Investigating the Safety Effects of Degraded Wireless Performance on Connected Longitudinal Driver Assistance Functions

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Abstract: In the near future, Vehicle-to-Everything (V2X) based technologies will enable vehicles and other road users to exchange information with each other, even in cases where the applicability of other sensors is limited. This technology will be able to ensure the operation of advanced driver assistance systems, in cases where the other sensors are malfunctioning. In such situations, where only wireless communication can be relied upon, it is essential to be able to react to possible changes in network performance metrics. The objective of this paper is to address the aforementioned problem by characterizing the safety-risk associated with vehicle dynamic parameters and the factors influencing the network performance metrics in different scenarios. The network can be divided into seven distinct layers that are responsible for data transmission, and the research primarily focuses on the physical layer, with the objective of studying its impact on the packets sent. In the research, the Signal-to-Noise Ratio (SNR) is considered to be the primary network influencing parameter. This will facilitate the enhancement of not only the safety of transportation but also its reliability.

1 INTRODUCTION

In the near future, new technologies and developments will emerge in the automotive and transport industries to make them perform better and more efficient. One of these technologies will be wireless communication between vehicles and other road participants (Llatser et al., 2019). With this improvement, vehicles will be able to exchange the necessary dynamic and static information with each other to increase the safety awareness of a vehicle. Unlike other environmental perception sensors (camera, radar) vehicles equipped with V2X technology can detect vehicles from all directions and use their data to create a local dynamic map (LDM) to improve ad hoc decision making to mitigate safety risks and avoid traffic accidents. To provide real-time wireless communication the IEEE 802.11p standard (IEEE, 2012) was introduced to support safety-critical application such as forward collision warning (FCW), cooperative adaptive cruise control (CACC) and blind spot warning (BSW) (Mannoni et al., 2019). Building on its foundation, the emerging IEEE 802.11bd standard (Xue et al., 2024) aims to enhance performance by offering higher data rates, improved reliability, and backward compatibility, making it a promising solution for next-generation vehicular communication systems.

Vehicle-to-vehicle (V2V)-based safety communication can effectively support non-line-of-sight (NLoS) scenarios by using relay techniques and multi-hop communication to bypass obstacles and maintain connectivity between vehicles. Although there are some major limitations of wireless transmission, such as signal attenuation (fading, path loss (Bae et al., 2020)) due to obstructed visibility, interference from other wireless devices or environmental factors and these have a direct impact on Quality of Service (QoS).

The degraded QoS in V2V communications directly affects the reliability and efficiency of data exchange between vehicles, influencing by factors such as transmission latency and packet loss. Inadequate Packet Delivery Ratio (PDR) can compromise the availability of critical safety information, potentially increasing the risk of accidents and reducing the

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effectiveness of advanced driver assistance systems (ADAS) and automated driving functions (ADF) (Cui et al., 2018).

The validation of V2X communication-based applications necessitates the creation of a substantial number of test and evaluation scenarios. This can be achieved through a combination of analytical, simulation, and prototyping techniques.

In order to develop a functional simulation environment and a reliable and robust feature, it is essential to conduct a comprehensive review of the existing literature on this topic. In the study conducted by (Saponara and Gagliardi, 2018) a simulation environment was created in Simulink where they are able to test the reliability of V2X communication. Furthermore, they compared the simulation results with experimental results. The proposed tool may prove useful in studying the impact of vehicle distance, speed and operating scenario on the reliability of the communication system. In their article, (Xing et al., 2019) proposed a method where the CACC model considers communication delay and is able to reduce the minimum string-stable time gap. This was achieved by a Smith predictor and introducing a master-slave architecture. The results were validated by simulation, but other factors such as packet reception were not taken into account.

In their study, (de Almeida et al., 2022) conducted a comparative analysis of the results obtained from the utilisation of commercial On-Board Units (OBUs) and Road-Side Units (RSUs) data, with those derived from the application of diverse simulation software. The authors concentrated on three key metrics: maximum communication range, packet delivery ratio and inter-reception time. These were evaluated while varying the vehicle speeds within an 802.11p domain. However, in this study, the effect of noise on the communication network was not investigated.

(Shagdar et al., 2017) carried out an analysis of Cooperative Awareness Message (CAM) messages for CACC using the IEEE 802.11p standard. They investigated the potential of the CAM for platooning and demonstrated that V2V communication could facilitate the formation of a stable platoon in highway scenarios. They compared their analytical results with those obtained from NS-3, but their focus was on the impact of road density on communication, rather than on the effects of noise.

In (Bae et al., 2020), the researchers evaluated the performance of Dedicated Short-Range Communication (DSRC) based V2X technology on real test tracks in multiple Line-of-sight (LoS) and NLoS scenarios. They assessed various key performance indicators (KPIs), such as Packet Error Rate (PER), Received Channel Power Indicator (RCPI), Packet Reception Rate (PRR). The research proved that the PRR is significantly higher in LoS scenarios. Authors also emphasize that in the future they would like to evaluate the performance of the next generation short-range communication protocol like 802.11bd which will provide services for autonomous driving such as sharing sensor information. To evaluate this large messages will require new methods.

Knowle et al. (Knowles Flanagan et al., 2021) investigated V2V communication performance and its impact on safety distance. They were able to demonstrate the importance of a reliable network as a key to reducing stopping distance and reaction time.

Fitah et al. (Fitah et al., 2018) evaluated the performance of 802.11a (Wi-Fi) and 802.11p (DSRC) communication protocols for Intelligent Transport Systems. Their results showed that the DSRC protocol outperformed the Wi-Fi protocol in the scenarios they performed. They used multiple simulation tools like ns-3 for network and SUMO for traffic simulation, but for a safety critical application vehicle dynamics is essential which was not performed.

In (Rayamajhi et al., 2018), the authors conducted three different experiments to investigate the performance of DSRC in real-world and on CACC. They considered thoughput, latency and characteristics of the packet loss process for these experiments which they validated through laboratory and experimental tests. However, they are not focused on additional interference effect on CACC.

In this book chapter (Fallah and Gani, 2018) the authors evaluated the high fidelity DSRC physical layer modelling tools and the radio channel modelling approaches, including the discussion about channel propagation models (path loss, shadowing and fading effects). However, the impact of vehicle dynamics on wireless communication was not considered.

In (Mannoni et al., 2019), the group of researchers compared the Cellular and DSRC technology and examined the network physical layer. They also applied widely used indicators for the evaluation such as PER, SNR and latency for both version of V2X. Also they evaluated the vehicle density on the communications and when its increasing, then the performance gap is reduced between Cellular and DSRC.

Lian Cui and colleagues (Cui et al., 2018) evaluated a CACC under cyber attack and proposed a simulation platform to examine the effects of such attacks. The research considered multiple parameters, including vehicle dynamics, sensor errors, and communication latencies. The platform proposed in the paper is capable of quantifying the crash severity. The conclusion notes that cyber attacks do not always result in crashes, and that GPS jamming is the most dangerous cyber-attack for CACC-based platoons.

Most studies focus on latency and other parameters that affect the network, and do not directly consider the impact of noise levels, which are often the cause of random communication failures. This study, therefore, aims to investigate the impact of the SNR on the physical transmission process (link-level performance), with a specific focus on the packet delivery ratio (PDR).

The objective of this research is to examine the various modulation effects, path loss, shadowing and other noise factors that can impair wireless communication performance.

1.1 Main Contribution

The primary contribution of this work is the development of a MATLAB Simulink-based DSRC simulation platform that enables the evaluation of driver assistance functionality under degraded wireless network conditions in safety-critical scenarios. On the other hand, a significant contribution is the impact analysis of the SNR on the number of packets delivered, providing insight into how different SNR levels affect the reliability and efficiency of safety-critical data dissemination. For CACC application, reliability and latency are critical performance metrics. Based on 5GAA technical report (5G Automotive Association (5GAA), 2023), reliability is defined as 99.9%, ensuring that almost all control messages are successfully delivered to maintain seamless and synchronized vehicle coordination. In addition, the latency requirement for acceleration and deceleration control is set at 10 ms, emphasizing the need for ultra-low delay to support real-time responsiveness and safety in dynamic traffic scenarios. The technical report specifies C-V2X service level requirements, but is also applicable to DSRC.

2 METHODOLOGY

In this research we used Matlab Simulink 2023b to simulate a DSRC communication physical layer to perform V2V communication. MATLAB Simulink is well-suited for the analysis of the impact of degraded V2V communication on driver assistance functions. This is due to its ability to seamlessly integrate detailed communication models with vehicle dynamics and control systems in a single environment. This enables precise simulation of time-sensitive interactions between communication delays, packet loss, and driving behaviour. The following figure presents the four main blocks of our model which performs the simulation.

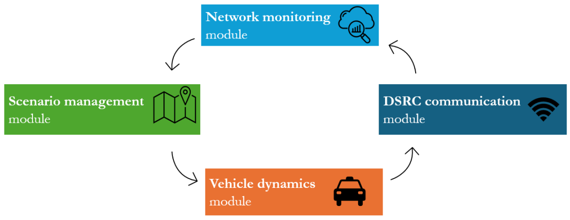

Figure 1: Simplified methodology diagram.

2.1 Vehicle Dynamics Model

The vehicle model used for this research is a six-degree-of-freedom model, powered by a single electric motor on the rear axle. This model was selected to enable the simulation of more complex vehicle dynamics in a variety of scenarios and for future research. In addition to the dynamics, the vehicle control is also located here, where it performs the adaptive longitudinal control of the vehicle under test. In this paper, we utilise a CACC system, which receives inputs from a wireless network and subsequently converts the acceleration data into torque, which is then fed back into the vehicle dynamic model to calculate the vehicle speed and position.

2.2 Scenario Management Module

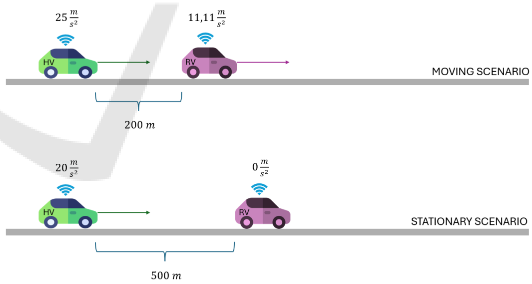

Figure 2: Implemented scenarios.

This block is responsible for the initialization and execution of all scenarios. It simulates the positions and velocities of the different actors and cooperates with the vehicle dynamic block. For the purposes of our research, we conducted multiple scenarios to evaluate the impact of varying SNR values on network performance. Accordingly, testing under degraded communication conditions is important is that we need reliable information on how much we can rely on V2X communication while the other environmental sensors are partly or completely unavailable. In the scenarios presented in 2, only V2X wireless communication was used, as the focus of this research was to evaluate the effectiveness of wireless communication with added interference without the presence of additional environmental sensors. In these scenarios, we distinguished between two vehicles, which we defined as the "host vehicle" (HV) and the "remote vehicle" (RV).

In order to simulate the effects of noise on the performance of the network, we have considered a range of different noise levels. This allows us to evaluate the impact of noise on a connected driver assistance feature. The additional noise levels that we have chosen are as follows: 0 dB, 10 dB, 20 dB, 25 dB.

2.3 DSRC Communication

This section serves as the central area of our research, focusing on facilitating wireless communication among vehicles. For the simulation, we created a basic frame which contains the necessary parameters. These include the 3-dimensional positions, velocities, angular velocities and the roll, pitch, yaw indexes. Furthermore, it contains the actor IDs and timestamps, with 3 additional slots for other parameters. These 18 parameters were then translated into 16-bit integers. In terms of bit size, this correlates with the size of a CAM basic container field, where the vehicle parameters are stored (ETSI, 2014). Initially, we need to establish the methodology for computing and adjusting the SNR value. Throughout our study, the transmission power remained fixed at 23 dBm, a default parameter for DSRC communication. Since our main goal is to assess how SNR affects packet delivery, it is crucial to determine the receiving power according to Eq. 1.

$$P_R = P_T - FSPL - X_\sigma \tag{1}$$

$$FSPL = 10 \cdot log_{10}\left(\frac{4 \cdot \pi \cdot d \cdot f_c}{c}\right)^2 \tag{2}$$

The free space path loss (FSPL) (Ghasemi et al., 2016) is a straightforward method for simulating the message power attenuation between the transmitting and receiving sides . In Eq. 2, we consider the distance between two antennas (d), the carrier frequency (f_c) and the speed of light (c). In the research we used the single-slope model. Based on the measurements of Kryszkiewicz et al (Kryszkiewicz et al., 2022) the difference between the characteristics of a single- and a double-slope model was insignificant. At distances exceeding 200 meters, ground reflections begin to induce modifications to the path loss model. This is the reason why the focus of control is maintained below this threshold, in order to ensure the safe operation of the CACC application. Shadowing (X_σ) uses a log-normal random distribution with zero mean. For our research we used 3.7 dB for standard deviation (Kryszkiewicz et al., 2022). After we know the receiving Power we can finally calculate the SNR for the communication (see in Eq. 3). This can be done as follows:

$$SNR = P_R - N_0 \tag{3}$$

$$N_0 = N_{thermal} + N_{other} \tag{4}$$

The performance of background noise can be affected by a number of factors, including ambient noise and radio frequency interference. In the present study, thermal noise was used as the main noise source and its value was calculated as follows:

$$N_{thermal}\ [dB] = 10 \cdot log_{10}(1000 \cdot k \cdot T \cdot B) \tag{5}$$

In order to conduct our study, we considered the 10 MHz bandwidth (B), which is dedicated for DSRC communication, and an ideal 297 K temperature (T). The last element of the equation is the Boltzmann constant (k). This allows us to calculate the SNR value by subtracting the noise from our receiving power. In our study, we evaluated the impact of varying SNR values on network performance. To this end, we considered additional interference (N_0) values that would degrade the network.

In the second stage of the process, the requisite data must undergo an intricate series of transformations before reaching the ego vehicle. Our approach involved following the IEEE 802.11p standard to establish the physical layer of DSRC communication in Simulink, as demonstrated in Fig. 3.

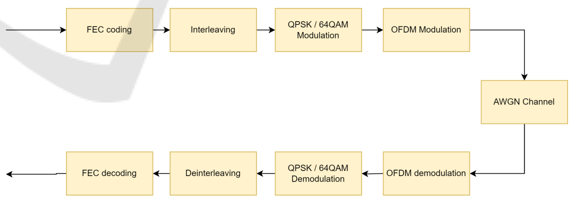

Figure 3: Bit stream through physical layer.

Once the requisite data has been converted into bits, forward error correction (FEC) is applied to the bit stream, contingent on the chosen modulation mode. In our paper we have selected 4 different modulations, as in Table 1, covering a significant transmission distance in the operating range of DSRC communication.(Bazzi et al., 2017)

Table 1: Different modulations.

Mode	Coding rate and modulation	Receiver sensitivity [dB]	LoS range [m]
1	1/2 QPSK	-82	541
2	3/4 QPSK	-80	439
3	2/3 64QAM	-69	139
4	3/4 64QAM	-68	125

Following the FEC coding, interleaving is employed to prevent the occurrence of long sequences of adjacent noisy bits. The required modulations are then applied to the bitstream before it is transmitted to the channel. The chosen Orthogonal Frequency Division Multiplexing (OFDM) modulation (see Table 2 is applied last, prior to transmission. In order to simulate the effects of environmental noise on the message, we have incorporated additive white Gaussian noise (AWGN) into the channel. The default parameters for OFDM modulation were employed, in accordance with the standard specified in 802.11p (IEEE, 2012).

Table 2: OFDM modulation parameters.

Data subcarriers	48
FFT length	64
Guard bands (left-right side)	6-5
DC null	yes
Pilot subcarriers (positions)	4 (12, 26, 40, 54)
Cyclic prefix	16
OFDM symbol	6 (QPSK), 2 (64QAM)

At the receiving end, the process of decoding the message is opposite to that of encoding. Initially, the receiving device assesses the message reception power and, if it is below the receiving sensitivity threshold, our simulation assumes that the message has not been received. Conversely, if the reception power is above the sensitivity threshold, the device attempts to decode the message. Decoding is a crucial aspect of this layer, as it enables the recipient to obtain the information they require from the sender.

2.4 Network Monitoring Module

The network monitoring module performs the calculation of network performance metrics like PDR or PRR for the whole process. The PDR provides a last second mean value, which is essentially a sliding window method-based aggregation. Without this module, it would not be possible to evaluate the network performance. In the future, this could be expanded to include communication delays and other parameters, which could be essential for testing V2X-based control solutions and support application testing and validation.

3 RESULTS AND DISCUSSION

In our research, we conducted multiple scenarios to assess the impact of varying SNR values on network performance and to examine their effects on different modulations. Each scenario involved a simulation time of 50 seconds (CAM transmit frequency was 10 Hz, resulting in 500 packets transmitted) and commenced with the HV's initial velocity set at 20 m/s. Subsequently, in the CACC system, the HV accelerated to a predefined speed according to the scenario. To ensure the smooth functioning of the CACC system, the algorithm assumes that a vehicle is leading at a given distance (in our case, 300 meters) if no neighboring vehicles are actively transmitting messages. Once the first packet is successfully received, the perception module can then calculate the relative distance between the RV and HV positions. To address the fact that CACC alone is not designed to bring the vehicle to a complete stop, we incorporated a basic Autonomous Emergency Brake (AEB) into the model. This functionality triggers when the time-to-collision (TTC) between the vehicle and an obstacle ahead is less than 1.8 seconds. Upon activation, the AEB applies full brake force, halting the vehicle and maintaining it in a stationary position until the end of the simulation.
Orange highlighting in Table 3 and Table 4 shows where even AEB could not stop in time.

3.1 Moving Target with Constant Velocity

In our research, we aimed to provide a more realistic use case scenario for CACC. The results of the network analysis are presented in Table 3. In this scenario, the velocity difference between the two vehicles was 13.89 m/s. Initially, under stable network conditions, all modulations yielded similar results, and the CACC system effectively adjusted to the velocity of the RV, as illustrated in Fig 4. Subsequently, we intentionally introduced gradual degradation into the network. At an additional 10 dB of noise, the QPSK modulation remained unaffected. However, with the 64QAM modulation, there was a noticeable delay in receiving the first packet. The system received the first correct message at a distance of about 100 meters. Despite this delay, the CACC system was still able to respond adequately, thus averting a potential collision. As the noise level increased to 20 dB, a number of significant changes were observed. The reception distance for QPSK modulation was found to be halved, while there was also observable shifting among different coding rates. With 64QAM modulation, the reception distance dropped below 25 metres, necessitating intervention from the AEB. A notable difference was observed between the coding rates. While a coding rate of 2/3 enabled the vehicle to stop in time, a rate of 3/4 resulted in the vehicle being un-

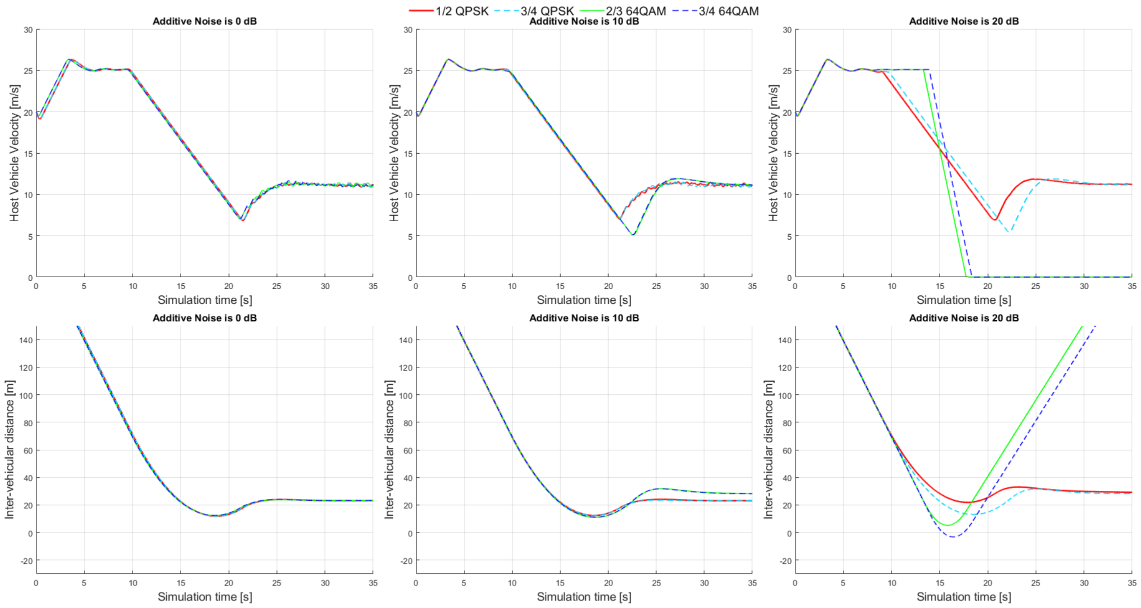

Figure 4: Host Vehicle Velocity and Relative Distance - Moving scenario.

able to stop even with AEB activation. Further degrading the network to an additional noise level of around 25 dB, the AEB activates in all scenarios. This occurs because the CACC system lacks the capability to adapt to the velocity of the leading vehicle in time. While accidents are avoided during QPSK modulation, only the impact velocity can be mitigated with QAM modulation.

Table 3: Results - Moving remote vehicle (HV velocity 25 m/s, RV velocity 11.11 m/s. Sent packets 501, Simulation time 50 seconds).

Received packets	PRR [%]	First reception distance [m]	min TTC [s]	Coding rate and modulation	Interference level
501	100.0	200.5	3.77	1/2 QPSK	0 dB
501	100.0	200.5	3.77	3/4 QPSK	
466	93.0	198.6	3.85	2/3 64QAM	
458	91.4	198.6	3.86	3/4 64QAM	
492	98.2	198.6	3.85	1/2 QPSK	10 dB
479	95.6	198.6	3.85	3/4 QPSK	
396	79.0	87.1	3.62	2/3 64QAM	
385	76.8	87.1	3.66	3/4 64QAM	
412	82.2	101.7	5.18	1/2 QPSK	20 dB
398	79.4	89.1	3.97	3/4 QPSK	
43	8.6	22.7	0.96	2/3 64QAM	
57	11.4	13.6	0.22	3/4 64QAM	
88	17.6	57.4	1.76	1/2 QPSK	25 dB
66	13.2	43.3	1.64	3/4 QPSK	
47	9.4	13.1	0.22	2/3 64QAM	
46	9.2	8.6	0.15	3/4 64QAM	

3.2 Stationary Target

In this test, our aim was to simulate a worst-case scenario where the RV is stationary, allowing us to assess the maximum reception distance of various coding schemes. Similarly with the previous scenario, the results are presented by Table 4. When the SNR remained unaffected by additional noise, clear distinctions between different modulations emerged. QPSK modulation successfully received the first message at approximately 500 meters, which represents the maximum distance between the two vehicles. However, 64QAM modulation only managed to receive the message at around 200 meters. The difference between coding rates was minimal, with only a slight variation observed in PRR, amounting to just a few percentage points. As the network became noisier, reception deteriorated significantly. With a 10 dB increase in noise, the reception distance halved, leading to a noticeable decline in PRR. Further degradation of the network resulted in delayed activation of safety features. In the case of the more complex 64QAM modulation, from a 20 dB increase in noise, the system failed to stop the vehicle in time, even with AEB intervention. The high PRR values observed in these scenarios can be explained by the fact that the AEB stopped the vehicle in the reception zone (regardless of whether a collision occurred), therefore the HV

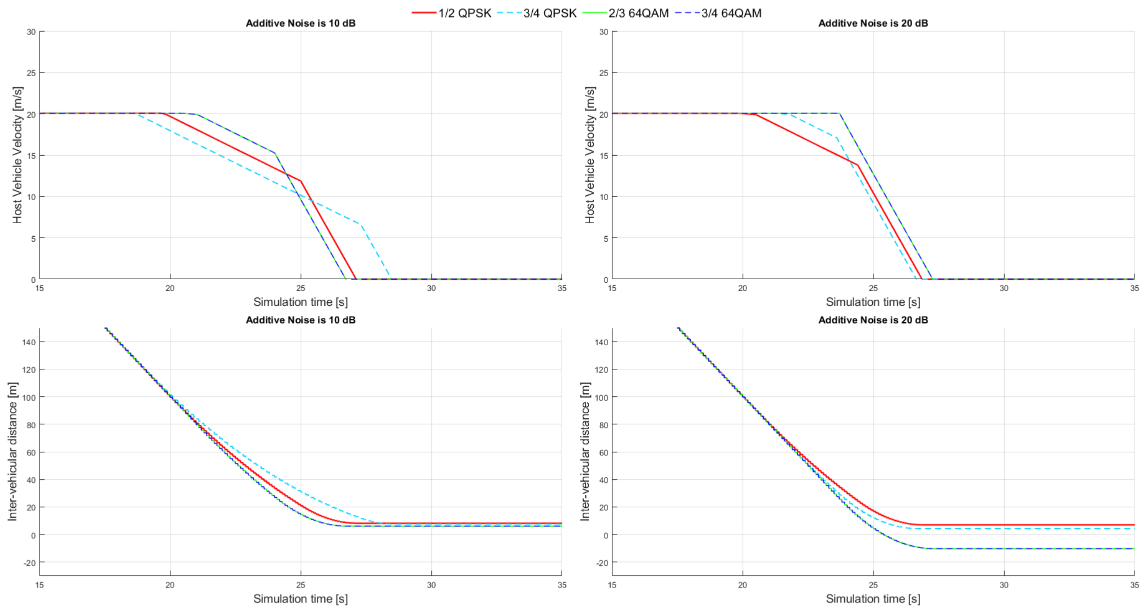

Figure 5: Host Vehicle Velocity and Relative Distance - Stationary scenario.

continued to receive messages after reaching the stationary position. In case of highest additional noise the HV stopped outside of reception zone resulting in low PRR.

Table 4: Results - Stationary remote vehicle (HV velocity 20 m/s, Sent packets 501, Simulation time 50 seconds).

Received packets	PRR [%]	First reception distance [m]	min TTC [s]	Coding rate and modulation	Interference level
498	99.4	497.6	1.53	1/2 QPSK	0 dB
493	98.4	495.6	1.52	3/4 QPSK	
333	66.5	206.0	5.60	2/3 64QAM	
326	65.1	206.0	5.60	3/4 64QAM	
383	76.4	340.2	1.71	1/2 QPSK	10 dB
365	72.9	272.1	1.76	3/4 QPSK	
281	56.1	91.7	1.48	2/3 64QAM	
288	57.5	91.7	1.48	3/4 64QAM	
293	58.5	103.7	1.59	1/2 QPSK	20 dB
282	56.3	75.6	1.25	3/4 QPSK	
261	52.1	25.5	0.15	2/3 64QAM	
253	50.5	25.5	0.15	3/4 64QAM	
275	54.9	51.6	0.47	1/2 QPSK	25 dB
272	54.3	47.6	0.56	3/4 QPSK	
19	3.8	11.5	0.12	2/3 64QAM	
12	2.4	11.5	0.12	3/4 64QAM	

4 CONCLUSION

In our study, we investigated the impact of variations in SNR on transmitted packets and examined the effect of different noisy network conditions on a safety-focused driver assistance feature (CACC). Our findings align with previous research, indicating that as SNR decreases, the operational range of more complex modulations also decreases. Furthermore, we developed a simulation environment suitable for future V2X-based developments. In the future, our objective is to further improve the available control concepts utilising network performance metrics to mitigate the severity of various scenarios. Furthermore, we intend to expand our simulation platform to include latency assessment throughout the packet sending process. This extension will provide a more comprehensive understanding of the system's performance and aid in developing future V2X systems. The forthcoming iteration of the proposed system may be utilised in scenarios of greater complexity. This would require the simulation of transmission in a more dense environment, thereby enabling an investigation into the manner in which the diverse wireless communication-based driver assistance systems respond to alterations in their surrounding environment.

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