5G-enabled V2X Communications for Vulnerable Road Users Safety Applications: A Review

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Abstract Intelligent Transportation System (ITS) is continuously evolving alongside communication technologies and autonomous driving, giving way to new applications and services. Considering the significant rise in traffic casualties, protecting vulnerable road users (VRU), such as pedestrians, cyclists, motorcycles, animals, etc., has become ever more critical. That said, technological advances alone can not meet the requirements of such crucial applications. Therefore, combining them with architectural revolutions, particularly cloud, fog, and edge computing, is essential. In this review, we scrutinize the VRU safety application with regard to technological evolution. This review establishes the foundations for designing resilient, more reliable, end-to-end VRU protection services. It illustrates the possibility of combining the performance of different technologies through exploiting 5G architectural advantages (function placement, direct/indirect communication, etc.) for the intended application. In the context of 5G architecture, collision avoidance systems consider network and application-related challenges and solutions. This survey provides standardization, studies, and project efforts related to the use case and considers the different types of messages in the V2VRU communication-based safety application. We investigate how adapting the application parameters to the network state and devices' available resources can use network resources efficiently and provide reliable services.

Keywords Vulnerable road user safety · collision avoidance system · communication architectures · application requirements · edge computing

1 Introduction

With the evolution of the automation level and communication technologies towards 5G, the car will no longer be considered a means of transport. Instead, its role is extended to enhance road safety and security. Nowadays, autonomous and connected vehicles can perform intelligent decisions and cooperative communications

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with other road users to exchange data and expand their environmental awareness. This communication is introduced as vehicle-to-everything (V2X).

Despite this progress in the automotive industry and communication technology, the number of road accidents is still high [1]. Indeed, the alarming statistics reflect the critical importance of the VRU safety issue. According to World Health Organization (WHO), the number of deaths is estimated by 1.35 million people dying each year in road accidents, where more than half are among VRU. More specifically, pedestrians and cyclists account for 26% of all VRU deaths [2]. Significant risk factors for VRU injuries could be related either to the driver's state and its behaviour (e.g. drunken, aged, driving at high speed, violating traffic laws) or the VRU behaviour (e.g. inattention)[3]. Government efforts (law regularization), constructors, and industrial engineering solutions have reduced the number of accidents by avoiding or reducing the fatality degree of the injuries. Despite the existing solutions, more efficiency is needed to decrease the number of deaths [2] significantly. Then, the indirect visibility of VRU in non-line-of-sight cases or a sudden change in its behaviour [4] (e.g., using a smartphone while crossing the street) are the most dangerous factors to be treated.

To overcome those limits, the exploitation of the smart connected vehicle capabilities decreases human error. Moreover, integrating VRU into an intelligent collision prevention system can help to prevent road accidents. As we discuss further below, three classes of solutions exist: *Vision-based perception:* where the system places a heavy computing load on the graphic processing units (cameras, LiDARs, radars) due to the high signal processing requirements. *Network-based perception:* they rely on the information (e.g., positioning messages) that vehicles and cyber-physical infrastructures can provide. *Hybrid solutions:* based jointly on the signalling network traffic and the graphical units' analysis, thanks to data-fusion techniques.

In addition to the expected growth in the number of connected vehicles, the global penetration of smartphones and connected devices of VRU also rises very fast due to urbanization. These factors drastically revolutionize road safety services and make the applications constantly sensitive to the underlying technologies' evolution. As the development and standardization of 5G are finished, and the deployment of 5G networks is in progress, academic research and industry are moving to develop beyond 5G, called 6G, to support the growing number of connected devices that overtake 5G limitations. This can directly impact the VRU safety when the 6G is expected to extend the network capacity and add new services that can respond to the road safety application challenges and meet the requirements by providing more intelligence compared to the current ITS technologies. Consequently, the accordance between the application and the communication technology is necessary to use the network resources more efficiently.

The remainder of this survey is organized as follows. Section 2 discusses existing surveys and highlights the gap we aim to fill with the current survey; it also presents the scope of our survey and the research methodology. Section 3 depicts the general context where the related standards, the existing projects, and the different use case classes are presented. In Section 4, we describe the collision avoidance system in the context of VRU protection while giving details on the collision prediction algorithm and the communication messages. Section 5 describes the potential communication architectures. Section 6 identifies the network challenges as well as the application requirements following 5G and ITS standards. Then it surveys the proposed solutions and enhancements to tackle these issues. We sum up the survey with a table recapping the main enhancements areas in section 7. In Section 8, we discuss the open issues and the future research directions. Section 9 concludes the survey.

2 Related work

2.1 Existing surveys vs the current review

The safety of vulnerable road users has concerned researchers and has already been reviewed several times. For instance, El Hamdani et al. surveyed pedestrian issues for ITS and provided a classification of the existent protection solutions [5]. Authors of [6] come up with a VRU literature-based taxonomy and a precise definition of VRU in the context of human-computer interaction (HCI) research. In [7], authors proposed a design framework and a classification for the V2P system while comparing the VRU role in the ITS. Dasanayaka et al. argued the available countermeasures, challenges, and solutions to enhance VRU protection [8]. Pedestrian safety has been discussed in [9] in the context of Internet of Things (IoT) where authors presented the collision alert system through V2P communication. In addition, Jing et al. have systematically reviewed the reliability of V2P communication systems based on vehicular Ad-Hoc networks (VANET) [10]. Regarding path prediction for V2P application through Outdoor Localization, smartphone use for VRU safety has been discussed in [11]. Autonomous vehicle (AV) and VRU interactions have been studied in [12, 13] where the behaviour of VRU have been analysed.

Although these surveys focus on VRU safety countermeasures (Cooperative-ITS (C-ITS) and non-C-ITS countermeasures) from multiple perspectives, they present the VRU safety application only in the 4G era, which can not meet the future autonomous cars' demands, thus, an update is in order. In particular, they did not cover the new key requirements of the application, such as the energy consumption of VRU devices. More specifically, they do not present the collision detection algorithm, a critical component of this application system, or provide a classification of the existing algorithms and their types. In addition, a comparison between different architectures and function placement is lacking.

Moreover, current surveys are limited to outdated projects. For example, communication architectures were not detailed, and collision avoidance algorithms have not been highlighted. Thus, complementary to the aforementioned surveys, this review fills the gap and suggests a new approach of classifying the recent contributions, going the way up to 2022, in the 5G and beyond era. In table 1, we provide a comparison of the existing surveys with this review. The contributions of this survey are as follows:

- Provide an overview of the existing communication standards and the recent research projects considering a VRU safety use case.
- Detail the required communication architecture while discussing the placement of the functions in a 5G context.
- Highlight the features of collision prediction and avoidance systems.
- Summarize the whole key performance metrics used for analysing both the network and the application performance.
- Take a step back to analyse the literature and show how recent works try to overcome the VRU safety service challenges.

Table 1: Current survey vs existing surveys.

Reference	coverage	Scope	Topic	Common points with this survey
[5]	2010-2020	Pedestrian Safety	- Pedestrian issues - Traffic lights, RSU, V2I, V2P - Pedestrian detection - ADAS and Vehicular Cooperation - AV Acceptance and Interaction - Behaviour Analysis and Modelling	 ✓
[7]	2008–2018	V2P communication system	- V2P systems - Convenience Applications - VRU Safety applications - Communication Technologies	✓ ✓ ✓ ✓
[8]	2007-2020	VRU protection	- VRU protection countermeasures - Challenges - C-ITS solutions	✓ ✓ ✓
[10]	2005-2017	Car-to-pedestrian communication safety system	- V2P communication systems in the context of VANET	–
[11]	2000-2019	VRU warning using smartphones	- Vehicle to Pedestrians Systems - Path prediction for V2P application: - Outdoor Localization, - Smartphone use for VRU safety	✓ ✓
[13]	1994-2021	AV-VRU interactions	- Definitions of VRU - Vehicle-to-VRUs collisions on limited-access highways - AV-VRU related studies, news and articles	–
[12]	1991-2018	AV to VRU interactions	Pedestrian behaviour studies: - Pedestrian–driver interaction - Pedestrian-AV interactions	–
[9]	2015-2021	Pedestrian safety in the context of IOT	- Pedestrian safety systems - Existing obstacle detection - Collision alert systems - Vehicle–Pedestrian communication	✓ ✓ ✓
[6]	2000-2020	Vulnerable Road Users for HCI	- Literature-based VRU taxonomy - Precise definition of VRUs in the context of HCI research	–
Our	2015-2022	5G-enabled VRU protection	- Communication standards - Recent VRU projects and studies - 5G V2VRU-based Communication architectures - Role of V2VRU communication messages. - Collision avoidance systems. - Classification of the existing algorithms. - VRU protection application and network related KPI - Challenges of VRU safety service. - Existent solutions for VRU protection	–

2.2 Review methodology

We have collected the relevant scientific contributions and resources published in high indexed conferences and journals using keywords related to our review topic, e.g., "vulnerable road users' collision avoidance", "pedestrian detection", "5G collision detection system", "VRU communication architectures", "MEC/Cloud based collision avoidance" etc. We used various scholar databases and digital libraries. Then we defined the review outline, title, and keywords and explored the expected advances and trends to select the most pertinent and up-to-date works. Finally, we included a critical discussion where we identified open issues and future directions. As for writing this article, the reviewing procedure was systematic where the papers' selection was manual; however, it is worth mentioning that the literature was continuously updated with papers recently published.

3 Standards, projects, and use case classes

We introduce in this section the general context where we give the different use case classes, the communication standards, and technologies. Then, we present recent projects and studies considering a VRU safety use case.

3.1 The European strategy towards cooperative, connected, and automated mobility ETSI C-ITS

The European Telecommunications Standards Institute (ETSI) working group is responsible for supporting regulations and developing C-ITS systems' technical standards. The ETSI-ITS defines reference architectures, V2X communication technologies, and studies on ITS use cases such as cooperative road safety, traffic efficiency, etc. More specifically, the ETSI-ITS release two addresses VRU protection use-case [14]. The ETSI is a partner in the 3^{rd} Generation Partnership Project (3GPP), where it helps to study and develop mobile communications. In the United States, the Society of Automotive Engineers (SAE) is responsible for developing and updating standards to advance automotive engineering [15]. Despite the SAE International and ETSI have different names for ITS awareness messages, their function may be the same.

3.2 Standards

3.2.1 IEEE 802.11p

The 802.11p is the first Wi-Fi based standard specifically designed for vehicular communications [16]. It works in the licensed ITS band of 5.9 GHz (5.85–5.925 GHz). IEEE 802.11p supports mobility and dynamic topology of the vehicular network, where mobile nodes directly communicate without any association. It is considered as the best candidate for vehicular ad hoc networks (VANET) while allowing vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications.

The ITS-G5 in Europe [17] is a radio access technology based on the IEEE 802.11p standard that enables V2X communication, and it is called Dedicated Short Range Communication (DSRC) in the United States. It guarantees privileged access for critical applications by differentiating channel access according to the application type and the priority level of the messages sent between ITS-G5 stations (vehicles and Road Side Unit (RSU)) in a purely distributed network operating without a coordinator. Further, the ITS-G5 provides new features as the Decentralized Congestion Control (DCC) mechanism to control the network load. The messages' transmission is based on Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) algorithm, where only one frame can be transmitted at a time [18]. To support technological advancements and V2X requirements, 802.11p is followed by its successor 802.11bd. The latter presents physical layer enhancements to improve the throughput and the transmission range while guaranteeing the interoperability with legacy 802.11p [16].

3.2.2 3GPP standards

In addition to defining use cases for V2V and V2I communication, 3GPP also investigates vehicular-to-pedestrian (V2P) communications for VRU safety [19]. The key features of 3GPP use cases are centred on cellular-based V2X communications (C-V2X). They cover the settings of the transmission periodicity of cooperative safety messages, warnings for the driver and the VRU, the definition of end-to-end latency, and the reliability requirements. For instance, releases 14 and 15 studied the LTE support of V2X services such as road safety via infrastructure where servers and RSUs generate traffic safety messages for road users and warn the pedestrians against hazardous events in NLOS scenarios. 3GPP worked on ultra-Reliable Low-Latency Communication (uRLLC) to meet the stringent reliability and latency requirements of critical use cases [20]. In release 14, 3GPP have defined two types of V2V resource reservation for C-V2X: *(i) mode 3* where the resource are allocated by the eNB under cellular coverage, and *(ii) mode 4* where vehicles select autonomously their resources using a Semi Persisting Scheduling (SPS) scheme independently of cellular infrastructure. Further, in C-V2X vehicles communicate through two interfaces: *(i) PC5 interface* used for side-link V2V direct communication and *(ii) Uu interface* used by vehicles to communicate with eNB to request transmission resources on PC5 channel. In release 15, the group introduces enhancements to support 5G-V2X safety (e.g., autonomous driving, platooning, etc.) and non-safety services (e.g., high data rate comfort services and map updating). Further, in release 16 they introduced New Radio V2X (NR-V2X) and physical layer improvements to fulfil more rigorous 5G quality of service (QoS) requirements and support interoperability with multiple Radio Access (RAT) (e.g., 3GPP RAT: LTE-V2X, NR-V2X, and non-3GPP RAT: ITS-G5, DSRC).

Undoubtedly, these standards significantly contributed to the format definition of the messages and harmonized the specifications for each use-case and set requirements for the upcoming ITS.

3.3 Use case classes

Several use cases have been defined by the ETSI standard and the 3GPP group [21]. The 5G Automotive Association (5GAA) has proposed seven use case classes to group them according to the application service and their technical requirements [22]. On its part, the 5G Communication Automotive Research and Innovation (5GCAR) proposes another classification with five use case classes: *Cooperative manoeuvre, cooperative perception, cooperative safety autonomous navigation, and remote driving* [23, 24, 25]. Hereinafter, we briefly introduce them.

- Cooperative manoeuvre: vehicles share their driving intentions to negotiate the planned trajectories and efficiently coordinate them to increase awareness and avoid risks.
  For example, lane merge, lane change, convoy driving, and cooperative intersection management are based on coordinated manoeuvre between vehicles to increase driver safety and optimize road capacity.
- Collective perception: vehicle exchange with other connected road users and infrastructure raw or processed data and merge them to extract useful information and build collective awareness (e.g., relative position, see-through or Bird's eye view at an intersection, 3D video composition).
- Autonomous navigation: based on the cooperative perception, collected data and other sources of information, an intelligent map is updated with more accurate context information and distributed among other vehicles depending on their location. This real-time high definition (HD) map is used to increase awareness of the road users by their environment to avoid accidents and quickly react in emergency situations, to optimize the traffic flow by selecting the best trajectory to destination.
- Remote driving: in this use case, the vehicle use sensors, HD map, and infrastructure information to control remotely through wireless communication its actuators (steering wheel, brake, and throttle).
  Remote parking, public transport, remote driving are examples where a remote server controls the vehicles.
- Cooperative safety: vehicles exchange data about the detected road elements (using sensors, cameras, positioning system, communication system, etc) directly, with other road users, or via the infrastructure. Vehicle on-board-units (OBU), RSUs and edge/remote servers are responsible for processing the received data and extracting useful information and decisions, to generate alert messages if the danger has been detected. The vehicle can avoid it by reducing the speed, changing the trajectories, or braking.

The most relevant use case of the cooperative safety class is undoubtedly the vulnerable road user protection. Precisely, the one which interests us in this survey and specifically when it is network-assisted. Indeed, this use case can also be supported by vision-based [26] and hybrid perception approaches. However, considering the detection of the VRU from the vehicle's perspective, without involving the VRU as an active actor in the C-ITS can lead to more vulnerability. Therefore, our survey focus on studying the aforementioned use case while investigating the technical and the application related requirements and challenges. In the next section 3.4 we will introduce the most relevant projects conducted in the VRU safety use case.

3.4 Projects and Studies

Many international research projects have been conducted on V2X services and architectures. The outcome of these projects and studies has contributed to the standardization efforts to develop end-to-end solutions for intelligent transportation systems. In table 2, we look through the most recent projects (since 2015) that treated the VRU safety use case. We specify the outstanding contributions, the studied scenarios, and the used communication technologies for each research project.The PROSPECT and InDeV projects studied VRU scenarios to understand the causes of the accidents. PROSPECT provided testing in realistic traffic scenarios. However, it relied on sensing without communication when considering the VRU as a passive actor. The vehicle, equipped with sensors, actively takes necessary actions in risky situations. TIMON project provided a unified cloud-based platform to process data intelligently for real-time VRU protection through smartphone applications. The project considered hybrid communication technologies (802.11p and LTE); however, the integration of 5G is lacking. Similarly, the XCYCLE project was based on the use of 802.11p technology, which no longer responds to the new requirements of today's needs. Moreover, the project considered only studying one type of VRU (cyclists). Transmitting positioning data to an external server can raise security and privacy problems not explored by the projects mentioned above. 5GinFIRE and 5G-Transformer supported different communication technologies in centralized and decentralized architectures. Throughout merging sensing with communication data, 5G-Routes, 5G-Croco, and 5G-Heart projects enhanced VRU safety by anticipating potential risks. Even though all the cited projects handled the VRU protection issue from different perspectives, the automation level of vehicles and the penetration rate of connected or autonomous cars need to be further investigated.

In addition to the projects mentioned above, we provide, in table 3, the most recent and international studies related to VRU safety. They can be classified according to the general scope of VRU safety use case. For instance, [27, 28, 29, 30, 4, 31, 32, 33] focused on studying the interactions between VRU and vehicles, and also examined the behaviour of the driver and the VRU. The references [2, 34, 35, 36, 37, 38] reported death and injury statistics. Concerning collision avoidance systems, the studies in [39, 40, 41, 42, 43, 44] investigated the role of the VRU as an active actor in road accident prevention through V2VRU communication. The work in [13] provides more articles, reports, and news covering VRU-related issues since 1994.

4 Collision Avoidance System Features

This section strives to highlight the types of communication messages and describe a collision-avoidance system's key components in VRU protection use case. Based on our related work-study, a collision-avoidance system comprises many parts (data-collection, message processing, collision detection algorithm, alert dissemination, etc.). It effectively operates thanks to the received communication messages.

4.1 Collision Avoidance System description

The collision avoidance system is composed of four steps as shown in figure 1.

Table 2: List of projects implicated in VRU safety application.

Project	Coverage	Reference	Use case scenario	Technology	Contribution
PROSPECT	2015-2018	[45]	VRU protection: pedestrians and cyclists	–	Developed the next generation active safety systems to protect VRU by improving VRU sensing and situational analysis as well as enhancing vehicle control strategies. Test in realistic traffic scenarios.
InDev	2015-2018	[1]	VRU protection: pedestrians and cyclists	–	Provided a better understanding of road accident causes and their costs, while focusing on vulnerable road users such as pedestrians and cyclists.
TIMON	2015-2018	[46]	Cooperative real time VRU and vehicles safety prediction	802.11p, LTE	Proposed a cloud-based platform using the road users data and V2X hybrid communications, then processing it with AI to provide real-time services to all the users through a smartphone application.
XCYCLE	2015-2018	[47, 48]	Bicycle interaction with vehicles at intersections. Cyclists approaching traffic signals.	802.11p	Developed technologies improving active and passive detection of cyclists, as well as cooperative systems to inform both drivers and cyclists of a hazard at intersection.
5GCAR	2017-2019	[23, 24, 25]	VRU protection: road user detection	5G	Proposed a 5G system architecture providing enhancements to optimize the network and to meet the service requirements. VRU detection is handheld by combining data from their connected devices with vehicle on-board sensor readings and the communication system.
5GinFIRE	2017-2019	[49]	VRU protection	802.11p, LTE, 5G	Developed an open source Management and Orchestration 5G NFV-enabled platform (MANO) to support different technologies and critical safety requirements.
5G-Transformer	2017-2019	[50, 51, 52]	Pedestrian Collision Avoidance	802.11p, LTE, 5G	Developed virtualized 5G network for uRRLC services, a prototype 5G RAN orchestrator, 5G network slicing, NFV and MEC integration mechanisms, connected cars and traffic flow control.
5G-CARMEN	2018-2021	[50]	Situation Awareness: preventive knowledge of any critical issues encountered along the road.	C-V2X, 5G	Proposed 5G solutions for the management and the orchestration of specific use cases with mission-critical and low-latency service requirements.
BiDiMoVe	2018-2021	[53]	Cyclists and Pedestrians protection	ITS-5G	Increase the safety and efficiency of the road traffic by providing a test field which prevents cyclists and pedestrians from colliding with busses.
5G-Croco	2018-2021	[54]	Anticipated Cooperative Collision Avoidance (ACCA)	5G	Extended the ITS architecture using Cellular infrastructure and Interoperability as well as C-ITS Security areas.
5G-ACIA	2018-2022	[55]	Support of Functional Safety	5G	The project aims to implement the functional safety as a native network service to determine the target safety provisioning.
CSCRS	2018-2022	[56]	VRU protection	–	The Collaborative Sciences Center for Road Safety provides numerous projects regarding VRU safety systems: (Investigating VRU road fatalities, applying AI to improve V2P interactions, analysing data to examine VRU injuries, proposing and evaluating safe systems approaches, etc.)
5G-HEART	2019-2022	[57]	Smart junctions and network assisted cooperative collision avoidance	5G	Provide 5G URLLC with data fusion of detected objects so that the vehicles can anticipate what is ahead and react in real time to avoid the collision.
VIDETEC	2020-2021	[58]	VRU protection	–	Enhance the road safety for pedestrians and cyclists based on an intelligent infrastructure, sensors and V2X communication.
5G-ROUTES	2020-2024	[59]	Sensing Driving: Vulnerable road user collision avoidance	5G	Enhance the VRU safety using sensor gathered information and communication exchanged data between VRU and vehicles to warn them in advance against collision risks.
Analysis of Intelligent Vehicle Technologies to Improve VRUs Safety at Signalized Intersections	2022	[60]	VRU protection	–	The project investigates the role of the Intelligent Vehicle Technologies (IVT) in improving VRU safety under different conditions, and it studies the risk factors at signalized intersections.
SAKURA	2018-2025	[61, 13]	Vehicle-to-VRU interactions to support the development of AV.	–	The project provides scenario generation and traffic data analysis and acquisition. It focuses on autonomous driving services and VRU safety.
5G OPEN ROAD	2022-2024	[62]	VRU protection	5G	Enhance the safety of high risk exposed areas such as intersections and decrease the traffic congestion through real life experiments

Table 3: List of studies implicated in VRU safety application.

Study	Year	Region	Targeted VRU group	Contribution
[39]NHTSA	2016	USA	Pedestrian protection	Studied road collisions involving pedestrians and investigated the role of vehicle-to-pedestrian (V2P) communication in crash avoidances
[2]WHO et al.	2018	Worldwide	VRU	The study reports statistics of road traffic injuries and road safety risk factors. It summarizes the current state of road regulations and proposes measures to improve VRU safety.
[40] Euro NCAP	2017	Europe	VRU	The report provides test conditions and procedures (car-to pedestrian, car-to-bicyclist, and car-to motorcyclist) under multiple environmental conditions for autonomous emergency braking VRU Systems.
[27] Allen et al.	2017	Australia	motorcycles	The study examined the contributing factors to crashes and the interactions between drivers and VRUs.
[34] Coleman et al.	2018	USA	Pedestrian and bicyclist	The report provides Traffic Safety Facts obtained from the Fatality Analysis Reporting System (FARS)
[28] Sander	2018	USA and Germany	VRU	In this study, the V2X communication-based and the sensing-based approaches were compared using real-accidents and driving data from the USA. Intersection autonomous emergency braking was simulated using real-accidents data from Germany to evaluate their effectiveness in mitigating accidents and injuries.
[29] de Miguel et al.	2019	Europe (Spain)	Pedestrians	The study examined the interactions between full driving automated vehicles and pedestrians through experiments in public roads.
[41] Cummings et al.	2019	USA	Pedestrians	The study investigates how advanced technology can assist VRU protection by conducting experiments of crossing pedestrians holding their smartphone to receive alerts.
[30] Rasch et al.	2020	Europe	Pedestrians	The study analysed and modelled the driver's behaviour in pedestrian-overtaking manoeuvres on rural roads.
[42] Gelbal et al.	2020	USA	Pedestrians	This study evaluated pedestrian collision avoidance systems for low-speed autonomous shuttles based on Vehicle-to-Pedestrian (V2P) communication.
[35] Wang and Cicchino	2020	USA	Pedestrians	The study analysed the fatally injured pedestrians' data from FARS to determine the characteristics of the crashes and propose countermeasures.
[36] IHS-HLDI	2020	USA	Pedestrians	The report provide pedestrians fatality statistics.
[4] Yannis et al.	2020	Worldwide	VRU	The study provides data on VRUs' self-declared risky and unsafe behaviour.
[37] International Transport Forum Japan	2021	Japan	VRU	The report provides statistics on road fatalities classified by VRU category, age and road type in Japan.
[43] Brown et al.	2021	Europe	Powered two-wheelers and Bicycles	The study provides collision investigations and data analysis to understand the causes of accidents and to improve the safety.
[44] Tan et al.	2021	China	Pedestrians	The study developed and tested active safety systems using car-to-pedestrian pre-crash scenarios.
[31] Tabone et al.	2021	–	VRU	This study surveyed researchers opinion on future introduction of autonomous vehicles and their interaction with VRUs.
[32] Bella and Silvestri	2021	Europe (Italy)	Pedestrian	The study provides a behavioural-analysis of the interaction between the drivers and the pedestrians while evaluating the effectiveness of ADAS, pedestrian detection and warning systems.
[38]Macek	2022	USA	Pedestrians	The report provides a comprehensive look at pedestrian traffic fatalities by state and roadway type.
[33] Wang et al.	2022	USA	Freight-related VRUs safety	The study put into the spotlight the impact of large vehicles in increasing the probability of road fatalities and severe injuries.

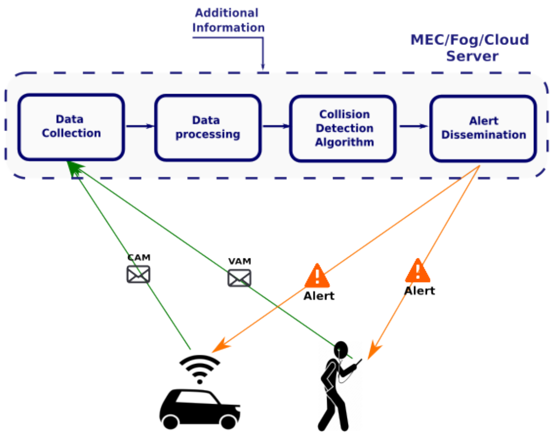

Fig. 1: Collision avoidance system features.

4.1.1 Data collection

The first step in ITS VRU safety application is data collection. It provides the capability to gather essential data (e.g., location, speed, neighbouring vehicles or VRU, surrounding objects, road traffic conditions, etc.) encapsulated in vehicles and VRU messages for instance CAM and VAM as presented below:

– Cooperative Awareness Message (CAM): road users exchange safety-specific messages periodically with their surrounding environment. These messages, called CAM in the ETSI standard or Basic Safety Message (BSM) in Society of Automotive Engineers (SAE) standard, enclose context-awareness (i.e. vehicle ID, type and role in the road traffic, length, width, position, speed, heading angle, lateral and vertical acceleration, etc.) [63]. They are triggered with $1-10$ Hz frequency that depends on vehicle characteristics: speed, position, heading angle, etc.
– VRU Awareness Message (VAM): VRU with Smartphones can send another message type more flexible than CAM. It is characterized with a shorter length, and it is context-specific. This VAM message is introduced by the ETSI standard [14] and Personal Safety Message (PSM) in the SAE standard. It includes location information, VRU type, speed, direction, etc. VRUs devices are in charge of generation and construction of VAMs while including motion prediction and other context information to improve the positioning accuracy.
– Decentralized Environmental Notification Messages (DENM): composed of four containers, they are used to alerting road users when a triggering application detects a dangerous event [64].
– Cooperative Perception Messages (CPM): vehicles exchange sensing information to improve driving environment perception using CPM. They contain information about surrounding detected objects. ETSI standard defines their format, generation and transmission rules [65]. They are updated every 1 s or if any change in the detected object conditions occurs. The current ETSI-CPM implementation

is characterized by high frequency CPMs transmissions, while the CPMs contain small Information about detected objects. In [66], authors have proposed a new CPM generation algorithm that predicts the behavior of the detected objects to optimize the generation rules. Their approach consists of less frequent CPMs transmission, while a CPM contains higher number of detected objects.

The different fields of the messages cited above are depicted in figure 2. It is worth to note that VAM and CPM messages have similar mandatory fields to CAM and DENM respectively.

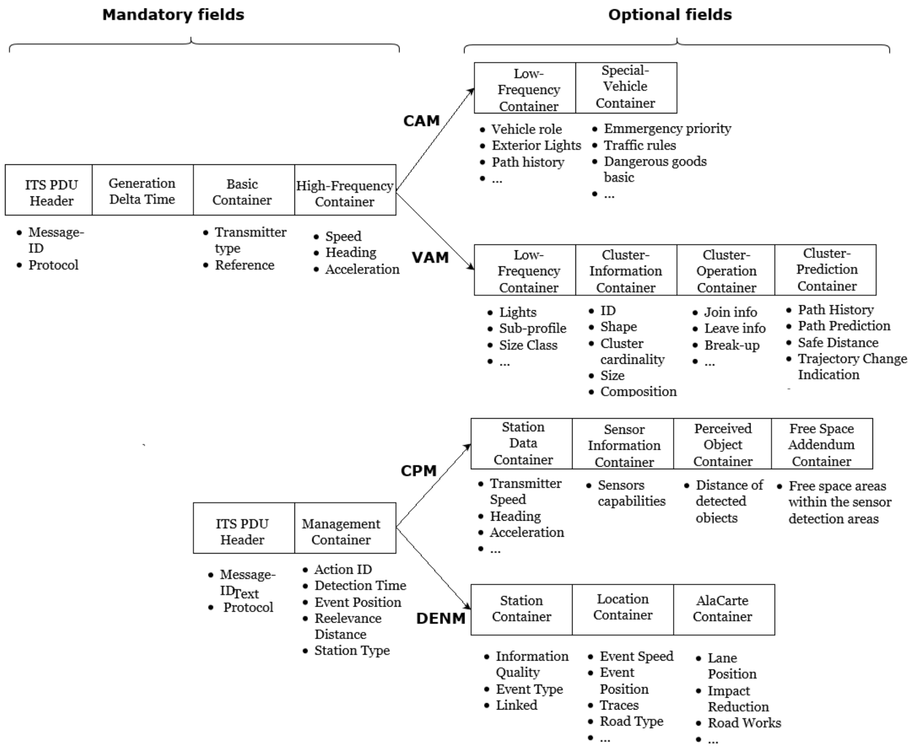

Fig. 2: Type of communication messages.

The Awareness messages have a paramount role in the collision avoidance system, where they allow the VRU to participate actively in the communication process by sending VAMs to the servers and vehicles. Alternatively, they can participate passively by being detected by other vehicles that will include their related data in CPMs or in DENMs (e.g. in the collision risk field). The data collection phase is not limited to the collection of communication messages. It can be extended to collect information from multiple data sources (e.g., road cameras and sensors data, network functions data, VRU self-positioning, etc.). It is worth to mention that collision avoidance application can be placed in a server or runs directly on vehicles or VRU smartphones. In this survey, we consider the ITS messages as the essential information source that should be provided to the collision avoidance algorithm to operate correctly.

4.1.2 Message processing

After the collision avoidance application receives the messages correctly, it verifies their freshness and stores them in a table before being forwarded to the collision avoidance algorithm, otherwise, it discards them. For instance, authors in [50] set the up-to-date threshold equal to 0.8 s. Furthermore, the process differentiates the types of the received messages based on their characteristics [52]. It determines whether they are received from pedestrian VAMs/PSMs or vehicles CAMs. This phase gives the advantages of avoiding the computation of pedestrian to pedestrian collision and adapting the algorithm according to the available information.

4.1.3 Collision detection

Regardless of the server type or location (cloud or Edge), the server's role is twofold: the detection of a risky situation and the identification of the involved users. Several collision avoidance algorithms have been proposed in the literature. We group them as follows:

- Benchmark Algorithm: the simplest way to approach things is to go through four steps: *(i)* Predict future positions of the entities function of their current position, velocity [67], acceleration [50] or deceleration information [68]. *(ii)* Compute the distance between the vehicle and the VRU. *(iii)* Compute the minimum distance or time between the two nodes and compare it to a threshold. This threshold is a configurable parameter that depends on the time to reaction. *(iv)* Select the group of endangered vehicles and VRUs to be alerted if the minimum distance and the time before collision are less than the defined threshold, otherwise the algorithm goes through to the next iteration.
  Other approaches [69, 70, 71], compute the collision probability ($P_{collision}$) while considering the impact of sensors inaccuracy (e.g. position, speed, direction measurement errors) on the accuracy of the collision detection. Then, according to $P_{collision}$, an alert is generated when the probability exceeds a predefined threshold.
- Multi-Threshold based Algorithm: this type proposes multiple thresholds to improve the detection system performance compared to the benchmark algorithm, which is simple and based on a single threshold. For instance, in[49], the collision avoidance algorithm is divided into two principal parts: *(i)* Timely predict the future trajectory using the Trajectory Computing Component Virtual Network Function (TTC-VNF). This latter, processes in real-time the received contextual information from the OBUs and the VRUs to calculate the future positions and directions. *(ii)* Avoid anticipated collision events between VRUs and vehicles through the Hazard Identification and Notification Service Virtualized Network Function (HINS-VNF). HINS-VNF is responsible for evaluating the computed trajectories and detecting possible collisions. It provides an efficient, scalable collision detection algorithm with low run-time and complexity. Instead of using a single threshold to detect collision, three types of thresholds have been defined

to improve the performance of the algorithms: *Collision Threshold:* for each possible collision event a collision counter is incremented, if this counter exceeds the predefined collision threshold, an Alert is generated. It is used to control false positive alerts. *Tolerance Threshold:* to avoid the impact of prediction errors or a change in vehicle velocity. *Immediate Threshold:* used to ignore the collision counter and send an immediate alert if a collision is predicted for an immediate event. It controls the false-negative alerts. Authors of [72] started from the benchmark algorithm and then enhanced it by adding more thresholds and conditions. They defined a vehicle to pedestrian distance threshold and a pedestrian safety threshold to trigger alerts. They considered different thresholds configurations to reduce unnecessary alert generation in the warning system.
- Risk level based Algorithm: Instead of only relying on thresholds to determine the collision possibilities, authors of [73, 74, 75, 76] proposed to evaluate the risk level related to the danger area. The risk level depends on several parameters such as the proximity to vehicles, the location (e.g. urban or rural, intersections). In this way, the driver awareness is increased in NLOS scenarios by visualizing invisible pedestrians according to the danger zone evaluation.

In table 4, we summarize the contributions mentioned in this section where we identify, for each work, the used data, how the data was processed, the collision detection algorithm, and how the alert is disseminated.

Collision detection algorithms can exploit AI algorithms, in addition to the conventional trajectory prediction techniques (based on the velocity, the acceleration, or the direction, etc.) to perform intelligent predictions and enhance the detection latency and accuracy [77, 78]. Edge or Cloud servers can intelligently predict future trajectories using machine learning techniques, deep learning [79] or by using a Kalman filter [80, 81] to estimate possible risks before they occur with better accuracy. For instance, in [82], an interaction-aware Kalman neural network (IaKNN) has been proposed to make trajectories prediction. Diverse open problems and challenges related to the collision avoidance algorithm must be handled (e.g. complexity, processing time) that will be discussed in section 6.2.

4.1.4 Alert dissemination

After the collision detection step, if a collision risk is detected, a warning must be sent to the identified VRUs and vehicles. It can be encapsulated into a DENM or a CPM message. The alert can stay active as long as the triggering conditions remains valid. Once the alert is received, it can be displayed on the vehicle's dashboard, for example. For the smartphone, it can be adapted according to the current state of use to attract the attention of the pedestrian: a message in the screen, a voice alert or both [83]. If the smartphone is in the VRU pocket, the alert can be a vibration. In [80], authors proposed the warning grading according to the drivers' reaction time that varies from 1 to 6 seconds. They defined three warning level; high, medium and low risk, and adapted the warning type accordingly. To target the alert only for the for concerned elements, risk filtering algorithms can be used. This reduces the unnecessary receivers in the down-link traffic by evaluating the collision risk for the specified vehicle or VRU [84, 72].

Table 4: Collision Avoidance Systems
For each contribution (**row**), The used data (**columns**) as well as the data process and the collision avoidance algorithm {(1): Benchmark, (2): Multi-threshold, (3): Risk level based} have been listed. The alert dissemination methods are also listed.

Reference	The used data	Data process	The collision detection algorithm			Alert Dissemination method
			(1)	(2)	(3)	
[49]	CAM	- Extract and processes context information -Predict future trajectories - Compute collision probability - Identify imminent road hazards using : Collision threshold, tolerance window, Immediate threshold.		✓		Forward notification messages (Normal or Immediate Alerts) towards the involved VRUs/OBUs.
[50]	BSM	Extract: - position, speed, and heading -lateral and vertical acceleration - vehicle length and width. Determine possible collisions	✓			Alert concerned colliding entities
[67]	CAM	- Parse CAM and verify its syntax - Store useful data - Compute distance between vehicles and VRU - Determine possible collisions	✓			Alert concerned element via DENM
[68]	POST messages	Extract: - ID, position, speed, deceleration -Compute collision probability	✓			Alert concerned colliding entities
[69]	CAM	Extract: - position, speed, direction - pedestrian context: (walking, running, crossing) - Compute collision detection probability - Evaluate collision detection accuracy	✓			Send DENM in case an impending collision between two road users is detected
[70]	CAM, VAM	Extract: - position, speed, direction	✓			Send Alert in DENM for concerned road users.
[71]	REP and REQ message	- Define the Alert zone - Estimate the probability of collision based on the information in the REP			✓	Alert vehicles in the Alert zone via REQ message
[72]	Beacons	- Evaluate distance between vehicles and VRUs - Verify direction conditions - Compare distance between vehicles, pedestrians, and the crossing with the alert distance threshold and the pedestrian safety threshold		✓		Alert concerned elements in case all conditions are respected to reduce false positives.
[73]	Beacons	Extract : position, speed, direction - Evaluate danger zone - Compute collision point and time to collision			✓	A warning message is sent to the driver/pedestrian in case of high collision risk
[74]	CAM	- Limit the area for sending warning - Predict accidents using a fuzzy system - Classify real conditions to high, medium and low risk level			✓	Alert according to the risk level, in case of high risk take action
[75]	BSM	- Compute risk level and collision probability using location, speed and heading data - Adapt beaconing rate to the risk level			✓	Alert concerned vehicles and pedestrians
[76]	BSM, PSM	- Perform threat analysis using incoming beacons - Adjust pedestrian's beaconing rate to the risk level			✓	Alert concerned vehicles and pedestrians using push message

5 Communication Architecture for VRU protection

There are two types of communication architectures to support a VRU safety system. The main difference between them is the use or not of the network infrastructure, depending on the communication technology and the availability of the network to fulfill the critical requirements of the safety application.

5.1 Infrastructure based architecture

The components of an infrastructure-based architecture are depicted in figure 3. As shown in this figure, there are two main parts: the 5G core network and the radio access network (RAN). Notably, this architecture counts connected VRUs and vehicles, Cloud and Edge servers, base-stations, RSUs, etc. Further, V2X communication links exist to support vehicle to vehicle (V2V), vehicle to infrastructure (V2I), vehicle to network (V2N) or vehicle to VRU (V2VRU) communications (e.g. vehicle to pedestrian(V2P), vehicle to cyclist (V2C), etc.).

5.1.1 Radio Access Network

The key elements of the Radio Access Network are as follows:

- VRU: Vulnerable road users can be humans or animals. The latter are considered as VRU since they can cause safety risks, especially wild animals in rural areas or in the highway. They can be passively detected by cameras or by vehicles sensors, or may have a connected gadget (e.g. pets in the city). In this survey, human VRU will be studied. VRU can be classified according to their characteristics. For instance, pedestrians are characterized by their average walking speed 5 km/h, that can vary with age and physical ability. The cyclists' speed is around 15 km/h, and for motorized two wheels (e.g. scooters), it is around 50 km/h in urban area [14].
  VRUs can communicate with gadgets [85] such as connected Helmets, Tags, etc. However, exploiting the fact that smartphones are very used and widespread [86] among VRUs instead of buying specific gadgets is more relevant. In addition to their intelligent capabilities in terms of computation and communication, they have multiple sensors (motion, Global Positioning System (GPS), magnetometer, accelerometer, gyroscope, etc.) that can provide valuable raw data to enrich context information. Using their smartphone, VRUs periodically send specific messages, namely PSM or VAM, using cellular communication to exchange context-awareness information with other road users or servers. This way, smartphones can participate in VRU protection, instead of being a source of distraction [11].
- Vehicles: the vehicles are characterized with their high mobility. Their Advanced Driver Assistance System (ADAS) helps to improve safety and to decrease human driver errors [87]. It reduces the reaction time by assisting the drivers to take the appropriate action and avoid road accidents. Besides, the cars are equipped with Lidars, Radars, and cameras to detect road users and increase its surrounding environment awareness. Nevertheless, in NLOS scenarios (e.g., buildings in urban areas, intersection corners, bad weather conditions that deteriorate camera performance) a vehicle relies on cooperative communication via its OBU.

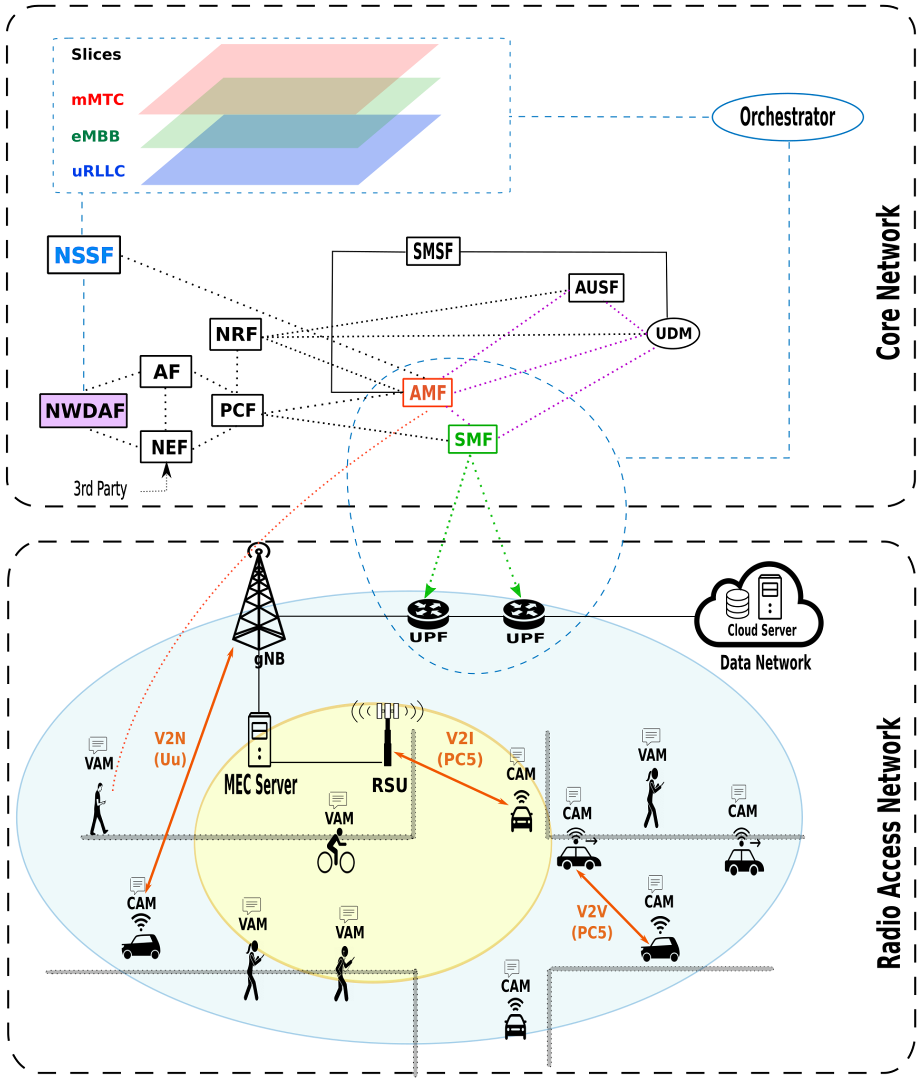

Fig. 3: In this 5G Communication architecture, an orchestrator coordinates the core network functions and slices to support the safety application. The road users exchange safety messages in the RAN. The gNB cellular coverage is defined by the blue circle when the yellow circle delimits the RSU coverage.

Indeed, the vehicle exchanges safety-related information encapsulated in specific messages (DENM or CAM) with its neighbours or with VRUs or the network infrastructure using Vehicle to everything communication technology (V2X). They can communicate under the cellular coverage using C-V2X or 5G NR-V2X communication directly using the mode-3 PC5 interface or indirectly via the cellular

infrastructure employing the Uu interface[52, 88, 89, 90]. With the advent of Connected Autonomous Vehicles (CAV), human driver errors and reaction time no longer exist thanks to advanced intelligence and high automation. However, their penetration rate is still in progress that puts the system in a transition phase. Many studies have proved that autonomous vehicles in mixed traffic enhance smooth driving and improve traffic safety, increasing their penetration rate [91, 92].
- BS-RSU: Base Station (BS) or Road Side Unit (RSU) forward the received packets to a fog or a cloud server when they do not process them locally with their Edge server. As well as that, they also disseminate messages and alerts from the network to the cars and the VRUs through down-link transmission.
- Servers: Once a server receives the packets, it uses them to compute collision events. If any danger is detected, alerts are sent to involved vehicles and VRUs. Undoubtedly, the server placement impacts the application performance in terms of latency and the expected outputs. Thus, the configuration should be carefully chosen according to the application requirements [93, 49]: *(i) Cloud server:* placed in the cloud, it benefits from the high storage and processing capacities [94, 75, 49]. However, the transmission of data to and from a far situated cloud server increases the bandwidth and latency, making it unsuitable for critical application requirements. *(ii) Fog server:* to alleviate the additional delay, Fog computing is introduced to bring computing, storage, and network services down to the data plane. Unlike the centralized cloud, Fog servers can be placed anywhere, thereby providing distributed services to reduce the network traffic load and the latency thanks to its placement [95]. *(iii) Edge server:* If the server is placed on the edge of the network, it allows Multi-access Edge Computing (MEC). MEC brings cloud computing capabilities and V2X services closer to vehicles and VRUs [96, 51]. By getting more computational power closer to the users, the goal of MEC is to reduce the latency as well as decrease the signalling overhead in the cloud core and the task offloading time [50].

5.1.2 5G Core Network

The 5G system architecture offers the opportunity to meet a large set of V2X application requirements. Network functions are defined instead of network entities, and the control plane is centred around services instead of interfaces. Moreover, the introduction of network slicing and virtualization offers more flexibility and raises intelligence [97] in the network management. Aside from securing the network via logic isolation where the failure of one slice does not affect the operation of the others, network slicing reduces the cost by sharing the same physical infrastructure. Additionally, it enhances the flexibility by enabling customized network slices for different scenarios and managing the network resources in real-time [98]. Slicing can also be extended from only resource slicing to service and function slicing to satisfy the requirements of V2X critical applications. Service slicing improves the service access efficiency, where the function slicing enables dynamic monitoring and scheduling [99]. The introduced network functions offer efficient use of network services that helps to improve the safety applications compared to classical 4G architectures. As shown in figure 3, several network functions have been introduced in the 5G architecture. Hereinafter, we present them:

- The User Plane Function (UPF) relays the packets, identifies the application according to the flow structure, interconnects with a data network, and adds or removes the packet headers.
- The Access and Mobility Management Function (AMF) communicates with the non-access stratum to manage access mobility.
- The Session Management Function (SMF) controls the PDU sessions and allocates IP addresses.
- The Authentication Server Function (AUSF) manages the authentication keys.
- The Unified Data Management (UDM) is responsible for user identification and subscription.
- The introduction of the Network Slice Selection Function (NSSF) determines, for each UE, the network slices that are allowed to access. In the context of collision avoidance application, NSSF associates the UE to uRLLC slice to guarantee high reliability and reduced latency and to mMTC to optimize the energy consumption.
- Another important function is the Network Data Analytic Function (NWDAF), which provides other network functions with load level information on the slice level, which can be helpful to adapt the application to the network condition.
- The Application Function (AF) interconnects with the control plane and the 5G core network. It implements procedures such as traffic routing and interacts with the core network via the Network Exposure Function (NEF).
- The NEF is in charge of exposing network functionalities and data collected from the control plane and other sources (e.g., location information, channel quality, achievable QoS, estimated or predicted latency, etc.).

The network orchestrator is responsible for slice orchestration and controlling the SMF and AMF to guarantee resource allocation flexibility. Mainly, it enables or disables the SMF and AMF instances and reduces the number of UPFs, leading to energy saving and load balancing. For example, the 5G-Transformer project was dedicated to end-to-end service orchestration and network slicing. On its part, the European 5GCAR grant proposed enhancements and possible projections on road safety application to the 5G existing architecture to support constraining V2X use case requirements [23].

5.2 V2N-less architecture

In a V2N-less architecture, VRU safety applications can be supported without the need of cellular coverage when road users autonomously select their communication resources. Moreover, VRU can be protected using perception based solutions that ensure its tracking and detection.

5.2.1 Communication based

When the network communication infrastructure is not available, direct communication between the nodes could be the solution. The most-widely-used technologies that offer direct transmissions in vehicular communications are DSRC via 802.11p and C-V2X mode-4 or NR-V2X mode-4 in 5G. Visible Light Communication (VLC) can also be used for direct communication. With the introduction of 6G, it is predicted that the achievable data rate of VLC will reach hundreds of Gbps [100].

Undoubtedly, this improves the signal robustness and enhances the communication quality. In [85], IEEE 802.15.4g has been used as a physical layer standard to send packets. If the network function discussed above are not more available, thus an autonomous and distributed collision avoidance system is needed to avoid accidents.

The RSU enables the road to communicate with users, namely, vehicles and pedestrians, through Infrastructure to Infrastructure (I2I), V2I, and Infrastructure to Pedestrian (I2P), as shown in figure 4. In [83], hardware and software architectures for vehicle and pedestrian collision avoidance have been presented. Different warning modes fitting to the current state of use have been described to attract pedestrians' attention.

The proposed architecture is composed of vehicles with 802.11p enabled OBUs. They can exchange road information about detected objects via 802.11p with the surrounding vehicles and run an application that can predict collisions. Moreover, the OBU is also equipped with Wi-Fi to communicate with the pedestrian smartphone, which contains a safety application that communicates with OBUs through Wi-Fi and alerts them if a risk arises.

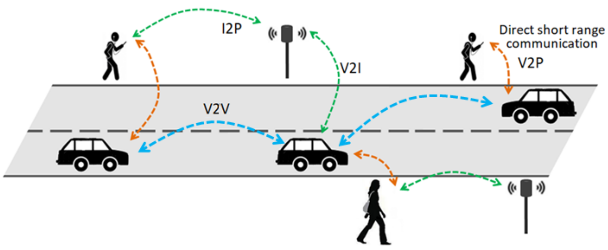

Fig. 4: V2N-less architecture.

When cellular communication is not possible, the use of Wi-Fi in pedestrian smartphones can introduce latency. Otherwise, another device (tags, gadgets, etc.), with 802.11p or other technology, is proposed instead of a smartphone to communicate with the VRU [7].

Likewise, C-V2X Mode-4 is a direct short-range communication technology with enhanced performance for vehicular communication [101]. C-V2X mode-4, where vehicles can communicate directly via PC5 interface, select and manage their resources autonomously without the network infrastructure support or cellular coverage using their SPS (Semi persistent scheduling) scheme. Inevitably, this makes it suitable for critical safety applications where reliability and maintaining the connectivity under heavy traffic is paramount [89]. Moreover, it offers interoperability with the future 5G communication standards such as NR-V2X [102, 16]. According to [103], this communication mode outperforms the IEEE-802.11p, especially in high load conditions. Nevertheless, their performance is still under debate [104, 105]. It is expected that future smartphones will communicate via 802.11p and C-V2X [106]. However, to the best of our knowledge, current smartphones in the market are still not equipped yet with side-link communication. The penetration of LTE-V2X PC5 in smartphones is by no mean sure, and the incorporation of 802.11p is considered unlikely [107].

5.2.2 Cooperative Perception based

The freestanding solutions do not require an exchange with the pedestrians, as the vehicles rely on cooperative perception. In fact, they collect data about detected elements of their surrounding environment, exchange it with their neighbours, analyse it, and make a global view to take decisions and actions. The action could be velocity variation or stopping the vehicles, changing the trajectory [108], braking, or even warn other vehicles. This data is collected via the vehicle's vision and radio sensors. Then, it is analysed to extract useful information to be fed as an input to an intelligent collision avoidance algorithm implemented inside the vehicle. This algorithm builds a perception of the environment to detect and track VRUs, predicts their future trajectories, and computes the collision risks to make the appropriate decision. For instance, in [109], authors have proposed a real-time pedestrian detection system based on convolution neural network (CNN) for AV equipped with cameras. The camera video stream is fed into the CNN to be processed and to extract features in real-time. In [110], a vehicle-pedestrian detection algorithm based on CNN has been proposed to solve the safety problems in the interaction between AV and pedestrians. The algorithm in [110] provide a recognition accuracy of 81.98% while reducing the data transmission delay, when in [109] the obtained recognition accuracy is more significant than 96.73%. In [111], the authors proposed a vision-based approach using a camera. A 4 step state-of-the-art tracking algorithm has been exploited to analyse a signalized intersection video collected in Ningbo, China. They obtained real-time trajectories and estimated the vehicle-to-pedestrian collision probability at intersections. They defined the critical time before collision based on different collision patterns of perception-reaction failure and evasive action failure. In [112], authors proposed to evaluate crash risk of VRU using Empirical Bayesian estimation model based on a safety performance function. They used probe-vehicle data with pedestrian collision warning information in unsignalized intersections. An architecture is proposed in [113], called safeVRU platform, involving the vehicle localization module, the environment perception, the motion planning, and the control. Unlike the other solutions, the objective is to prevent arising from the beginning where the vehicle can plan real-time collision-free trajectories in the presence of VRUs.

Smartphones are capable of running not only the client side of the VRU collision avoidance application as for example in [67], but also of implementing algorithms to detect risks as in [71, 114]. However, limited resources such as power consumption should be taken into consideration as they significantly impact the lifetime of the smartphone [90, 88]. Accordingly, smartphones may avoid local processing and offload their computing task instead, or raw sensor data to the MEC servers [49] or to the vehicles that do not have energy limitation.

5.2.3 Hybrid approach

A hybrid approach consists of over-passing the limits of communication-based as well as vision-based methods. In [115], the authors proposed a cooperative system that combines communication and the perception to benefit from the advantages of both approaches and build a more reliable system. They used a Wi-Fi-enabled distributed communication protocol to exchange CAM messages, including GPS data, and vehicles equipped with laser range finders to track the VRUs. This approach improves the system performance in terms of localization accuracy and VRU detection in NLOS compared to a system based only on perception or Wi-Fi communication. IEEE-802.11ac has been used in [116] as a V2I communication technology and combined with vehicle's sensors to build a robust collision avoidance system. Similarly, authors of [117] combined 5G and LTE communication with smartphone sensors data to detect the VRU stepping onto the road. In [118] authors proposed an edge-computing intersection assistance system that relies on the use of cameras and LiDARs data to detect potential events in the intersection. They considered DENM messages only to send warnings. Authors of [119] combined perception with communication where they used Kalman filter to make prediction of camera video traffic of the perceived environment and then alert road users via V2V smartphone based communication.

6 Vulnerable Road User safety solutions

In this section, we introduce state-of-the-art solutions specially designed for VRU safety applications. Firstly, we identify the key requirements of such applications while also highlighting the network role.

6.1 VRU application requirements

The major requirements of a safety application or V2X service especially designed and deployed for VRU protection are as follows:

- **Latency:** one of the most paramount requirements of VRU safety applications is the highly reduced system latency. The latency requirement is the longest period that the application can tolerate, to meet the safety context's reliability. The messages must be up-to-date, sent, and received in a bounded time interval; otherwise, they will no longer help compute collision risk. Indeed, to determine if there is a collision risk, the collision detection algorithm should use these timely messages. The algorithm could be deployed either on a server, on the VRU's smartphone, or the vehicle's OBU depending on the system architecture. The latency includes the processing time taken by the collision avoidance application. Therefore, it could be related to different factors: *(i) Communication delay* affected by the propagation time, the physical channel conditions, and the network congestion. It is also impacted by the routing time, type of communication (direct or indirect), and the server's location. According to 5GCAR [25, 24], the end-to-end communication latency should be less than 60ms. Indeed, direct communication takes less time than indirect communication via network infrastructure. *(ii) Computation delay:* the processing delay can be impacted by several parameters, such as the server type and its CPU performance. A high number of parallel processes (batch processing) can significantly reduce the computing load and make the application run faster. Further, it is essential to mention that the complexity of the application algorithm should be low to minimize the processing time.
- **Reliability:** protecting VRU from potential collision risk is a mission-critical safety application that requires high reliability and high service availability. It reflects the ratio of the packets successfully received within a bounded delay. A

maximum packet delivery ratio and a weak congestion are crucial for a proper system operation. Indeed, the reliability should be higher than 99%, particularly in VRU safety use cases [25]. The evolution of communication technology plays an essential role in the enhancement of reliability. 3GPP Release 16 defined the latency in the range of milliseconds and the reliability, as high up as 99.999%, for 32 bytes messages thanks to the introduction of physical improvements to 5G NR technology for uRLLC [20]. The quality of the service reliability can be characterized by the accuracy of detecting a collision in time, where a tiny percent of false positives and false negatives is imposed.

- **Scalability:** to avoid or reduce the impact of network congestion, the network capacity should be dimensioned to support a massive number of road users to avoid packet loss. Indeed, the ETSI standard has estimated the scalability being 5000 users in the same $300m$-radius communication area [14].
- **Power consumption:** vulnerable road users usually brings smartphones or are equipped with connected gadgets that can be involved in V2X communication infrastructure. However, Those devices have power bounded batteries that the application should not overuse. Consequently, optimizing the power consumption is a major concern to extend the battery lifetime and to guarantee the effectiveness of the safety system [75].
- **Localization accuracy:** collision avoidance systems between vehicles and pedestrians are based on processing and predicting the spatial proximity between cars and pedestrians. Therefore, a certain level of localization precision is needed to ensure the proper functioning of the system. Accordingly, ETSI standard [14] set up that safety applications require precision not exceeding 1 m for vehicles. In VRU use cases involving pedestrians and bikes, higher positioning accuracy is necessary. Indeed, precision should be less than 0.5 m [120], and 25 cm accuracy would be the ideal case [25]. Nevertheless, current positioning systems do not provide the required precision. For instance, GPS accuracy varies between (1 m to 5 m). Moreover, VRU smartphones cannot meet the positioning requirements ($3 - 10$ m precision). They are equipped with low-performance GNSS antennas characterized by a noise measurement phase that introduces inaccuracy [120].

To meet the aforementioned application requirements, many parts of the overall system must push their performance metrics to levels seldom reached before. For instance, the network performance is being extended continuously with the evolution of the 3GPP releases. Precisely, the technology-related constraints raise issues on the efficient use of the network to deliver the requested road safety service in time with high priority and high accuracy without degrading the quality of service. Thus, the network evolution with the 5G and beyond aim to guarantee this QoS. Thanks to the high throughput, the ultra-low latency, the high connectivity and coverage, the efficient spectrum use, the higher reliability, and the support of increased mobility, road safety applications should no longer suffer from the 4G limitations [121, 122, 123, 100].

6.2 Review of the technical contributions

To face the scientific challenges and to respond to the requirements described in section 6.1, intelligent mechanisms, algorithms, and schemes have been proposed in the literature. We classify them according to the above-mentioned requirements.

6.2.1 Latency awareness

Numerous latency-aware solutions have been proposed in the literature, most of which consider examining processing placement, offloading to MEC server given its proximity, or an opportunistic combination between cloud and MEC offloading. Other researchers examined the impact of network architectures by comparing the delay of a distributed and a centralized approach, or studying the advantages of network slicing.

For instance, in [124], the authors proposed an end-to-end slicing mechanism for ITS-G5 vehicular communication based on setting priority to decrease the latency and improve the Qos of road safety use cases. A MEC-based architecture has been presented in [50, 67], where vehicles and vulnerable road users can exploit different network technologies to send Cooperative-Awareness Messages (CAMs) toward a centralized collision detector and receive collision alert messages. In [89], authors compared MEC-based and the conventional cloud-based architectures' performance. In addition, they studied the impact of the two approaches on the end-to-end latency of VRU communication. They found that the MEC architecture can offer up to 80% average gains in latency reduction. Authors of [49] proposed a 5G-based lightweight and low complexity algorithm that predicts trajectories and detects in real-time potential collisions while addressing critical 5G requirements in terms of low end-to-end latency and high reliability. Moreover, they have proposed a hybrid architecture that exploits MEC and cloud computing resources in a coordinated manner to optimize the end-to-end latency. Their approach shows an end-to-end latency of less than $100ms$. In [88, 90], authors investigated the impact of the processing placement of VRU context information, whether to offload to a server or to compute locally, then the effect of the two approaches on the latency. They also studied the local processing time of pedestrian movement detection with a machine learning algorithm-enabled smartphone and the average end-to-end delay if the offloading to a MEC server is selected. They studied in [69] the impact of pedestrian activity detection and the communication delay in a collision detection use case. In [50], a distributed IEEE-802.11p V2V communication-based approach where every vehicle runs its collision detection system has been compared to a centralized approach where the computation is placed on a MEC server to determine which approach better guarantees minor delay. In [67], the authors compared the end-to-end latency between the client application implemented in the VRUs' smartphones and the server application on edge versus the cloud.

Even though the contributions are different, most of the papers above agree on using a MEC-based architecture to benefit from its proximity to the road and thus guarantee a minimum latency.

6.2.2 Scalability

Available network, computing, and storing resources must satisfy and support the increasing number of road users. To this aim, scalability remains a crucial challenge, given its impact on network congestion. Therefore, researchers utilized clustering strategies, frequency, and message-size adaptation in the literature to reduce network load and filtering. Further, they studied the impact of resource selection architecture according to the number of users.

For instance, in [49], a dynamic and hybrid resource selection architecture between MEC and the cloud is proposed depending on the collision avoidance scenario's specification. Precisely, it shows that the MEC operation outperforms in specific scenarios with a small number of OBUs. In contrast, the cloud-based operation could be more valuable in up-scaled scenarios and showed overall robust and stable performance. The authors proved that a dynamic resource selection approach depending on real-time network resource availability and network state information could lead to high gains. On the other hand, clustering can be an effective technique to group road users when their number in a specific area gets high. It can increase the network capacity without additional infrastructure by considering the VRUs' cluster as a single object and electing a cluster-head to transmit a VAM. The VAM contains the cluster's total dimension and other information (e.g. velocity, reference position) instead of individual VRU transmissions. For instance, in [125], the authors create low-power small cells called clusters that allow the frequency reuse in other clusters while decreasing the interference and increasing the capacity. The scheme starts with the first phase to define the clusters using K-means algorithm, then a second phase to select the best link quality node as a cluster-head to relay the cluster members' data to the base station. Authors of [126] proposed a Multi-channel Clustering-based Congestion Control (MC-COCO4V2P) algorithm to mitigate the congestion caused by the high number of pedestrian safety messages. The clustering mechanism groups pedestrians based on their location and direction. It reduces the signalling overhead by separating the clustering and safety messages while saving the energy consumption of pedestrians' devices. Authors of [127], proposed an enhancement of the current standard policy by adapting the CAM and VAM transmission frequency for VRU and vehicles respectively, to optimize network resources selection based on both location dynamics and the surrounding environmental' context. Their scheme help reducing the unnecessary transmissions and thus optimizing the network load. The efficient use of radio resources is considered as another challenge that needs to be properly addressed, given the size of CPM messages and the wireless channel's limited bandwidth. CPM can contain many perceived objects and can be generated frequently, which can lead to exceed the channel capacity or increase the channel load. In [128], the authors introduced the filtering that exploits the communication redundancy and discards objects with low kinetics status as an effective technique to reduce the number of detected objects included in a message while keeping a good perception quality.

Although there are many possible alternatives to manage scalability challenges, it is predicted that by 2030, the number of connected devices will reach 125 Billion [123], which will increase the network load and the high demand for bandwidth. The introduction of 6G is expected to extend the network capacity to support high connected device density and guarantee ubiquitous connectivity [122, 121].

6.2.3 Reliability

Saving VRU from potential collision risk is a mission-critical enhanced safety application. Existent works are tackling reliability from different perspectives. For example, some research directions considered improving the network reliability by increasing network-related metrics such as packet delivery ratio. In contrast, others handled the application reliability by decreasing false positives and negatives.

According to [24], a maximum packet delivery ratio indicates a minimum packet collision and thus a good communication and connectivity quality. The high communication range, without degradation of connectivity with the increase of the traffic load or the distance, is an index of reliability. In [129], authors evaluated the performance of V2P crash prevention system's reliability in terms of delivery ratio and channel access. They also studied the impact of beaconing intervals on the network load. In [130], an on demand QoS mechanism has been proposed. It informs the surrounding vehicles about the crucial communication and requests them to lower the priority of their safety messages to improve the beaconing delivery ratio and thus the reliability.

In addition to the above-mentioned metrics, false positives and false negatives are considered as indicators of the collision avoidance system reliability by the majority of the technical contributions. They reflect the inaccuracy of the system. A false negative happens when the road users do not receive the relevant warning do collide. On the other hand, false positives mean that the users receive an alert, when they are not actually at risk, think that they are in a risky situation, and an imminent reaction is needed. Authors of [50] considered that false positives could be as harmful as false negatives because they can decrease the driver's confidence in the system's effectiveness. To handle this issue, they have evaluated the collision avoidance system's effectiveness by studying the variation of the time and space to collision and their impact on reducing the false positives and increasing the overall reliability. They have focused, in [52], on the safety application for automotive collision avoidance at intersections and study the effectiveness of its deployment in a C-V2I-based infrastructure. They also accounted for the server's location running the application as a reliability-enhancing factor in the system design. The simulation-based results, derived in real-world scenarios, indicate the reliability of car-to-car and car-to-pedestrian collision avoidance algorithms, both when a human driver is considered and when automated vehicles (with faster reaction times) populate the streets. Authors of [49] have also studied the impact of missed collisions and false positives to evaluate the performance of their proposed algorithm for VRU protection in identifying imminent road hazards between vehicles and VRUs. They used the accuracy parameter, precision, recall, and F1-score as Key Performance Indicators (KPI) to study the reliability of their proposed MEC and 5G NFV based architecture, the network communication (deadline respect, MEC and cloud operations), and the validity of the algorithm under different thresholds. In [131], the authors proposed a communication model based on collision probability between vehicles and cyclists. They designed an application that takes periodic CAMs and informs car drivers to take action in collision risk. To evaluate their proposed solution's reliability, they compared two scenarios with and without collision avoidance application, and they assessed the collision probability and the obtained false positives and false negatives.

As pointed by [132], the insufficiency of the limited information (speed, position, direction) used to estimate pedestrian's trajectory and the effect of the NLOS could lead to false collision detection. To handle this problem and improve the detection inaccuracy, additional context data is used to adjust warning thresholds or to correct the measurement data concerning missed and false collision warnings.

6.2.4 Collision Avoidance Algorithm Complexity

A significant problem of the real-time collision avoidance algorithm is its complexity that should be optimized to avoid impacting the other application KPIs (e.g. latency and reliability). All road users' trajectories are compared in a binary manner to determine possible collisions for N nodes. However, if each VRU trajectory is examined for potential intersection with each of the rest moving vehicles' trajectories, the complexity is equal to $O(n^2)$. Authors of [49] proposed detecting hazardous events by identifying potential intersections of the predicted trajectories while each trajectory is computed and stored in a data element. In this way, they reduced the algorithm running time and complexity from $O(n^2)$ to O(n). To relieve the time complexity, authors in [52] exploited the fact that the server can distinguish between the received CAMs transmitters and skip analysis for the pedestrian-to-pedestrian collisions.

Regarding space complexity, [133] is one of the few papers that tackled this issue by proposing a Collision Avoidance Integrator (CAI) system to protect the memory of the computing device from collapsing. However, given the importance of considering computing memory in a safety-critical application, especially when the number of nodes and the amount of data are the main parameters, space complexity needs further investigation.

6.2.5 Energy Consumption

Energy consumption must be optimized to use the VRU devices as part of the active safety application. Many methods were studied regarding this matter. The popular are the adaptation of the message transmission frequency according to several parameters (e.g., context information, risk level, neighboring, etc.), the intermittent utilization of GPS, and offloading computing tasks to the MEC or Cloud servers.

According to [134], instead of using greedy GPS for the limited battery life of smartphones, an energy-efficient consumption positioning method must be investigated. They proposed a best-effort application called V2PSense that notifies road users if any nearby danger is detected. A potential arrival area is calculated for each pedestrian using intermittent GPS information and mobile sensing data to determine if he is close to a dangerous spot. Results indicate that the proposed mechanism saves 20.8 % energy compared to always-activated GPS. In [76], the authors have implemented a collision-avoidance system that adapts the transmission rate to control the congestion of the wireless channel and reduce the energy consumption of VRU smartphones. Their approach consists of minimizing GPS receiver's active duty cycle by turning off the GPS and even the DSRC radio based on the context information (e.g., indoor, stationary, inside the vehicle, etc.). Moreover, the smartphone stays on listening mode to the channel. If a BSM transmission is needed, the transmission range should be controlled according to the surrounding environment (e.g., risk level, number of nearby vehicles). Authors of [70] adapted the rate of communication messages according to the risk probability to relieve the network load and optimize the energy consumption for the VRU side.

In [75], the authors developed an energy-efficient solution based on wireless V2P communication to avoid collision and save smartphones' battery lifetime. This paper's main contribution is to adapt the frequency of sending beaconing messages of smartphones with the situation risk level. They defined a full rate beaconing for

vehicles and smartphones in a high-risk situation and a low rate beaconing for mobile smartphones in a low-risk case. The solution runs in a server placed at the cloud level. When the algorithm detects a risky situation, a request to switch to full rate beaconing mode is sent to increase precision and obtain up-to-date Geolocation information. In case of accident detection, it sends an alert to concerned elements. Results show that the proposed solution enhances the total battery lifetime compared to a full rate beaconing case. Authors of [135] have also suggested the adaptation of the beaconing rate according to the predicted collision risk level. They proposed an energy-efficient fuzzy logic adaptive beaconing rate management system to overcome the mobile devices' energy consumption limitations. The prediction is computed based on minimum information exchange distance while considering various source of information and risk-pulling factors. Results reflect that their system reduced the energy consumption to half while having an insignificant energy overhead compared to full-rate beaconing schemes. The energy consumption could be affected by vehicle arrival rates and risk pulling factors.
The difference between the two previous works is that the method based on fuzzy logic model considers many types of factors that affect collision risks that have been neglected in [75]. Moreover, three collision risk levels (high, medium, low) have been defined in [135] instead of two in [75]. In [127], authors proposed a new neighbouring scheme that optimize the standard policy to adapt the VAM transmission frequency with respect to the energy consumption constrains for vulnerable road users.

Other research directions focus on studying the impact of collision risk processing placement on the smartphone's energy consumption, whether to locally compute the safety-related tasks on a smartphone versus offloading to a MEC server. For this purpose, the authors of [88, 90] examined the two modes' performance separately and suggested a heterogeneous scheme that combines the two modes. They proposed an adaptive system architecture with two levels. At the data level, smartphones can compute context information locally or with the MEC server support by offloading raw data collected by their sensors. At the service level, they process the collision avoidance algorithm locally or offload it to the server. The decision should be made while considering the situation's risk rate and the smartphone's available resources to make a trade-off between latency and energy consumption optimization.

6.2.6 Localization accuracy

With the evolution of 5G and the introduction of 3GPP 5G NR in Release 16, the localization will be based on the signals of the NR transmission links as well as new GNSS technologies (BeiDou, Galileo, GLONASS, GPS), Terrestrial Beacon Systems (TBS), Bluetooth, WLAN, RFID, and sensors [136]. Moreover, NR-V2X communication will enable the possibility of cooperative localization in dense networks where nodes intercommunicate to exchange measurements related information. The use of mmWave in 5G brings the advantage of large bandwidth that improves the robustness to multi-path and exploit it to obtain additional position information from radio signals. In this context, LOCUS and IoRL projects have focused on providing location accuracy for less than 10 cm for safety concerns[137, 138]. Besides, with 5G, localization involves infusing data and measurements collected from heterogeneous sensors with contextual information. Moreover, it is expected that the 6G will improve the localization and, consequently, the accuracy of the application. For instance, with the 3D localization, the number of false-positive alerts will decrease when VRUs are on a footbridge crossing a road [100]. Inertial Navigation System (INS) data fusion with GPS sensors can significantly improve the vehicle positioning, as proposed in [73]. Authors in [23] developed a smartphone-based collision avoidance system for pedestrians called (WSB) that exploits the smartphones' context information and the user activity to improve the collision detection accuracy and accurately detect the direction of the dynamic movement of the pedestrian. They demonstrated that even with exact estimation of speed and direction, a position accuracy less than 1 m could deteriorate the system performance. Besides, their approach based on curb detection improves the warning system.

Similar approaches are in [69, 132], where the authors demonstrate the benefit from additional contextual information to decrease positioning inaccuracy. Authors of [80], used Kalman filter to enhance the GPS positioning accuracy and reduce its error. The collision avoidance algorithm reliability was significantly improved by their approach. Kalman filter has been used in [70] to estimate vehicles trajectory to predict future collision and in [81] for pedestrians' motion prediction. In [54], the bikes send periodically CAM messages that will be exploited to estimate high localization accuracy. They developed a hybrid pilot to perform a high-precision localization system based on the fusion of different information sources. They have combined multi-sensor hybrid solution to estimate position, velocity, and altitude. In [74], the authors proposed a smartphone-based warning system with three phases for activation, prediction, and warning. They have evaluated their system' performance on detecting the correct risk level warning under the impact of the position and direction inaccuracy. The authors of [139] investigated the required accuracy to recognize VRU movement in a cooperative collision avoidance system. They evaluated the collision detection performance in terms of missed and false alarms depending on the measurement error distribution of position, speed, and direction. They determined for different pedestrian's crossing angle scenarios, the corresponding accuracy of the required position, direction, and speed to keep the probability of a missed alarm low in a defined time before the collision.

The following approaches focus on improving the localization accuracy for pedestrian detection and activity recognition. In NLOS scenarios, the detection of VRU becomes a challenging task. Authors of [140] used the camera to detect future collision between vehicles with variable speeds and distinct road users' types (pedestrian, cyclist), having different speeds. They compared the probability of collision detection of a camera-based solution and a cooperative-based system in NLOS scenario. They proved that NLOS scenarios influence camera-based systems. Even in LOS scenarios, they can detect a pedestrian while a bike is not detectable if its speed is higher than 15 km/h. Nonetheless, the cooperative communication system is not influenced by LOS situations, and it proved its ability to detect both pedestrians and cyclists. It also presents a higher probability of collision detection, but it depends on positioning accuracy that should be less than 1 m. To anticipate the pedestrians' intention and future behaviour, [141] proposed a biomechanically Inspired long short-term memory network called "bio-LSTM" for 3D pedestrian pose and gait prediction to foretell the global location and 3D full-body mesh with articulated body pose inside the metric space. This ability allows vehicles to avoid collisions and improve ride safety and quality. To improve activity recognition and support context filter in identifying VRUs stepping onto the road, [117] focused on short and non-periodic activities. They used the combination of context filter, 5G and LTE communications, and smartphone sensors' data to solve the challenges of inconsistent sensor data, over-representation of periodic activities, and the evaluation of the recognition. They evaluated their solution using precision and recall metrics.

7 Synthesis

In this section, we synthesize the contributions related to the protection of vulnerable road users. The applications and the scenarios referred to in these works are based on network communication and the collection of positioning and signalling messages. The latency reflects most of the time the computing placement impact, and the reliability is related to the accuracy of the algorithm in detecting collisions. In Table 5, we highlight the consideration level of the requirements presented in section 6.1 and identify the communication technology targeted by each contribution.

Although all the contributions have tried to meet these requirement indicators in varying degrees, almost all the papers have placed latency and reliability as major concerns. It is worth to note that energy conception and localization are also important concerns in those solutions, namely those involving using smartphones. Undoubtedly, network congestion need to be further investigated when the density of vehicles and connected devices is growing. The choice of the communication architecture is principally related to the communication technology, except for the works that use hybrid or multi-RAT.

The direct communication between vehicles and VRU using C-V2P or 802.11bd is not yet explored. In the same context, the experiments in 5G networks are still limited due to the fact that the deployment phase of 5G is in progress. Existent simulation tools can also limit the research to the use of IEEE 802.11p, LTE and C-V2X as we will discuss later in section 8. The used RAT and the enhancement area are strongly correlated to the deployed communication architecture. The latter can offer advantages in terms of solving heterogeneity issues when direct communication between road users is not possible and vice versa. Moreover, it can offer advantageous function placement for the appropriate application.

In addition, there is no global approach that optimizes both network and application related metrics. The heterogeneity support and the integration in a 5G architecture is limited to some few works. The scalability problem can impact drastically the performance of the collision avoidance algorithm when the number of road users is high, however, a lot of papers do not consider it.

Table 5: Comparison of contributions.
For each solution (**row**), Performance metrics (**columns**) are listed with an asterisk or more as much as it is considered in the paper (* low, ** medium, *** high). Technology and evaluation technique (Analytical modelling, Experimental design, Simulation) are also listed.

References	Year	Contribution /Enhancing Areas						Communication Technology	Architecture		Evaluation
		Localization	Reliability	Energy Consumption	Latency	Congestion control	Algorithm		Infrastructure-based	V2N-less	
[75]	2016	-	*	***	*	*	***	LTE	✓	-	Numerical, Experiment, Simulation (SUMO [142])
[76]	2017	*	*	**	*	**	***	IEEE 802.11p	-	✓	Simulation (ns-3 [143])
[129]	2017	-	***	-	-	**	-	IEEE 802.11p	-	✓	Simulation (Veins [144], Omnet++ [145], SUMO)
[52]	2018	-	**	-	**	-	***	C-V2X	✓	-	Simulation (SimuLTE-Veins [146], SUMO)
[74]	2018	***	**	-	*	-	***	4G	✓	-	Experiment, simulation (Virtual CRASH 3 [147])
[89]	2018	-	-	-	***	*	-	LTE, 5G	✓	-	Numerical, Simulation
[134]	2018	***	-	***	*	-	-	LTE	✓	-	Experiment
[90]	2019	-	*	***	***	-	-	5G	✓	-	Experiment, Simulation(Veins LTE, Omnet++, SUMO)
[85]	2019	-	-	***	-	-	-	IEEE 802.15.4g	-	✓	Experiment, Numerical
[72]	2019	*	***	-	-	*	***	IEEE 802.11p	-	✓	Simulation (SUMO, MASON [148])
[67]	2019	-	-	-	***	-	***	Wi-Fi, LTE	✓	-	Experiment
[50]	2020	-	***	-	***	*	***	IEEE 802.11p	-	✓	Simulation (SimuLTE-Veins, Omnet++, SUMO)
[49]	2020	*	***	-	***	-	***	IEEE 802.11p	✓	-	Experiment, Simulation (SUMO)
[140]	2020	***	*	-	-	-	-	5G or IEEE 802.11p	✓	✓	Simulation
[69]	2020	*	*	-	***	-	*	LTE	✓	-	Simulation (Veins LTE)
[88]	2020	-	*	***	***	-	-	5G	✓	-	Experiment, Simulation (Veins LTE, Omnet++, SUMO)
[126]	2020	-	***	-	-	***	-	IEEE 802.11p	-	✓	Simulation (Veins, Omnet++, SUMO)
[135]	2020	-	-	***	-	-	***	LTE	✓	-	Simulation (Matlab)
[139]	2020	***	***	-	-	-	-	-	-	-	Experiment, Simulation (Simulator developed by the authors)
[130]	2020	-	***	-	-	**	-	IEEE 802.11p	-	✓	Simulation (Veins, Omnet++, SUMO)
[68]	2020	-	-	-	***	-	***	5G	✓	-	Simulation (SUMO, Californium library)
[80]	2021	***	***	-	-	-	*	Wi-Fi	-	✓	Simulation (PTV VISSIM 8 [149])
[70]	2022	*	*	***	-	***	*	IEEE 802.11p	-	✓	Simulation (Matlab, SUMO)
[127]	2022	-	**	***	**	***	-	C-V2X	✓	-	Simulation (ns3,SUMO, ms-van3net [150])

8 Open issues

Although 4G supports safety applications, the performance of VRU safety applications still suffers from different limitations. There is a need to be further optimized to benefit from the 5G and beyond 5G evolution, offering high mobility support, large bandwidth, high data rates, and accurate positioning.

Although many contributions have been designed for vulnerable road user safety services, bearing objectives ranging from energy efficiency to reliability, there are still many new design issues. Again, based on the table of contributions comparison, we list a few possible future research topics in the following:

- ***Scalability:*** in the future networks, it is expected to have around billions of connected users. Consequently, the network scalability to support massive data generated by a large number of VRUs and autonomous or connected vehicles raises the challenge of the network capabilities extension to the automation level using artificial intelligence and Machine Learning techniques [49, 151]. These techniques help the network to build programmable operational decisions and optimal resource allocation [152, 153].
- ***Collision avoidance system:*** the collision prediction algorithm needs to benefit from the existing network infrastructure by resorting to AI algorithms [127, 154] to surpass system limitations (e.g. computing resources, detection accuracy) and architectural limitations (e.g. multi-RAT/link). In fact, this brings more smartness for the system to better take into account the whole environment parameters (available radio resources, localization history, weather condition, driver state, VRU age, etc.) [155] leading to more reliability of the detection algorithm.
- ***Performance analysis tools:*** in most projects, the simulation is ubiquitous compared with real-world experiments.
  Vehicular communication simulators can be classified according to various parameters such as the scalability, the accessibility (open source or not), the supported wireless technologies, the mobility interaction, etc. The paper [156] provides a good state of the art of the existent simulation frameworks. Despite the existence of multiple simulators, simulation tools need to be enhanced to support the beyond 5G technology evolution and relieve the complexity of the interaction with 5G platforms to exploit the architecture's functions and services. The VRU integration in both mobility (i.e. SUMO, VISSIM, etc.) and network (i.e. ns3, veins, omnet++, etc.) simulation tools is a complex procedure regarding their different characteristics (mobility, radio channel communication type, etc.) compared to vehicles. There is a need to develop a simulation tool that helps the integration of all these elements and extends it to interoperate with AI modules. Moreover, the CPM and VAM messages implementation is not yet available on existing network simulators.
- ***Multi-RAT and multi-link connectivity:*** vehicular network environments are heterogeneous, where different communication technologies are present. This heterogeneity has limitations in terms of interoperability. Still, it benefits the reliability of critical applications by optimizing the selection of the communication mode or the RAT according to the current conditions. For instance, if an imminent collision is foreseen, it is more advantageous to use direct communication, either C-V2P or NR-V2P, instead of using the network infrastructure. Besides, based on our use-case specific performance requirements and network conditions,

a multi-link solution would be attractive when a single link cannot deliver the use-case required quality of service. Indeed, use case-aware multi-RAT and multi-link connectivity would improve data rate, reliability, and latency. The main challenge of this technical issue is to keep reasonable resource consumption (in case of exploiting diversity gain). Undoubtedly, cooperation between different RATs and more complex vehicles' transceivers is needed to enable multi-link/RAT connectivity.
– ***Edge-enabled function placement:*** as shown above, V2X services have stringent performance requirements, particularly in latency and energy consumption. Multi-access edge computing has been proposed as a potential solution for such services by bringing them closer to vehicles and other road users. However, this introduces new challenges, such as where to place these V2X services, mainly because of the limited computation resources available at the edge nodes.
– ***AI-based localization improvement:*** The estimation of the collision probability is a problem widely studied in the literature. The accuracy of the location and the choice of the impacting parameters are paramount for a reliable estimation. There is a need to collect representative data over a long period, even with different configurations. Thus, we could determine the impacting parameters, which could depend on the climatic and visibility conditions or the nature of the mobility of the VRU.
– ***Coexistence and interoperability of the communication standards:*** Car manufacturers are geared towards the selection of standards and communication technologies with various characteristics. The interoperability of standards and the treatment of heterogeneous devices constitute a promising direction.
– ***Optimization:*** The system optimization, as a whole, is a function of the network plus the constraints of the application. The protection of the VRU application needs a reasonable latency and an even high level of reliability. We should not optimize the application performance to the detriment of the energy consumption induced on the connected objects of the vulnerable. Similar use cases suggest optimization of joint functions of various performance metrics. The application that we target is not an exception and requires the definition of appropriate functions.
– ***Machine Learning:*** VRU safety applications can largely benefit from machine learning techniques. Besides its use for VRU detection, learning is an effective way to estimate the future states from the history of positions to make trajectory prediction [77, 78], study the VRU intentions and behaviours [157, 158] and improve localization accuracy. The use of AI in communication-based collision avoidance systems for VRU is still limited and need to be further investigated. It can benefit from multiple data sources, as in fuzzy systems [74, 114, 135] where the weather conditions, the environment features, the driver and the VRU characteristics are fed into a fuzzy engine to determine the collision risk level. Moreover, learning can intelligently make decision through massive amount of communication data, or sensors [159] and environment information through data fusion[160]. Another open direction is that reinforcement learning can also enhance resource allocation by optimizing the transmission frequency of the communication messages according to the network and the sender state. This will decrease the network load and reduce the energy consumption for VRU. Furthermore, learning can predict network traffic demands based on network performance metrics (such as

latency, packet delivery rate, channel utilization rate, etc.) to orchestrate the radio resources efficiently and solve congestion problems.

9 Conclusion

In this review, we have studied V2X communication architectures for the VRU safety use case, given its importance in protecting people's lives. Among existing solutions, we focused on exploring communication-based approaches where road users exchange data between them and with the infrastructure to increase awareness and avoid road fatalities. We detailed the collision avoidance system architecture and possible communication architectures in the 5G network, while projecting possible enhancements to support the technical evolution. We depicted the most critical challenges related to both network and application sides and classified them according to the enhancing area. We projected the application in the beyond 5G era to overcome the shortcoming of existing solutions. Finally, we synthesized the most relevant works and discussed potential enhancements and open issues, while giving new suggestions and future directions for VRU protection. Undoubtedly, the network function placement and the application parameters could be adapted jointly using AI techniques to meet the need for multi-criteria optimization of both user and operator points of view.

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