have shown that there is a need for a new V2X architecture (based on 5G new radio, multi-RAT, network virtualization, MIMO, etc.)... to meet the stringent requirements of some existing and future use cases.

In [23], the authors proposed a multi-channel wireless communication architecture and protocol to support safety applications and non-safety commercial applications (e.g., toll collection, service announcements, video download). This proposal seeks to enable channel access for non-safety communications (on services channels) while ensuring priority for safety messages on safety channels (control channels) without violating the QoS requirements. All safety messages (e.g., cooperative collision warning, intersection collision warning) were considered in a single priority class with maximal delay requirements between 100 and 500 ms and ranges between 50 and 300 metres. The simulation results for operating within a multi-channel show that reception failure probabilities (RFPs) for a safety message exchange do not exceed 0.17%. In this study, the main challenges are to ensure safety messages delivered with high probability and maximize the bandwidth available for non-safety applications.

In [24], the authors presented an analytical model based on the exponential distribution of MAC access delay to evaluate the performance of the 802.11p standard. They proposed the use of a higher priority DENM for emergent safety messages and a lower priority CAM to analyse their impact on the requirements of real-time applications in different traffic densities (up to 0.1 vehicles/m). Numerical analysis and simulation results of the MAC access delay for highway scenarios were presented. Based on their results, the authors concluded that IEEE 802.11p can support QoS, meeting the requirements of safety messages in the broadcast mode at heavy traffic density.

To enhance the capabilities and efficiency of the C-ITS architecture, other works propose pushing cloud services and applications in proximity to vehicles for edge computing that enables faster access and minimizes latency. In [25], the authors proposed a heterogeneous framework of vehicular services to improve resource utilization and service performance. They consider the vehicles' available resources to form a vehicular cloud and use edge-based roadside units to allow computation and storage units closer to the end user. This approach makes these resources in close proximity to vehicles to facilitate efficient data processing and minimize latency, rather than routing it to a central cloud. As a result, the authors demonstrated the capability of RSU-based edges to improve the performance in terms of latency measurements and bandwidth utilization compared to that of traditional cloud solutions. In [26], the authors focus on the capabilities of edge computing servers in a 5G network to help in offloading services and bring them closer to the requester. They consider proactive migration based on intelligent resource management to determine the next edge server, which maintains low latency in high-mobility vehicles. In the simulation, the authors analysed the effects of prediction errors on the efficiency of service migration and showed that it induces additional latency.

The evolution of communication technologies introduces more challenging issues to meet the continuing increase in application requirements. The significant performance provided by the next generation of ITS-G5 and C-V2X is expected to better support C-ITS services. The development of the next generation of mobile communication 5G [27] has accelerated in recent years, where its objective is to provide greater capability in terms of latency, data rate, mobility, massive connectivity, energy efficiency, spectrum efficiency, and so on. To achieve these goals, 5G identifies three service categories, namely, enhanced mobile broadband (eMBB), massive machine type communication (mMTC) and ultra-reliable low latency communication (URLLC), to support a diverse set of use cases. These advances introduce additional capabilities to vehicular environments. In this direction, the 5G new radio (NR) introduced in the first phase of 5G development (3GPP Rel-15 [28]) addresses V2X services. In this phase, 5G NR focuses on supporting eMBB use cases and some critical applications of URLLC. Additional capabilities were introduced in 3GPP Rel-16 [29], expected to support eMBB, URLLC and mMTC use cases. These enhancements provide high levels of efficiency and capacity to advanced and automotive use cases (emergency electronic brake lights, software updates, platooning, high-definition maps, sensor data sharing, vulnerable road users and many more applications). The IEEE Standards Association continues the evolution and amendment of its 802.11 standard for greater support of V2X communications. In this context, the IEEE study group defined a new standard IEEE 802.11bd (named NGV: Next Generation V2X) [30], [31]. The work on this standard is being conducted to enable high-performance and to meet the stringent requirements of advanced use cases through innovation with regard to the PHY and MAC layer: channel coding (low density parity check (LDPC) codes), higher modulation and capacity, MIMO diversity through space-time block codes (STBCs), adaptive retransmission (1-3 retransmission (as a function of CBR)), multi-channel management and advanced channel estimation. These features should ensure greater reliability and efficiency for V2X communications (multi-channel operation, infrastructure applications, vehicular positioning, automated driving, location automated driving assistance, etc.). The consideration of real road traffic scenarios for improving performance of a vehicular communication system still suffers from a lack of detailed information about the data traffic simulation, especially under the dependence of various parameters: channel access, traffic load, vehicle penetration rate, signaling overhead, packet collisions (congestion situation), centralized scheduling and DENM rules (e.g., priority level, generation frequency, repetition delay). Various studies concluded that for some scenarios or use cases, ITS-G5 outperforms LTE-V2X and LTE-V2X outperforms ITS-G5 for others, without considering critical scenarios with higher priority messages (e.g., all V2X messages are transmitted with the same priority level). The performance requirements of these use cases, especially in terms of packet delay, depend on the situation encountered and the moment of event detection. Each use case is characterized by its own requirements and can be considered with different priority levels. In our work, we extend previous works by proposing a classification of C-ITS services based on their requirements to satisfy the specific requirements of the most critical use case in high traffic load.

V. CLASSIFICATION OF C-ITS SERVICES

A. USE CASE REQUIREMENTS

In this subsection, we provide an overview of the performance requirements for various use cases, including more advanced cases with more stringent requirements.

The primary scope of use cases for the deployment of ITS services is described in [32]. This work presents a set of applications and use case categories (basic set of applications) specified by ETSI ITS. Various warning messages are categorized into three classes of applications: road safety, traffic efficiency, and infotainment services. The first and second classes were used to improve road safety and traffic fluidity, and the third class was used to provide on-demand entertainment information for vehicles. The main requirements of this classification are based on the latency and frequency of message periodicity: (i) maximum latency 100 ms and frequency of the periodic message between 1 and 10 Hz according to the considered event for the first class (e.g., road hazard warning, road work warning), (ii) maximum latency 500 ms and frequency from 1 Hz to 10 Hz for the second class (e.g., traffic information and recommended itinerary, in-vehicle signage), and (iii) maximum latency 500 ms with 1 Hz of frequency of periodic messages for the last class (e.g., comfort and entertainment use cases).

To increase the capabilities of ITS systems to improve their performance, ETSI provides specification requirements of road hazard signaling (RHS) [33], intersection collision risk warning (ICRW) [34] and longitudinal collision risk warning (LCRW) [35] applications to improve road safety. The goal of primary road safety, as illustrated in Fig. 4, is to reduce collision risk either by (i) driver information based on fixed and variable messages deployed by road operators (in-vehicle signage), (ii) driver awareness based on CAM and DENM messages related to hazard detection (RHS), or (iii) driver warning based on CAM and DENM messages from vehicles in proximity (ICRW and LCRW). Related to these applications, many use cases are considered, namely, emergency vehicle approaching, emergency electronic brake light, safety-relevant lane change, stationary vehicles, merging collision risk warning, traffic light violation warning and so on. The performance required for these applications is based on the end-to-end latency to update the last warning messages: the minimal required time to avoid collision is 300 ms. The last application includes a time interval T0–T1, which is the time necessary for updated data to be ready to be sent. This time has been defined to support two performance classes: class A for critical safety situations guarantees that T0–T1 does not exceed 150 ms, and class B for non-safety situations (less than 1.4 s) with no specific requirement. Three priority levels were assigned to improve the requirements of class A: low priority (2) for awareness situations, medium priority (1) for warning situations, and high priority (0) for pre-crash situations. Fig. 4 summarizes the critical traffic situations for detecting a risk of collision and defines the immediate reaction to avoid collisions based on these priority levels.

In addition to the introduction of V2X services, in 3GPP release 14 [36], use cases and their requirements have been identified for LTE by considering the parameters and services defined over the first scope of ETSI ITS [32]. The main purposes for LTE V2X are regrouped into safety and non-safety

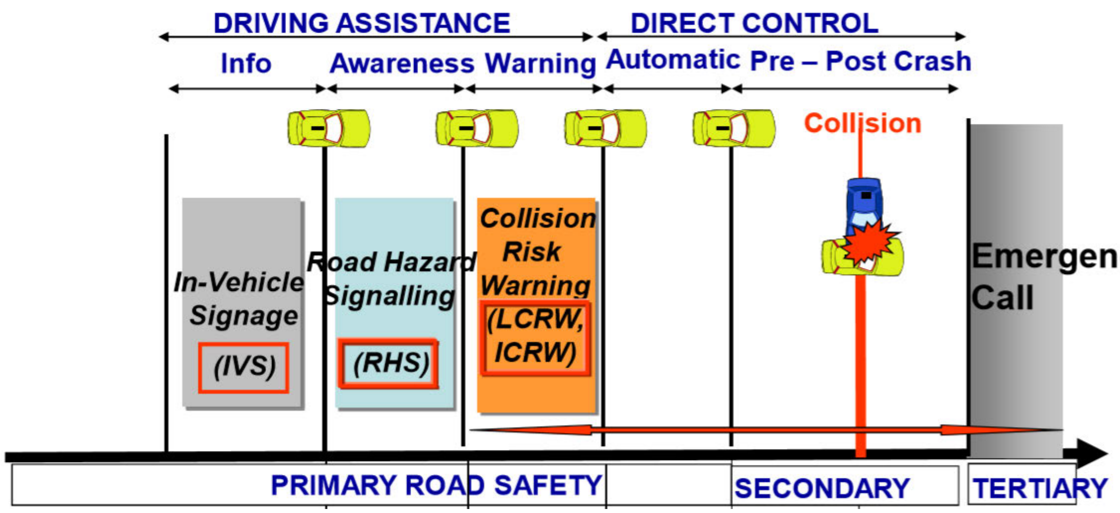

FIGURE 4. Overview of road safety applications [33].

use cases such as emergency vehicle warnings, road safety services, automated parking systems, wrong way driving warnings, vulnerable road users, and traffic management. The potential requirements to satisfy the different needs as defined in [37] are the maximal latency of 100 ms to support V2V, V2I or V2P use cases, maximum latency of 1000 ms for V2N application and no more than 20 ms for particular applications (i.e., pre-crash sensing). All communication modes require high reliability with a maximal frequency of the periodic message of 10 Hz.

Development trials to enhance 3GPP support for V2X services are provided in release 15 [38], and the introduction of 5G V2X services is in progress in release 16 [39], [40]. More advanced use cases have been identified, such as automated driving, vehicle platooning, remote driving, extended sensors, and vehicle QoS support, with more stringent requirements (i.e., latency, reliability, data rate, positioning, communication range). These requirements refer to the level of automation (LoA); for example, the maximal latency for vehicle platooning is 10 ms with high reliability communication (99.99%) in the case of a high degree of automation. For advanced driving, the latency varies from 3 ms to 100 ms, whereas the reliability is in the range of 90–99.999%.

The performance improvement of vehicular networks opens access to many innovative use cases with more stringent requirements. The classification of the C-ITS services described by ETSI and 3GPP used only two priority classes for safety and non-safety communications to guarantee these requirements. This classification cannot provide sufficient differentiation of services to support and protect the stringent requirements of advanced use cases, especially under high traffic load.

B. PROPOSAL FOR CLASSIFICATION OF C-ITS SERVICES

The main scope of the use cases as specified by ETSI and 3GPP standards have been served by two priority classes of safety and non-safety applications. New innovative use cases with stringent requirements should also serve as safety applications to guarantee transmission of the V2X messages. In dense vehicular environments, this current classification cannot support the critical requirements of new innovative use cases due to:

- channel load of safety applications caused by the high number of V2X messages,
- high transmission frequency of CAM and DENM messages,
- inability to differentiate and to identify the highest priority messages among all messages.

Another point of view must be considered. The requirements of many use cases depend on the traffic situations, i.e., it is difficult to establish fixed requirements for each use case, which helps to assign them to a single priority class. For example, in collision risk warning applications, the moment of detection of the risk of collision varies over time and location, giving different requirements for the same use case. Additionally, in the vehicle platooning use case, the requirement depends on the LoA with stringent requirements for highly automated driving and low requirements for partially automated driving. Through existing standards and works, several performance evaluation criteria were treated but not quantified, such as latency, reliability, data rate, coverage, speed, and frequency of message periodicity. Simulations require concrete data values, posing problems in the performance evaluation of C-ITS services. For this reason, our proposal considers these different points to ensure specific requirements for critical services, especially in congestion situations based on packet delay that refer to the time delay between two transceivers. The state of the art and the evaluation results previously described allowed us to identify concrete values of the packet delay for several use cases. Based on these packet delay values, four priority classes have

TABLE 5. Classification of C-ITS services.

C-ITS services	Packet Delay (ms)	Services Category	Example of Use Cases
Class 0	<10	Ultra-Safety Services: Cooperative Collision Avoidance Autonomous Driving (Higher degree of automation)	Cooperative Driving for Vehicle Platooning Information Cooperative collision avoidance for Advanced Driving Emergency trajectory alignment Cooperative Lane Change Remote Driving Pre-crash Situation Alert Emergency Brake
Class 1	<100	Safety Services: Road hazard warning Cooperative awareness Collision Risk Warning	Emergency Vehicle Warning Vulnerable Road User Warning Stationary Vehicle Warning Overtaking Vehicle Warning Intersection Collision Warning Road Works Warning
Class 2	<500	Non-Safety services: Cooperative traffic management Traffic Efficiency	Traffic Light Optimal Speed Advisory Cooperative Flexible Lane change to Enhancement of mobility efficiency In-Vehicle Signage Level Crossing Electronic Toll Collect Traffic Information and Smart Routing Parking, Park and Ride, Multimodality Multimodal Cargo Transport Optimization
Class 3	>500	No-requirement services: Comfort and Entertainment Traffic Management Support other services	Connected Vehicle Mobile high data rate entertainment Law Enforcement Payment Services ...

been proposed to differentiate the requirements of different C-ITS services:

- The first class, with the highest priority for meeting the stringent requirements of ultra-safety use cases related to cooperative collision avoidance and autonomous driving (high degree of automation),
- The second priority for the safety applications, with a less stringent requirement than the first class,
- The third class for non-safety applications, which requires maximum latency to guarantee its services such as traffic management and efficiency,
- The fourth class to support use cases, with nonspecific requirements such as communications with application servers, comfort, and entertainment.

The proposed classification and some use case examples are presented in Table 5. The objective is to map these classifications of C-ITS services and available resources onto existing technologies (e.g., multiple channel access, traffic priority) to support QoS. A description of this mapping and recommendations will be presented in the next subsection.

C. QoS MAPPING AND RECOMMENDATIONS

The basic idea of our proposal is to map the classification of C-ITS services to ITS-G5 and LTE-V2X QoS classes. We choose exactly four classes for traffic loads referring to the existing access queues and available resources of both technologies:

- the EDCA protocol, DCC profiles and multi-channel access for ITS-5G
- the scheduling mechanisms, QoS Class Identifier (QCI) and ProSe Per-Packet Priority (PPPP) for LTE-V2X.

The EDCA protocol with different queues, DCC algorithms and multi-channel operations are designed together to control and reduce the risk of collisions for C-ITS services. In DCC management, the DCC profiles identify and discriminate traffic based only on their type (e.g., CAM, DENM, SPAT) to adjust the traffic offered in the different layers. Traffic differentiation within the same type is not considered. Therefore, the main recommendation in ITS-G5 is to improve channel utilization by mapping traffic priorities with the appropriate queue/channel and ensuring the dissemination of critical messages under high traffic load.

For LTE networks in urban areas, LTE can be overloaded due to insufficient resources and excess signaling, which causes congestion in the control channels. This situation affects the performance required in terms of latency and data rate. Therefore, LTE networks adopt priority levels for their two communication modes (modes 3 and 4) to control packet forwarding treatment through PPPP and QCI values. The recommendation for cellular networks is to map C-ITS services with different priorities to the LTE QoS classes to guarantee the transmission of critical messages in congestion situations.

Research activities are carried out in different directions aim to improve C-ITS services. Both existing technologies ITS-G5 and LTE-V2X are promising solutions to support use case requirements. They mainly address the performance needs by the primary scope of ITS services, namely, information about road safety and traffic efficiency. However, advanced use cases such as the remote control of a vehicle, lane merging, platooning, and the autonomous vehicle can be considered with stringent performance requirements.

Therefore, the recommendation for future research directions is to consider the coexistence and hybridization between existing technologies to increase service availability and resiliency (e.g., co-channel sharing mechanisms, load balancing, traffic offload, handover mechanisms). Furthermore, the evolution of communication technologies introduces more challenging issues to meet the continuing increase in use case requirements. The main issue is how to exploit the performance requirements of advanced C-ITS services in designing the next generation of communication technologies for more reliable QoS.

VI. CONCLUSION

The development of vehicular technologies paves the way to improve C-ITS services and provides greater performance to enhance road safety. This improvement enables access to various innovative use cases with stringent requirements, especially in urban areas. This paper aims to illustrate relevant use cases and analyse their requirements through their specifications on ETSI and 3GPP standards. Moreover, most of these use case requirements are summarized and compared to the existing research studies. Based on these requirements, we introduce a new classification of C-ITS services, which is envisioned to better guarantee meeting the stringent requirements of use cases, especially in congested situations. This classification highlights four priority classes to differentiate packet delay requirements of the different use cases. The discussions of different protocols and mechanisms related to the existing technologies emphasize the feasibility of mapping this classification of C-ITS services with QoS mechanisms. Much research effort is still required for the implementation of this proposal on a simulator for performance evaluation of each technology, taking into account the development of a decision-making mechanism for selecting appropriate communication technology in a scenario with diverse technologies.

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