To DSRC or 5G? A Safety Analysis for Connected and Autonomous Vehicles

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***Abstract*—Connected Autonomous Vehicles (CAV) utilize vehicular communication to collect information about the surrounding environment to make informed decisions about speed and maneuvering. This enables safe driving and decreases the number of accidents and thereby the associated fatalities. However, vehicular communication may suffer from high latency and low reliability, especially in dense vehicle environments, which may negatively affect the safety of CAVs. Therefore, it is crucial to study the impact of these metrics on the safety application performance while taking into account realistic CAV kinematics and dynamics. In this paper, we address this problem by comparing the performance of the Short Range Communication (DSRC) to that of the Fifth-Generation New Radio (5G-NR) and their impacts on the safety applications in the CAV environment under different settings. We develop a full-fledged simulation framework that can realistically model both vehicular mobility and communication and can capture the impact of communication on safety applications. Within this framework, we implement an important CAV's safety application, namely, the forward collision avoidance system, in which following vehicles use vehicular communications to gather information from leading vehicles to compute the safe speed and avoid collisions. We then use this framework to study and compare the performance safety of the forward collision avoidance system using both DSRC and 5G-NR communications. The results show that the packet delays and drops in communication networks can adversely affect CAV safety. The results also demonstrate that 5G is more capable of supporting the safety requirements under higher packet traffic loads and vehicle densities.**

***Index Terms*—CAV, Safety, DSRC, 5G-NR, Simulation.**

I. INTRODUCTION

In Connected Autonomous Vehicles (CAV) environments, sensors in each vehicle collect information about the surrounding environment, based on which, the vehicle can make informed decisions to control its speed trajectory and maneuvering. By enabling vehicles to exchange data, Vehicle-to-Everything (V2X) communication is an important source of information that has the potential to significantly decrease the number of road accidents and thereby reducing the number of associated fatalities [1]. There are many types of safety-related applications in CAVs [2], [3], such as cooperative driving, traffic control and management, non-signalized intersection management, forward collision warning and lane change warning. These applications can benefit from V2X capabilities if communication sufficiently satisfies the application requirements and constraints in terms of latency, reliability and throughput. Therefore, several auto-manufacturers (e.g., Cadilac, BMW, and Audi) have already started to adopt Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication equipments in their vehicles.

Currently, safety systems in CAVs rely on sensors to learn about the surrounding environment and make appropriate driving decisions. Thus, the safety of CAVs in this setting relies heavily on the reliability of these sensors. The recent unfortunate 2 fatal accidents in 2016 of Tesla Model S with the Autopilot system, which was the most advanced autonomous system in the market, are caused by sensor failures (where sensors cannot reliably detect neighbouring cars). Such accidents trigger the concern of the reliability of these sensors, especially in severe weather conditions [4].

Although vehicular communication was initially introduced as a supplementary source of information to complement vehicle sensors, it is a major source of information in CAV. There are many situations where communication is the only available source of information that vehicles can rely on. For instance, on steep roads, measuring the distance to leader or follower vehicles using laser beams or ultrasound signals might not work because of the lack of line of sight. Light Imaging Detection and Ranging (LIDAR) and cameras are adversely affected by weather conditions, such as fog, that may hinder them from accurately detecting objects. In these scenarios, vehicular communication presents a more reliable source of information. Another problem associated with most vehicle sensors is that they are prone to errors [5]. Moreover, errors from different sensors may accumulate when computing safety parameters. For example, when computing the speeds and acceleration of other vehicles, distance sensor errors may accumulate with localization errors resulting in a large deviation from the actual speeds. In such cases, vehicular communications can avoid both errors by enabling vehicles to communicate their actual parameters (i.e, its accurate speed that is computed based on the engine rotation speed).

On the other hand, vehicular communications may suffer latency and reliability issues. Several works have studied and compared the latency and reliability of DSRC and 5G in vehicular environments, e.g. [3], [6]–[8]. Yet, little attention was given to thoroughly investigating the impact of these metrics on the actual safety of vehicles, given their realistic mechanical kinematics and traffic dynamics. Therefore, it is

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crucial to study the impact of these communication metrics on the safety application performance. In this paper, we address this fundamental gap by the following contributions.

- We develop a full-fledged simulation framework that can model both vehicles' kinematics/dynamics and the vehicular communications using both 5G-NR and DSRC, to capture the impact of communication on safety applications. More specifically, we develop a full coupling between Network simulator 3 (NS3) [9] and Simulation of Urban Mobility (SUMO) [10] simulators.
- Within this framework, we develop an important safety application; the forward collision avoidance safety system which computes the safe speed based on the vehicle's car-following model. This safety system can be used in different applications, such as cooperative driving and platooning, and can indeed significantly benefit from vehicular communication to gather information from leader vehicles to compute the safe speeds for the follower ones.
- We use the developed framework to study and compare the performance of the forward collision avoidance system using both DSRC and 5G-NR communication technologies under different vehicle traffic conditions and different packet loads.

To the best of the authors' knowledge, this is the first paper that quantifies the impact of communication reliability and delays on the performance of safety systems in CAVs.

II. BACKGROUND

The main objective of this paper is to study the viability of DSRC and 5G-NR to support safety applications in CAV environments. Therefore, this section gives a brief overview of the two communication technologies.

DSRC [11] was initially introduced as a supplementary source of information to improve road safety by enabling vehicles to exchange their state information by periodically sending Basic Safety Messages (BSM). DSRC also allows vehicles to exchange other information such as collision warning and accident reporting messages. DSRC is designed to operate in the 5.9 GHz frequency band, which has been dedicated to Intelligent Transportation Systems (ITS) applications in many countries. DSRC's physical and MAC layers are standardized by the IEEE802.11p standard, which is an amended version of the IEEE802.11a for low overhead operation. Subsequently, IEEE standardized the entire communication stack using the 1609 family of standards known as Wireless Access in Vehicular Environments (WAVE) [12]. Similar to IEEE802.11a, the MAC layer in DSRC uses a carrier sense multiple access with collision avoidance medium-access scheme. Consequently, it faces some challenges when strict reliability levels are needed, especially when the network load increases. However, it adopts two main modifications to improve the performance. In contrast to the IEEE802.11a, the IEEE802.11p receiver does not acknowledge received frames to reduce the overhead. Additionally, the contention window interval in the IEEE802.11p is fixed to minimize the delay [13].

5G New Radio (NR) is an emerging technology that can also be adopted to enable Cellular-V2X (C-V2X) which was developed by the 3rd Generation Partnership Project (3GPP) in its Rel. 14. In C-V2X, vehicles can communicate through cellular base stations by leveraging the existing cellular infrastructure. Moreover, since the existence of cellular coverage is not always available, especially in rural environments, other transmission modes are defined in the C-V2X standard to enable vehicles to directly communicate through sidelink channels over PC5 interface, without the need for base stations as specified in [14].

III. LITERATURE SURVEY

The safety of CAV attracted the research community's attention in the last decade. For instance, the author of [2] developed a mobility model to estimate the number of vehicles on the road as well as the probability of successfully receiving broadcasted safety messages for one hop and multi-hop connectivity. The authors of [6] studied the impact of different mobility models on the performance of routing protocols in Vehicular Adhoc Networks (VANETs). The authors in [3] evaluated the reliability of DSRC on expressways based on real measurements and the road structure. However, neither of these works quantified the impact of packet drop probabilities or packet delay on the safety of the vehicles. The authors of [7] studied the impact of different communication parameters on the Age of Information (AoI). They also made one step ahead by deriving a model to compute the error in the vehicle speed due to AoI. However, the unaddressed question in this work is, whether this speed error will cause safety problems. In this paper, we use car-following models to study if these errors can lead to accidents or safety-related problems.

Other researchers generated synthetic trajectories to evaluate the performance of mobility and communication. For instance, in [8], the authors generated trajectories and used them to compare LTE-V2V and IEEE802.11p and their ability to support cooperative awareness applications. Unfortunately, such a methodology cannot capture mutual interactivity between vehicles because of the fixed trajectories, and cannot thus be used to study the impact of these technologies on realistic safety applications. The authors in [15] provided a general overview on communication requirements for different safety-related applications in vehicular environments without deep analysis for each application.

In this paper, we cover the above-mentioned gaps by coupling two simulation platforms to build realistic simulation scenarios. To capture the impact of communication limitations on vehicle safety, we build a safety application in the SUMO simulator that utilizes V2X communications to periodically collect the leader vehicle speed, based on which the vehicle computes its safe speed while taking into consideration all the vehicle mechanical kinematics and traffic dynamics. To the best of our knowledge, this is the first simulation framework that assesses V2X-enabled safety applications and quantifies the impact of communication limitations of the safety in CAVs.

IV. SYSTEM MODE AND SIMULATION FRAMEWORK

Modelling and studying the impact of communication on safety in a CAV environment is challenging because for several reasons. Firstly, studying such a system is not possible in the real world because of the cost and associated dangers. Secondly, building mathematical models that can model these impacts is too difficult because of the intricate relationships between mobility, safety, and communication parameters. Consequently, most of the mathematical models address this topic based on unrealistic assumptions that oversimplify the use case or by addressing it from only one direction, either mobility or communication.

To realistically model safety application and communication, we couple two well-known simulation platforms, namely NS3 for communication modelling and SUMO for mobility modelling. Compared to the state of the art in this field (the VEINS simulator [16] that uses a similar technique), we take one step forward. This step is two-fold. First, we build the forward collision avoidance application in SUMO that utilizes vehicular communications to get the leader vehicle state information and compute the vehicle's safe speed. Second, we add a new API through which the communicated information in NS3 can be transferred to SUMO to compute the safe speed when a vehicle receives the state information from its leader. In what is following, we further describe the forward collision avoidance scenario and the simulation framework.

A. System Model: Forward Collision-Avoidance

In traffic theory, vehicles follow one another as shown in Fig. 1. The vehicle speed at any time is limited by three parameters, as per the following equation:

$$v_n \leq min(v_{r_{max}},\ v_n + a_n \Delta t,\ v_{n_{safe}}). \tag{1}$$

The first parameter $v_{r_{max}}$ is the maximum road speed which is a road parameter. A vehicle can drive at this speed when there are no vehicles in front of it and is thus called the free-flow speed. The second parameter is related to the vehicle dynamics and is based on the engine capabilities and the vehicle design. When a vehicle accelerates, it needs time to reach its target speed based on its maximum acceleration a_n which is a function of engine parameters such as the engine horsepower. A typical value for a_n is 4.5 m/s^2. Consequently, over a Δt time, the vehicle speed can't exceed $v_n + a_n \Delta t$. The same applies for deceleration, with $a_n = -4.5 m/s^2$. Additionally, the maximum deceleration rate can be increased in the case of an emergency to avoid accidents, which is known as emergency braking. The third parameter is the vehicle's safe speed $v_{n_{safe}}$, which depends on many parameters and is computed using car-following models [17]. A common car-following model is the Krauss model [18], which is a microscopic, space-continuous model, developed in 1997. In the Krauss model, the safe speed is computed as:

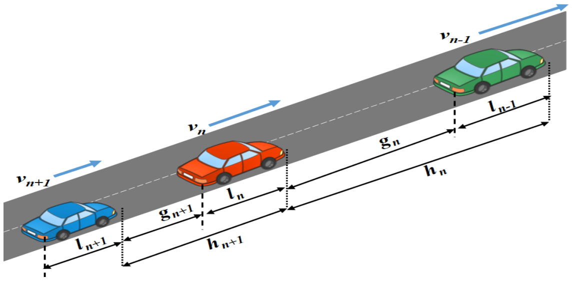

Fig. 1. The car following in CAV.

$$v_{n_{safe}} = v_n + \frac{g_n - v_{n-1}\, t_r}{\frac{v_{n-1} - v_n}{2b_n} + t_r}, \tag{2}$$

Clearly, this speed is a function of vehicle's current speed v_n in m/s, its maximum deceleration b_n in m/s^2, the gab g_n between to the leader in m, and the leader speed v_{n-1}. In this equation, t_r is the reaction time which is the time needed by the vehicle to react to any event. In human driven vehicles, a typical value of t_r is 1 second.

In our system, we assume all vehicles are connected and autonomous. Through the communication capabilities, each vehicle periodically broadcast its state information to other vehicles. The information includes the vehicle's ID, speed, acceleration, angle, and location. Upon receiving a message from its leader, the vehicle's autopilot uses the received leaser speed to compute the vehicle's safe speed.

B. Simulation Framework

To realistically model the impact of communication on the safety of CAVs, we developed the simulation framework shown in Fig. 2, in which NS3 and SUMO simulators are bidirectionally coupled. The objective of the coupling is to synchronize the two simulators in time and more importantly to exchange the required information between them. Within this framework, each vehicle is represented by two entities, one in NS3 to perform the communication tasks and another in SUMO for mobility and safety assessment.

The SUMO simulator reads its inputs (i.e., the road network information and vehicular traffic setting) and starts moving vehicles on the road network considering the traffic conditions on the different road segments, the vehicle's destination, the traffic signals (traffic lights and stop/yield signs) and the required maneuvering (e.g., changing lanes and taking over other cars). It also computes the vehicle speed based on its parameters, such as its maximum acceleration/deceleration rates, as described in (1) and (2). On the other side and in parallel, the NS3 simulator reads the communication settings and applies these settings to vehicles before starting the simulation. These settings include communication technology such as IEEE802.11p, LTE, or 5G-NR. For each of these technologies, other configurations should be defined such as the frequency band, transmission power, and transmission channel model.

While the simulation is running, NS3 and SUMO synchronize the number of cars and their positions as follows. NS3 periodically pulls the vehicle mobility information from SUMO. Particularly, it reads a list of the vehicles that are currently running on the road network along with their locations. Based

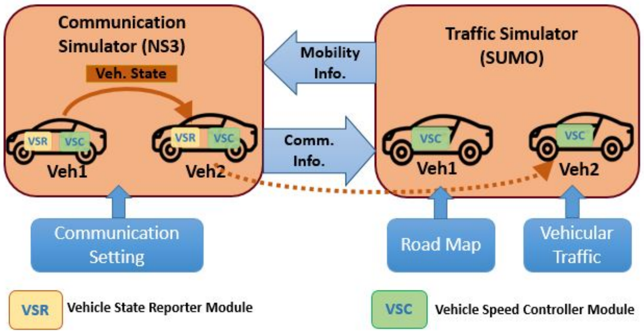

Fig. 2. The simulation framework.

on this information, NS3 updates the vehicle's locations and moves each vehicle to its new position. This synchronization is performed every time step Δt, whose typical value is 0.1 seconds. If there are new vehicles that entered the network during the previous time step, NS3 activates new ones and moves them to their positions. If a vehicle in NS3 is not on the vehicle list, this means is vehicle has left the road network. Therefore, NS3 deactivates this vehicle by stopping all the applications running on it.

C. Modeling Communication Impact on Safety

The forward collision avoidance safety application is modelled by two modules in each vehicle, namely, the Vehicle State Reporter (VSR) and the Vehicle Speed Controller (VSC), as shown in Fig. 2. The VSR module is responsible for periodically communicating the vehicle state information to other vehicles. The VSC is responsible for receiving these messages from the leader vehicle and compute the vehicle's safe speed. Because state information is exchanged within NS3 while the actual speed control is done in SUMO, the VSC is divided into two sub-modules, one in NS3 and another one in SUMO. The VSC in NS3 receives messages from other vehicles, if the message sender is the leader vehicle, the VSC communicate this leader speed (v_{n-1} in (2)) to the VSC module in SUMO through the communication information channel shown in Fig. 2. In the SUMO side, the VSC periodically computes the vehicle's safe speed based on the most recent received leader speed. Consequently, if a packet is dropped or delayed, the vehicle's safe speed will be updated using the previous leader speed. This captures the impact of communication imperfection on the forward collision avoidance performance.

It is important here to highlight that, in this paper, we only use the communicated speed parameter which sufferer's from error accumulation if computed based on the sensor data. When computing the safe speed, we use the actual distance between vehicles (g_n), i.e. we assume that the distance sensors are working correctly and report the correct distance. Hence, the impact captured by this model is only due to speed errors resulted from communication imperfection.

V. SIMULATION RESULTS AND DISCUSSIONS

We use the developed simulation framework to study and compare the suitability of both DSRC and 5G-NR cellular communication services to support the safety requirements of the forward collision avoidance system.

A. Simulation Setup

1) Traffic setting: We use the road network shown in Fig. 3, which is a real intersection in the city of Kingston, Ontario. The road network is 500x170 m, with the intersection approximately in the middle. At the intersection, there is a traffic light. So, vehicles may need to stop at the traffic signal when their light is red. In this road network, we create 8 traffic streams. The yellow arrows in Fig. 3 show the routes of the main 4 streams, which start at the beginning of the simulation and are repeated after 10 seconds. This traffic pattern allows vehicles to interact differently with leaders and with the traffic light at intersections, which produces realistic vehicle trajectories. Therefore we have a total of eight traffic streams. Each traffic stream represents a number of vehicles that start at a given time from an origin to destination points. This number of vehicles is called Traffic Scaling Factor (TFS), and its value determines the total number of vehicles that will be generated in the network. More importantly, the TFS determines the vehicle density, which is an important factor that affects communication performance. In our study, we increase the TSF from 1 to 5 at the step of 1 to study different vehicle densities.

Other than the extrinsic speed error parameter, there are two important intrinsic factors to the SUMO simulator that can affect the safety performance, namely the step-length and the Tau parameters. The step-length decides how frequently the safe vehicle speed is calculated. We use 0.1 seconds step-length, which is the default value that is commonly used in literature. The Tau parameter is driver perception reaction time (t_r in (2)). We use Tau = 1 second in our simulation, which is a typical value for human drivers. We also use this value here to make the simulation more conservative because decreasing it lower than the step-length will cause accidents in the simulation. We use this large value to make sure that all accidents are due to communication problems.

2) Communication setting: To compare 5G-NR and DSRC, we run each scenario using both technologies. In all cases, the safety application sends the vehicle state message every 100 ms which is the default interval for BSM in DSRC. Besides, we assume that vehicles communicate with other entities (e.g., Road-side-units or other vehicles) for infotainment applications in DSRC, or all sorts of cellular traffic in 5G. Thus, each vehicle generates another traffic load, which is referred

Fig. 3. The simulation network

to as Background Traffic (BGT). To represent typical variation in the BGT load, its rate is selected randomly for each vehicle within a maximum rate that we will refer to as Background Traffic Rate (BGTR). This bit rate is converted into packets based on an average packet size of 1000 bytes.

DSRC runs at the 5.9 GHz frequency. The transmission power level is 40 dB at a 6 Mbps data rate. For 5G scenarios, we use the Lena 5G-NR simulation package [19] for NS3. The current version of the 5G-NR simulator (and in fact the current implementations of 5G) does not support C-V2X through sidelinks. Consequently, we utilize infrastructure-based communication between vehicles through a base station as shown in Fig 3. The base station is assumed to employ a Time Division Duplex (TDD) mode, with 20MHz bandwidth at 3.5 GHz which are typical settings used by cellular operators.

B. Simulation Results

We run different simulation scenarios using both 5G-NR and DSRC. We used different TSF values (1 to 5), and for the maximum Background Traffic Rate (BGTR) we use 0 to 5 Mbps at the step of 0.5.

Our first and anticipated finding is that both DSRC and 5G can satisfy the safety requirements at low traffic levels, namely TSF = 1 and BGR $\in$ [0, 1.5]. Accidents started to appear as the traffic loads and vehicle densities started to increase, as will be detailed below.

For DSRC, the lowest setting that produced an accident is TSF = 2 and BGTR = 1.5 Mbps. Fig. 4 and 5 show the vehicle trajectories and the computed safe speeds for those vehicles involved in this accident. Fig. 4 compares the actual leader speed to the leader speed perceived by the follower vehicle based on the received information. The difference between the two curves is due to a combination of packet drops and delays. The actual speed curve shows that, at t = 6.5 seconds, the leader vehicle started decelerating. However, its state packets were not received at the follower vehicle until t = 7.7 seconds, in which case the follower vehicle kept using its last received leader vehicle speed. Even the packet received at t = 7.7 seconds was delayed by 0.5 seconds. All these inaccuracies in the follower vehicle's perception of the leader vehicle's speed produced errors when computing the safe speed of the follower vehicle. We can see that the safe speed error is very low most of the time. However, as this error continues over time, it causes the distance between both vehicles to decrease gradually until the accident happens at t = 11 seconds (when distance became 0), as shown in Fig. 5.

For the 5G Scenarios, the lowest setting that generated an accident is TSF = 4 and BGTR = 4.5 Mbps, which shows the capability of the 5G network to support the safety requirements for higher traffic loads and higher vehicle densities. One main reason is that it uses scheduled MAC compared to contention-based MAC in DSRC which wastes the network resources and increases the delay due to signal collisions and retransmissions, and the back-off technique.

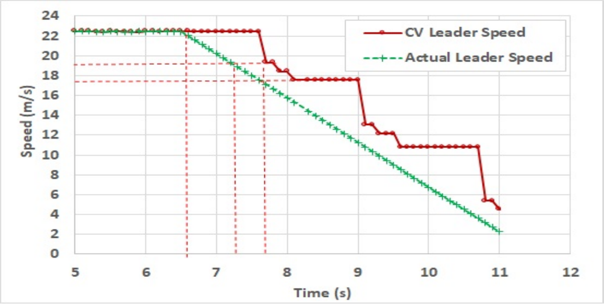

Fig. 4. The impact of communication error on the leader speed for TSF = 2 and BGTR = 1.5 Mbps using DSRC

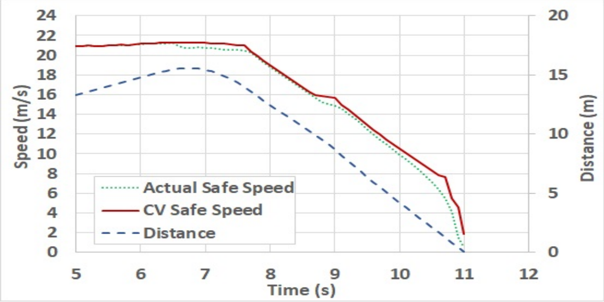

Fig. 5. The impact of communication error on safe speed computations and the gap distance for TSF = 2 and BGTR = 1.5 Mbps using DSRC

To fairly compare the performance of 5G to that of DSRC, we run both of them at TSF = 4 and computed the average network-wide packet drop rate and the packet end-to-end delay, which are illustrated in Fig. 6 for 5G and Fig. 7 for DSRC. The two figures also show the number of accidents that happened for each BGTR. Fig. 6 illustrates that the packet drop rate for low BGTR (0, through 1.5 Mbps) is at a very low value of 2.6%. Our analysis revealed that these are not

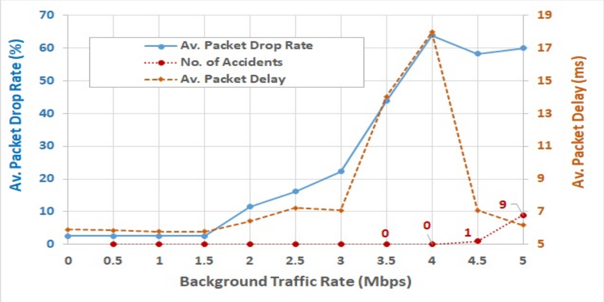

Fig. 6. Average packet delay and drop rates for vehicle TSF = 4 for 5G-NR

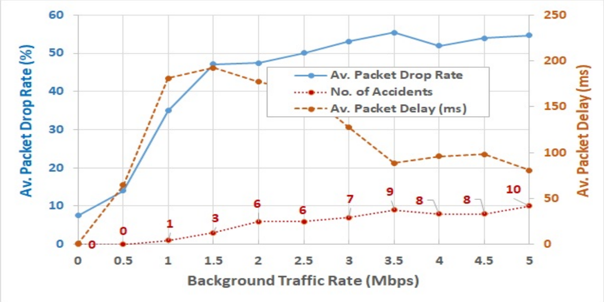

Fig. 7. Average packet delay and drop rates for vehicle TSF = 4 for DSRC

actual packet drops. These are packets that are sent by those vehicles that do not have followers to receive these packets, so they were not counted as received. This is also the reason why this drop rate is fixed while increasing the BGTR. When increasing the BGTR over 1.5 Mbps, the packet drop rate starts to increase and reaches 65% at BGTR = 4. At BGTR = 4.5 Mbps, an accident happened due to the high packet drop rate. We can see though that the average delay drops significantly at this BGTR. This is because SUMO removes the two involved vehicles from the network to continue the simulation after the accident. Removing these vehicles and their associated traffic reduces the packet load, and consequently, results in a lower packet delay.

Compared to 5G, DSRS results in a larger number of accidents even at low BGTR, as shown in Fig. 7. This figure also depicts that when a large number of accidents happen (i.e., 6 accidents at BGTR=2 Mbps), the delay significantly decreased, which is attributed to removing the vehicles involved in these accidents. Comparing the average packet delay and how it changes with the traffic load in the two figures shows that without background traffic (i.e., BGTR = 0), the average delay in DSRC is 0.735 ms compared to 5.9 ms using 5G. This very low delay in the DSRC is reasoned to the low contention over the wireless medium, while the MAC scheduler in 5G has to send scheduling requests and wait until it receives the grants from the base station. However, when increasing the BGTR, we can see that the delay in DSRC increases exponentially while it is stable at lower levels in the 5G cases.

VI. CONCLUSION AND FUTURE WORK

In this paper, we study the impact of communication imperfection on safety of CAV. We developed a simulation framework that realistically models communication and mobility in the CAV environment and can capture the mutual interaction between them and its impact on vehicle safety. in this framework, NS3 and SUMO are bidirectionally coupled to allow events that happen in each of them to reflect on the behaviours of the vehicles in the other. In this system, we also implemented the forward collision avoidance safety application and used it to compare the capabilities of DSRC and 5G-NR communication technologies to support the safety application and to study the impact of communication performance on the safety of CAVs. The comparison shows that 5G has a better capability to support the safety requirements in higher packet traffic loads and vehicle densities. One main reason is the more efficient scheduled MAC in 5G compared to contention-based MAC in DSRC.

A future extension is to develop techniques to overcome the errors in safe speed calculations that arise from communication limitations. For instance, if the follower vehicle did not receive from its leader for a long time, we will aim to develop a method (i.e., based on the history and available information from other vehicles) to avoid unsafe driving and the meanwhile do not affect the traffic flow. Moreover, we plan to study the Quality of Service (QoS) categories, especially in 5G, and their impact on safety. Additionally, an extended analysis will be carried out to understand the impact of communication on safety under different traffic conditions such as different road speeds or different road structures. Moreover, analysis of accident severity and its relationship to the different traffic and communication parameters will be further studied.

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