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Investigating the Technological and Political Challenges of V2V Communication in Light of an Experimental Scenario Set Up

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ABSTRACT The suggested benefits of automated vehicles are plentiful, but many of the benefits depend on connectivity with other vehicles and infrastructure to be useful to the society at large. This paper identifies two main research gaps: first, to identify whether ITS-G5 can be a reliable communication link for V2V communication. Second, to discuss which implications the results have for practitioners working with the future implementation of CAVs. We answer these research gaps by introducing a conceptualization of V2V communication operationalized through controlled experiments with vehicles on a closed runway. In the experiments, onboard ITS-G5 communication devices are used for measuring signal strength and package loss between the vehicles. The results indicate that ITS-G5 technology has some limitations, especially for long range communication (>1500 m), and in cases with other traffic shadowing the signal. We conclude that although ITS-G5 has high risk of reduced radio link in non-line-of-sight situations and in situations where the radio signal is shadowed by other traffic, the latency and operational range would be sufficient for safety critical services in line-of-sight situations. For policymakers and practitioners working with implementing communication for vehicles, the results imply that large-scale piloting is critical for testing the technology in a realistic environment outside of the laboratories. In such environments different stakeholders and disciplines can meet and collaborate to avoid siloed approaches.

INDEX TERMS V2V, ITS-G5, package loss, RSSI, radio communication, CAV, autonomous vehicles.

I. INTRODUCTION

The envisioned benefits of automated vehicles are many, including increased safety and efficiency, reduced congestion and emissions, and more comfort for the users. However, automated vehicles by itself will not necessarily lead to these benefits, and many of the new functionalities depend on connectivity with other vehicles and infrastructure to be useful for the society at large [1], [2], known as Connected and Automated Vehicles (CAVs). This indicates that communication is a precondition for implementation of many of the positive societal effects of automated vehicles. From a political point of view, the recognized importance of communication has resulted in several political processes aiming at securing communication for the transport sector. The development of the Delegated Act on C-ITS (Cooperative Intelligent Transport System) is perhaps the most frequently mentioned and discussed political process in Europe in this regard. This initiative was ultimately, however, rejected, which illustrates the complex political landscape in which communication for automated vehicles is situated. In the US, the 5.9 GHz band was in 2021 opened for other purposes than transport, a process that were met with considerable objections from many different stakeholders, also illustrating the complexity of this issue.

Even though the political landscape is complex, the implementation of automated vehicles is dependent on knowledge, expertise, and resources from the communication community to achieve policy goals concerning safety, environment, efficiency, and comfort. We argue that when introducing CAVs in traffic this leads to an increased coupling of two sectors which traditionally have been treated by policymakers as

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separate sectors. In the case of communication infrastructure for CAVs the challenges are related to both the potential and the limitations of communication technologies for providing a reliable communication link between vehicles in traffic (V2V), and between vehicles and the surrounding infrastructure (V2I, I2V). In this paper we limit our scope to V2V communication, and investigate dedicated short-range communication (DSRC) technologies, often referred to as ITS-G5 in Europe.

We identify two main research gaps. First, identifying whether ITS-G5 can be a reliable communication link for V2V communication. Several papers constitute evaluations of ITS-G5 with simulations and/or experiments of V2V/V2I [2]–[5], but few, to the authors knowledge, evaluate high speed highway V2V communication through an experimental design. LTE-V2X testing in the 5.9 GHz band in China [6] and 5G/ITS-G5 comparisons in Finland being two notable recent works [7]. Such studies are of interest both to practitioners and researcher, as this constitute a real-life driving situation were the quality of for instance traffic safety services is critical. For an extensive review of testing V2X (vehicle-to-everything) applications, and further motivation for the need of such experiments, the reader is referred to [8].

Second, we aim at discussing what implications the results from the experiments have for practitioners and policymakers working with the future implementation of CAVs. As an interesting illustration of why this is an important research gap, a literature review finds that two-thirds of papers within transportation literature only focuses on quantitative analysis alone [9]. We therefore argue that much of the scientific literature is focusing on the strengths and weaknesses of ITS-G5 technology from a highly technological point of view. However, practitioners and policymakers have an increased need to understand what the strengths and weaknesses are for various communications technologies to have a realistic view on whether CAVs will deliver the promised positive societal impacts including safety and reduced emissions.

To investigate communication quality of service we focus on measuring received signal strength indicator (RSSI) and package loss conducting experiments on four traffic situations, including multiple vehicles. RSSI and package loss represent two of the most important indicators of robustness of signal link and is crucial for future ITS applications. Latency was also investigated in earlier stages in this work, deemed non-problematic in all our experiments. The first traffic situation represents a rural two-lane highway, with two vehicles driving in opposite directions. The second situation is designed to replicate a situation with traffic shadowing the radio signal on a two-lane road. The third traffic situation emulates vehicle-following scenario while the fourth is performed with vehicles driving in parallel to replicate radio shadowing traffic on a multilane highway. In all cases, we focus on communication between two vehicles at several levels of driving speed, in some cases with a third or fourth vehicle acting as signal obstacle between the communicating vehicles.

A. TECHNICAL BACKGROUND

Future vehicle communication technologies, particularly related to autonomous vehicles, are expected to generate substantial amounts of data. For instance, Intel projects that each car will produce 4 TB of data every day [10]. However, millions of vehicles on the road are already connected using cellular communication technology. Ericsson expects this number to grow until 2024, after which every new vehicle entering the market will be connected [11]. Connectivity here refers to ''the capability of a vehicle to communicate to and from (and therefore, share information with) other systems (vehicles, infrastructure, roadside units, data portals, cyclists and pedestrians, and so on) that are located outside of a vehicle, via various relatively short- and long-range connectivity technologies'' [12]. Several emerging technologies are dependent on vehicles being connected to realize the positive effects for society, such as cooperative adaptive cruise control, efficient routing services, and services focusing on reporting accidents or other traffic-related incidents, road works, and weather events [1], [3], [12], [13].

Communication for the future transport system include a large variety of technologies, including Bluetooth, Wi-Fi, satellite, DSRC, in addition to cellular communication. Using On-Board Units (OBU), Roadside Units (RSU), in-vehicle advanced driver assistance systems (ADAS) and on-road sensors (e.g., cameras, traffic registrations and weather stations), vehicles will start communicating with each other and the infrastructure [2], [14]. Particularly interesting for our approach is the envisioned VANET (vehicular ad hoc networks), using DSRC communication to spontaneously create a wireless network of nearby vehicles and infrastructure [15], [16]. Such a network can efficiently and locally communicate traffic safety and efficiency related messages between relevant vehicles and infrastructure. For instance, by creating relay mechanisms for the radio signals, e.g., see the investigations in [17]–[19], and in many of the reference therein, for theoretical approaches both in general and with respect to ITS-G5 communication.

Significant effort has been put into investigating VANET solutions, two of the most relevant to our work are proposing signal path loss models in the use case of road tunnels [3] and investigating signal and package loss for extracting V2V propagation models [20]. Both these papers are collecting experimental data in different scenarios, including a heavy vehicle as an obstacle between moving vehicles and a traffic jam situation. The former of these papers also provides a proper and thoroughly introduction to VANET.

B. THE POLITICAL BACKDROP

As stated in the introduction, the political landscape where communication for automated vehicles is situated is highly complex. Collaboration among different stakeholder groups is needed for developing policies [21] including transport authorities, as well as private sector for providing communication technologies in infrastructure and in vehicles. Innovation and idea generation can be particularly successful within collaborative multidisciplinary environments [22], however, this stands in contrast to the situation for communication solutions within the transport sector. Here, the situation is characterized by strong competition between technologies [23], which leads to a polarized political picture.

Challenges are increased when the policies need to be addressed across national boundaries [24], as is the case for communication within the transport sector in the EU. At the European level there has been a strong drive to develop policies and legislation concerning digital technologies for future vehicles. The European Commission aims to increase coordination within the European Union concerning communication for the transport sector, through developing policies, standards, legislation, communications, roadmaps, and strategies developed together with the stakeholders [25]. As a response to the strong need for coordination, an expert group was created in 2014 for the deployment of cooperative intelligent transport systems in the EU, called the C-ITS Platform, consisting of member states, stakeholders, and the Commission [26]. The C-ITS Platform identified the need for an appropriate legal framework at the EU level as a key challenge. This led to the development of the Delegated Act on Deployment and Operational use of Cooperative Intelligent Transport Systems (C-ITS). The Delegated Act suggested ITS-G5 as the default technology for V2V communication [26].

The Delegated Act received criticism from several key stakeholders, including the telecom industry, technology providers and certain parts of the automotive industry. Some strong voices in this debate include the GSM Association [27], representing the mobile network operators worldwide, and the 5GAA [28], representing companies form the automotive, technology and telecom sectors. Among the main criticisms were that the Delegated Act was seen as not being technology neutral, and too supportive of the WiFi technology, in particular the ITS-G5 technology.

Ultimately, 21 of the 28 member states in the EU Parliament voted against the Delegated Act, which led to its rejection in July 2019. This result was seen as a victory for the telecom industry. According to several member states, the decision to select the preferred technology was premature, and they wanted more time to consider other alternatives, and particularly the upcoming 5G network rollout. There are still major disagreements on which technology is safer, most reliable, and most oriented towards the future. Volkswagen launched the new Golf 8 in October 2019, which was equipped with DSRC ITS-G5 communication technology [29]. On the other side, Ford has announced that they will start deploying cellular V2X in Ford vehicles in China in 2021 [30]. These two examples illustrate that there is no consensus regarding communication technologies within the automotive industry.

However, the European Commission continues to strive for increased coordination within the union and made an implementing decision in October 2020 to dedicate the 5.9 GHz frequency band to safety-related applications of ITS across all member states. This decision doubles the available radio spectrum for safety related ITS in Europe [31].

In the US, there has also been debates concerning how to provide communication to vehicles. The Department of Transportation (DOT) has primarily focused on DSRC, and the seven channels around 5.9 GHz were reserved for safety related applications for transport in 1999. However, due to slow progress and little use, the Federal Communications Commission (FCC) initiated in December 2019 a "Notice of Proposed Rulemaking" to reallocate parts of the 5.9 GHz band for unlicensed operations such as WiFi-technology which has an increasing need for more spectrum [23]. For instance, GM's Cadillac was the only brand to equip production models with DSRC capability, and the number of vehicles produced were only 50,000 [32].

The process concerning the 5.9 GHz band in the US has received much attention and criticism. A major concern was that the lower WiFi-spectrum of the 5.9 GHz band may be located too close to the V2X safety spectrum, potentially allowing for inference [32]. ITS America called the decision "reckless" [33]. Other comments made about the decision, concerned slower rate of deployment in the US, as argued by Toyota, or economic consequences of modifications of already connected infrastructure such as intersections, as argued by Georgia DOT [34]. Still, the FCC stood firm in the decision to split the 5.9 GHz band and made the ruling November 18, 2020. The FCC states in the report that "they recognize that the 5.9 GHz band play an important role in supporting ITS applications" [35], and that they therefore retain the upper 30 megahertz in the 5.9 GHz band for safety related DSRC.

C. RESEARCH QUESTIONS

While the political community struggles with priorities and intense discussions between different stakeholder groups, there is a strong need for research communities to develop evaluations, recommendations and knowledge concerning which technology or combination of technologies is best for providing reliable V2V communication, as well as for V2X. There are several challenges that are introduced in the traffic context which are necessary to explore further before any firm political decisions can be made about which technology or combinations of technologies will be best suited for CAVs. Understanding how the technology performs under different traffic situations is therefore important for understanding whether ITS-G5 will provide the transport sector with the needed quality.

Based on the current knowledge, we suggest three detailed research questions that needs to be answered before any conclusions can be reached on which technologies to deploy for V2V communication:

1. How does vehicle speed affect ITS-G5 communication?
2. At what distance with LoS does ITS-G5 provide sufficient radio communication between two driving vehicles?

3. How does radio shadows from surrounding traffic affect ITS-G5 communication?

To address both research gaps identified in the introduction, we also present implications for practitioners and policymakers for each research question. In the next section, we present our methodology, concepts, and data collection procedure. A descriptive analysis of the data collected is presented in Section III. Section IV considers how these results answer our research questions, along with a discussion of its implications for CAV. Finally, conclusions and suggestions for further research are presented in Section V.

II. METHODOLOGY AND DATA COLLECTION

A. CONCEPTUALIZATION AND OPERATIONALIZATION

This section explains the conceptualization and operationalization used in this paper. This specifically refers to the measurement validity of the study; does the operationalization and scoring of cases reflect the concept that we seek to measure [36]. As stated in the introduction, the main purpose of this paper is to investigate how different traffic situations affect the quality of ITS-G5 V2V communication. Our background concept is therefore V2V communication in different traffic situations, focusing on highways.

To capture the background concept, we have designed experiments where we emulate situations that arise in highway traffic, where the purpose is to identify how much speed, distance, and vehicle radio shadow matter for quality of the V2V communication service. Filtering out the effects from pure speed, distance or vehicle shadow was a key challenge for the data collection, demanding for instance a flat terrain that by itself did not reduce line-of-sight (LoS) between the vehicles. To secure an environment as controllable as possible, we used a closed airport runway as our test site. We have identified four traffic situations that happens frequently on highways: i) two-lane road with low density traffic, ii) two-lane road with high density traffic, iii) vehicle-following, and iv) multilane road, which is operationalized by several scenarios in specific traffic situations.

To score scenarios according to the quality of the V2V communication service, we use the following two parameters: i) received signal strength indicator (RSSI) and ii) package loss. These two parameters give an indication of how well the communication service is performing. RSSI measures how strong the signal each vehicle receives from the other is, meaning that low RSSI values means a risk of information loss. The package loss measures how many of the transmitted data packages that are not received by the other vehicle, giving a precise count of how much information that is lost.

B. DATA COLLECTION

To test V2V communication using ITS-G5 we conducted several experiments on an airport runway at Rygge airport in Norway. The location was chosen to secure as much LoS as possible (flat runway surface), and because we wanted to have as much control of the traffic situation in each experiment as possible, with no other disturbances around. That is, no other traffic is influencing the measurements other than what is introduced in the experiments.

Two ITS-G5 radios (Cohda Wireless MK5 IEEE 802.11p radio OBUs with SMW-303 antennas), were mounted on two passenger vehicles to test V2V communication in the different scenarios. The OBUs were set up to transmit messages of 200 bytes ten times per second, following the typical standard for CAM (Cooperative Awareness Messages) on the 5.9 GHz band [37]. Both OBUs where transmitting and receiving messages in all tests. To identify each individual OBU they were given the names ‘‘A’’ and ‘‘B’’, which will be used in the remainder of the paper.

A total of 11 experiments with V2V communication were conducted by driving the entire length of the runway, each of the 11 experiments emulated different scenarios. Both OBUs were mounted on the roof of vehicles with a height of approximately 1.5 m (VW Passat), which was accounted for when estimating LoS. The total distance of the runway used in the test was about 1600m, while the starting and stopping positions for each vehicle varied slightly between scenarios.

The experiments were conducted between 11 am and 1 pm in clear blue skies and little wind. Scenarios 1, 2 and 7 represent baseline scenarios with no radio shadow from other vehicles present. In scenarios 3 and 4, passenger vehicles introduced radio shadow, while in scenarios 5, 6, 8, 9 and 10 a heavy vehicle with a steel truck body was used as radio shadow. In scenarios 1-6 the vehicles are starting at different ends of the runway, passing each other, and ending each scenario when both vehicles have reached the opposite end of its starting point. In scenarios 7-11, both vehicles are starting at the same end of the runway and driving in the same direction, the scenarios ending when both vehicles have reached the other end. Most scenarios are conducted twice with different vehicle speeds, one scenario with 60 km/h and one scenario with higher speeds. Scenarios involving only passenger vehicles were driven with 100 km/h in the higher speed cases, while engine restrictions and slow acceleration of the heavy vehicle limited the remaining high-speed scenarios to varying speeds between 70-90 km/h, accelerating and deaccelerating through most of the scenario. Table 1 presents the vehicle behavior and communication challenges in the different groups of scenarios in detail.

C. METHODES FOR ANALYSING SIGNAL STRENGTH AND PACKAGE LOSS

As explained in Section II.A, we focus on RSSI measured in dBm and package loss measured by counting the number of received packages compared to the number of transmitted packages. Message delays were also investigated in the earlier stage of the analysis, observing very low delays for all received messages, averaging 0.001 s with a standard deviation of 0.001 s and maximum of 0.012 s. As this is deemed sufficient for our traffic situations, and the latency

TABLE 1. V2V experiments conducted at Rygge airport on october 15th, 2020. In scenarios 6 and 11, constant speed of 100 km/h was not possible to obtain with the heavy vehicle, driving instead between 70-90 km/h during the scenarios.

Operationalization	Scenario	Target speed (km/h)	Direction of OBUs	Vehicle shadow
Two-lane road, low density traffic	1	60	Opposite direction	No radio shadow from other vehicles
	2	100	Opposite direction	No radio shadow from other vehicles
Two-lane road, shadowing traffic	3	60	Opposite direction	Radio shadow with passenger vehicle in front of each OBU
	4	100	Opposite direction	Radio shadow with passenger vehicle in front of each OBU
	5	60	Opposite direction	Radio shadow with heavy vehicle in front of OBU 16228
	6	100	Opposite direction	Radio shadow with heavy vehicle in front of OBU 16228
Vehicle-following	7	60	Same direction	No radio shadow from other vehicles
	8	60	Same direction	Radio shadow with heavy vehicle in between the OBUs driving subsequently
	9	100	Same direction	Radio shadow with heavy vehicle in between the OBUs driving subsequently
Multilane road	10	60	Same direction	Radio shadow with heavy vehicle in between the OBUs driving in parallel
	11	100	Same direction	Radio shadow with heavy vehicle in between the OBUs driving in parallel

was very robust with no outliers to discuss further, we focus on RSSI and package loss in the rest of paper.

When plotted, the data is presented with time on the x-axis, giving us a common reference frame for both OBUs in all scenarios. In Figure 1 (scenario 1), the raw RSSI for both OBUs are plotted in bright red and pink points, while dark red points represent average values of all RSSI measurements from both OBUs in a +/− 1 s sliding window. As we can see, both OBUs report comparable RSSI values, and the average seems to represent the measurement sufficiently for our analysis. For package loss, we have used a +/− 1 s sliding window to calculate the percentage of missed messages, both for single OBUs (turquoise and bright blue) and the two OBUs combined (dark blue). The two point-curves for individual OBUs show a high correlation between measured

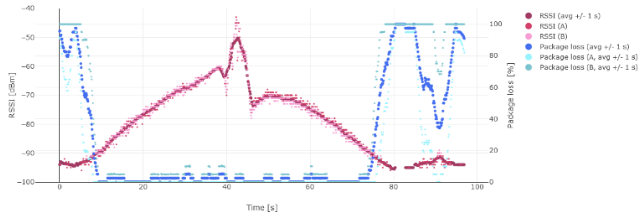

FIGURE 1. Visualization of package loss (blue) and RSSI (red) compared to raw data from both OBUs for scenario 1.

package loss for the two OBUs, but the absolute difference can be high. The most extreme case of difference in package loss seen in this example is at the 90 s mark where OBU A reports 5 % package loss and OBU B reports 70 %. Similar results can be found for the rest of the scenarios. However, due to the overall high visual correlation, we proceed with presenting the average package loss using data from both OBUs in the remainder of the paper. Overall, using a sliding window approach seems reasonable when presenting both parameters. The robustness of this approach has been tested and verified by varying the size of the window for both speed levels in use.

Some of the areas with high package loss can be explained by the terrain. Although the runway was picked for its communication friendly terrain, it is not completely flat, and some locations are far enough below other locations to block the LoS. This is shown in the bottom plot of Figure 2 (and the following scenario figures in Section III). The orange line represents the horizontal distance, as a function of time, between the OBUs, to investigate the effect of increasing/decreasing distance between the OBUs. To indicate LoS (or lack thereof) at each time step we calculate the terrain height profile between the vehicles, and the green line represents the lowest height difference between the terrain and the straight line between the two OBUs. If the terrain height profile at any point crosses the straight sight line, that means that the LoS is broken by the terrain. This is indicated by the green line crossing the black line (minimum height above terrain gets negative), and the black line disappearing. In Figure 2 for instance, the green line is mostly at around 1.5 meters indicating that the terrain between the vehicles is mostly flat (or slightly concave), but between approximately 80 and 90 seconds into the scenario, the LoS between the two OBUs is broken by the terrain for a few time steps.

III. RESULTS

In this section we present the technical results for the four operationalized concepts using our 11 scenarios. Readers who simply wants to read the implications of the results and the analysis in light of the research questions can skip reading this section. In Section IV, these results will be related to the three main research questions posted in Section I.C. In these coming sections, only the low-speed (60 km/h) cases are included as figures, but all scenarios are available in the supplementary material and is referred when necessary.

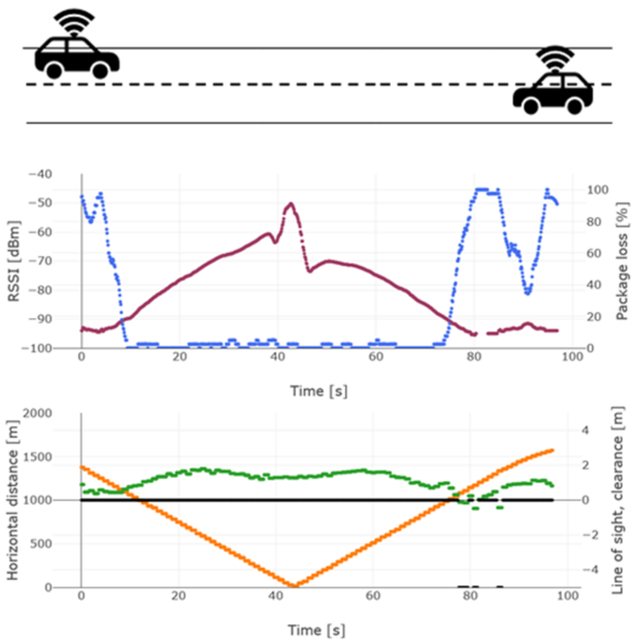

FIGURE 2. Two-lane road, low density traffic (scenario 1). No communication shadow between vehicles. Upper plot: RSSI (red) and package loss (blue). Lower plot: horizontal distance between vehicles (orange), and LoS clearance (green/black).

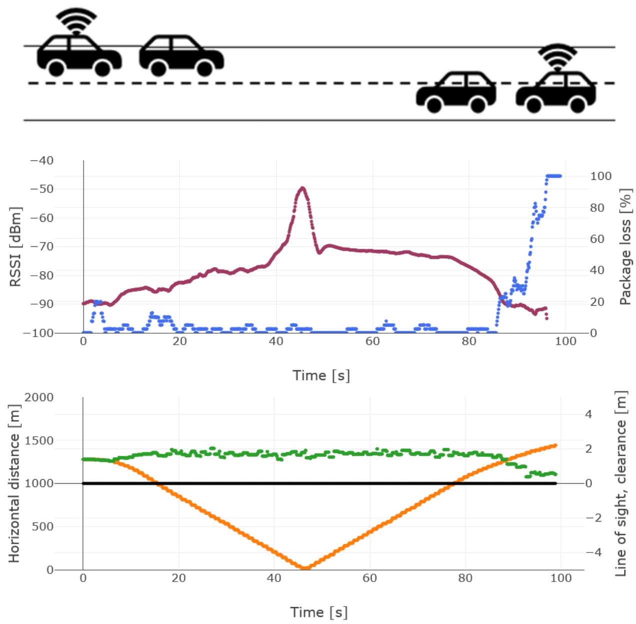

FIGURE 3. Two-lane road, shadowing traffic (scenario 3). Shadow imposed by two passenger cars in front of each communicating vehicle. Upper plot: RSSI (red) and package loss (blue). Lower plot: horizontal distance between vehicles (orange), and LoS clearance (green/black).

A. TWO-LANE ROAD, LOW DENSITY TRAFFIC

Figure 2 shows the results from baseline scenario 1. In this scenario there is no vehicle shadowing the communication, emulating no other traffic than the two communicating vehicles. Non-LoS occurs only because of the terrain. In the top plot RSSI (red) and package loss (blue) combining data from both OBUs are shown.

In Figure 2, we see RSSI decreasing with increasing distance between the OBUs, and that package loss is present for RSSI values lower than about −90 dBm. Some LoS shadow due to the runway height profile, or close to shadow, is seen at the end of this scenario, contributing to the increase in package loss when approaching 80 s. At the end of the scenario, LoS is restored, and RSSI and package loss are temporarily increasing and decreasing, respectively. See also Figure A.1 for scenario 2 in the supplementary material, where a similar pattern is observed.

As observed on the plot, the RSSI is slightly higher when the vehicles are driving towards each other, than when they are driving away from each other. This is also seen in scenario 2 (again Figure A.1), the other scenario without any communication shadows. There might be several explanations for these observations, the most probable being the antenna radiation pattern being slightly disturbed when the antenna is mounted atop the vehicle rooftops (approximately independent of directing in specifications of antenna), a known and studied effect [38].

In this scenario we observe the highest RSSI value (about −50 dBm) when the vehicles are passing each other, with a dip right before and right after the passing of the OBUs. These dips are also consistently present, and likely to stem from interference due to signal reflection on the ground and are to be expected in these tests [39].

B. TWO-LANE ROAD, SHADOWING TRAFFIC

In the second pair of scenarios, one additional passenger vehicle (without an OBU) where driven in front of each vehicle with OBU, which were expected to disturb the communication before the vehicles pass each other. In Figure 3, this hypothesis is strengthened, as the vehicles clearly need to be much closer to each other to reach higher RSSI values compared to the baseline scenario in Figure 2. For the package loss parameter, the influence of the extra passenger vehicles is not as clear, although in scenario 4 (Figure A.2 shown in the supplementary material) we observe larger periods with no signal (100% package loss), which may be caused by the communication shadow.

Turning to the scenario where a heavy vehicle is driven in front of OBU B, we see in Figure 4 an even stronger decrease in RSSI compared to the scenario with the passenger vehicles.

In this scenario, the vehicles must get as close as 150 m from each other before RSSI goes above −75 dBm, but then the OBUs shortly afterwards get LoS on the side of the heavy vehicle, and the RSSI increases quickly. We also observe a very high package loss in this scenario when the vehicles are far away from each other and hidden behind the heavy vehicle. Package loss is significantly higher in this scenario than the previous ones, and reasonably seems to be highly correlated to the low RSSI values. The results here are strengthen by the high-speed version of this scenario (scenario 6 shown in Figure A.3 in the supplementary materials).

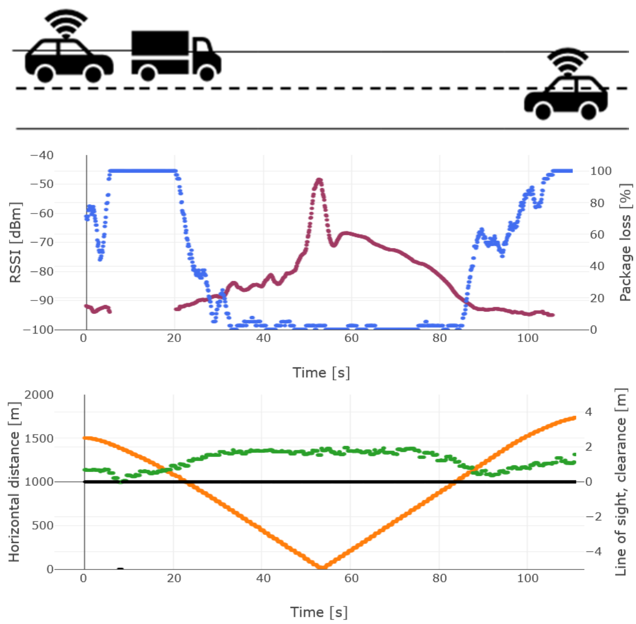

FIGURE 4. Two-lane road, shadowing traffic (Scenario 5). Shadow imposed by one heavy vehicle driving in front of vehicle with OBU B. Upper plot: RSSI (red) and package loss (blue). Lower plot: horizontal distance between vehicles (orange), and LoS clearance (green/black).

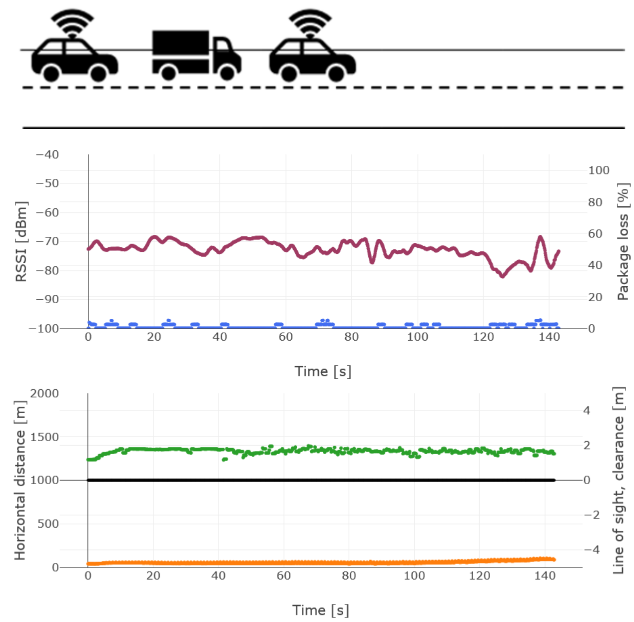

FIGURE 6. Two communicating vehicles vehicle-following (Scenario 8), with shadow imposed by a heavy vehicle driving between the vehicles. Upper plot: RSSI (red) and package loss (blue). Lower plot: horizontal distance between vehicles (orange), and LoS clearance (green/black).

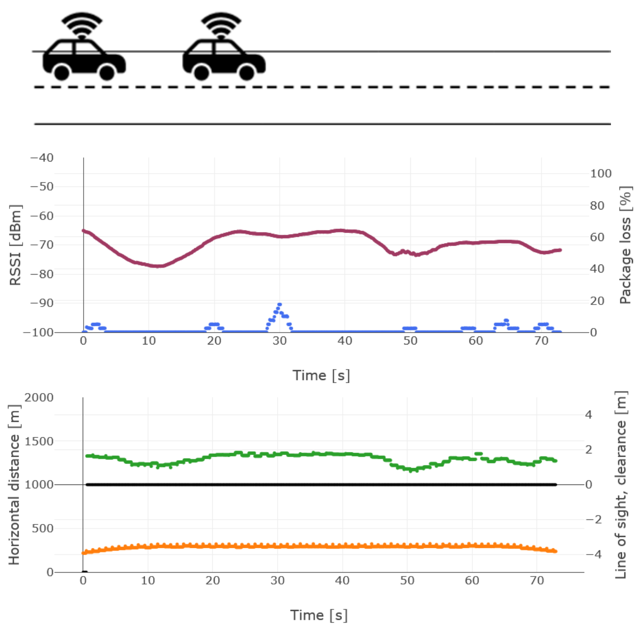

FIGURE 5. Two communicating vehicles vehicle-following (scenario 7). No imposed shadow between vehicles. Upper plot: RSSI (red) and package loss (blue). Lower plot: horizontal distance between vehicles (orange), and LoS clearance (green/black).

C. VEHICLE-FOLLOWING

In the vehicle-following scenarios the vehicles are driven closely behind each other, emulating following traffic. The baseline situation, scenario 7, is shown in Figure 5.

In the scenario displayed in Figure 5 the vehicles are driven approximately 250 m apart from each other, giving RSSI values varying between −77 dBm and −66 dBm, which corresponds very well to the RSSI values reported for these two distances in the baseline scenario 1 in Figure 3. It is worth noting that the two dips in RSSI value corresponds well with the dips towards closeness to non-LoS (green), indicating again that even close to non-LoS situations affects RSSI values. Package loss seems stable at low values for this scenario with, to us, an unexplainable slight increase around the 30 s mark with about 15-20 % loss. There was not conducted a high-speed case of this scenario.

For the next pair of scenarios, the vehicles drove the length of the runway with the heavy vehicle in between. In scenario 8 (Figure 6), the two vehicles were driven significantly closer to each other than in Figure 5, about 40 - 60 m. Moreover, in scenario 1 (without any other vehicles), an RSSI value close to −50 dBm and zero package loss was observed at this distance. In this scenario, however, we see that the RSSI value vary between −69 to −75 dBm when the vehicles are driving at a steady pace and constant distance from each other. Except from a sharp increase in packages loss at about the 30 to 40 s mark for scenario 9 shown in Figure A.4 in the supplementary material (60 % loss at most), almost all packages were constantly received during both scenarios.

D. MULTILANE ROAD

In these scenarios the vehicles were driven in parallel with the heavy vehicle between them, i.e., all three vehicles were driven on a straight line that was perpendicular to the driving direction. In these scenarios it was possible to drive even closer to the heavy vehicle than in the previous scenarios, and distances from 10-20 m were registered. In scenario 10

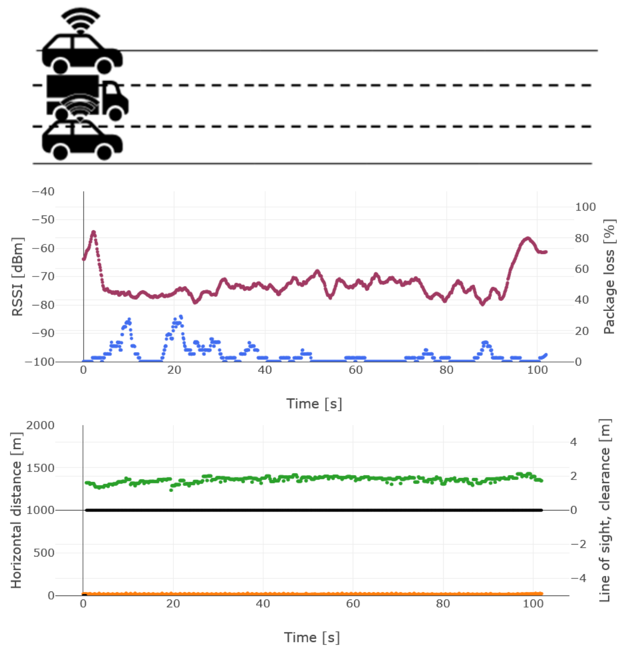

FIGURE 7. Driving in parallel (scenario 10) with a heavy vehicle in the middle position as shadow between communication vehicles. Upper plot: RSSI (red) and package loss (blue). Lower plot: horizontal distance between vehicles (orange), and LoS clearance (green/black).

(Figure 7) we observe RSSI values varying between −70 to −77, which corresponds well with the findings in Figure 6. All three scenarios, including the one in the supplementary material, indicates that driving with a heavy vehicle between communicating OBUs reduce RSSI from about −50 dBm down to −70 to 75 dBm. With respect to package loss, the scenario presented in Figure 7 show some areas of the tests with losses up to 25 %, slightly higher than observed in Figure 6, indicating that closer driving to the heavy vehicle might increase the package loss. It can be argued that when driving in parallel the area that the heavy vehicle occupy between the communicating OBUs are larger than when driving in sequence.

IV. DISCUSSION

The first aim of this paper was to identify whether ITS-G5 can be a reliable communication link for V2V communication in realistic traffic situations. The second aim was to describe which implications the results have for practitioners working with the future implementation of CAVs. Turning back to the proposed research questions in Section I.C, we now review our findings, and explain what the implications of these findings are.

A. RESEARCH QUESTION 1

Our first research question asked how vehicle speed affect ITS-G5 communication, and our scenarios document that neither RSSI nor package loss was significantly impacted by vehicle speed. This was observed through all pairs of scenarios where the only difference was vehicle speed. For RSSI and package loss, this finding is in line with radio theory, where speed does affect the wavelength of the received signal (doppler effect), but should not affect RSSI and package loss, as studied here.

1) RESEARCH QUESTION 1: IMPLICATIONS FOR POLICYMAKERS AND PRACTITIONERS

The findings made concerning research question 1 indicate that when planning and designing the roads of the future, considerations of speed limits and relative speed differences between vehicles is not important for successful V2V communication. This has implications for C-ITS services that operate on roads with high speeds, such as traffic flow stability and efficiency at high-speed intersections [12]. Hence, ITS-G5 technology would provide reliable communication for such services, regardless of the speed of the vehicles. This argument was also strengthened by the observed low latency.

B. RESEARCH QUESTION 2

For research question 2, we asked at what distance does ITS-G5 provide sufficient communication for V2V given LoS (no terrain or other vehicles shadowing the communication). From our data it is possible to estimate that in this case the operational range of the OBUs we used is about 1.2 – 1.4 km. This results from visually inspecting relevant LoS situations in scenarios 1-6. As radio shadow from other vehicles does not apply when the vehicles are driving away from each other, all of these scenarios have periods of direct LoS between the vehicles.

1) RESEARCH QUESTION 2: IMPLICATIONS FOR POLICYMAKERS AND PRACTITIONERS

The findings made when answering research question 2 indicate that when planning for new or changing existing road infrastructure, these distances should be taken into consideration. For instance, road planning should to a large extent secure sufficient LoS on road segments approaching critical road infrastructure such as intersections. Securing LoS for V2V communication at short and middle range distance could be an important traffic safety measure as vehicles are becoming increasingly connected. With the possible emerging technology of VANETs one can argue that in denser traffic connected vehicles will facilitate lower requirement on the volume of roadside infrastructure assisting ITS services such as vehicle location, speeds, and other "see-through" services [40]. Either way, knowledge of the range of different communication technologies is key both for planning the ITS service, and for planning roads of the future.

C. RESEARCH QUESTION 3

Our third research question asked how radio shadow from surrounding traffic affects ITS-G5 communication, and our measurements have shown a clear indication that LoS, and particularly shadowing traffic significantly impacts V2V ITS-G5 communication. At all distances (close, mediate and up to 1.4 km) the RSSI value is lowered significantly once the LoS is sufficiently weakened, and there is an increased risk of significant package loss when introducing other traffic that shadows radio link between vehicles. Our results also indicate that heavy vehicles possibly affect these parameters more, for example by comparing scenario 3 with scenario 5. Naturally, taller and longer vehicles, such as trucks, increase the area shadowing the signal between the OBUs and therefore decrease signal strength and increase package loss compared to smaller passenger vehicles. Also, the material of the truck body is expected to affect these parameters.

1) RESEARCH QUESTION 3: IMPLICATIONS FOR POLICYMAKERS AND PRACTITIONERS

The answer to research question 3 indicates that the level of heavy vehicles expected to be travelling on a road should be considered when planning for V2V communication. One should also consider the effect of the heavy vehicles itself communicating with V2V, a rather probable scenario, which to some degree lessen the need for this consideration. VANETs, spontaneous local networks of communicating vehicles and infrastructure, are envisioned to be the preferred implementation, solving the challenges of shadowing vehicles by establishing radio links with the shadowing vehicle or infrastructure that can route the signal around the shadow. While VANETs ideally can solve these problems, we argue that there will still exist challenges such as non-communicating vehicles for the overseeable future. Realistic scenarios including VANET functionality should be further investigated with experiments like the ones presented here to learn and documents its strength and weaknesses.

D. THE POLITICAL CHALLENGES OF V2V COMMUNICATION: WHAT IS NEXT?

A major challenge for practitioners working with communication for automated vehicles is dealing with uncertainty [41]. When road authorities build new infrastructure and conduct larger maintenance projects on current roads, the expected lifetime is typically decades. Implementation of new communication technology for automated vehicles may be held back due to uncertainties: Transport authorities will not spend money on costly infrastructure if they are not certain that this infrastructure will be used by vehicles and contribute to a safer, more efficient and less polluting transport sector. ABI Research has for instance estimated that there will be 41 million 5G connected vehicles on the road by 2030, rising to 83 million by 2035 [42]. Such rapid progress in technology represents a challenge in terms of knowing how to prepare the physical infrastructure to an unknown future [43]. Uncertainty is increased by the fact that the transport sector is also dependent on technological advancements in other sectors [44]. Until now, the transport sector has primarily operated in ‘‘siloed approached’’ [45], but this may be about to change.

There is also the question on whether policymakers and practitioners should take a strong position in this question, or if they should leave it to the marked. An argument in favour of taking a strong position is that realisation of the societal benefits of CAVs may require policymakers to pave out a way forward in terms of which solutions will realise most benefit for the users and society at large. Another argument could be that policymakers should engage in this debate to be better prepared for the future when building new roads. If roads built today can be adjusted to the need of the future, this may give a huge economic benefit later.

A priority in the way forward, should therefore be to reduce uncertainties related to technological maturity and the technology’s place in the socio-technical transport system. Based on the results from this study, an approach for doing relevant testing and pilot activities that will give practitioners insight into the uncertain future is suggested. The process of executing this trial involved discussions within the project group, the execution of the experiments, and the discussions afterwards in interpreting the results. The whole process was executed in close collaboration with researchers, practitioners, and OEMs. Furthermore, the research group have background from many different disciplines, including radio science, traffic engineering, social science and computer science. This illustrates the complexity of communication for CAVs. Even though such processes might require considerable time and effort, it is a dialogue that is necessary. This approach, where different stakeholders and disciplines meet and collaborate, helps build down ‘‘the existence of siloed approaches to managing transport’’ [45], which is needed for realization of the expected positive societal effects of automated vehicles.

Solving issues related to future need for communication for the transport sector will require collaboration among many different stakeholder groups [21], including practitioners, researchers, and OEMs within both the vehicle industry and within communication infrastructure, for instance when considering a future with VANET implementation. Governments around the world are starting to execute large-scale pilot activities testing V2V technology. For instance, in the US the Department of Transportation (US DOT) invested more than \$45 million into pilot activities of DSRC technologies to promote V2X innovation by merging research and practical engineering [46]. Such efforts will be important in the years to come to gain knowledge about the possibilities and challenges of communication technology. The US DOT highlights experiences in the Tampa pilot enabling ‘‘a close-knit relationship where problems could be openly discussed’’ [47].

Our findings give further support to the experiences of the US DOT. For instance, in the experiments we see that considerable small details affects the quality of the V2V communication service, such as the existence and size of shadowing vehicles, loss of LoS (or poor LoS) due to the terrain, or the antenna radiation pattern being altered by the vehicle roof. Technologies are often much more complex when they are moved out of laboratories and into a real-world environment, and applications may not be as mature and ready to deploy as suggested [47]. Thus, it is of high importance to understand how communication technologies function in the complex socio-technical system which the transport system represents [48]. This requires more knowledge on not just the technology, but also on the technology's place in society.

The result from our trial highlights the need to increase the coordination between the transport sector and the communication community, due to for instance the large impact of shadowing vehicles. At the same time, the process with the Delegated Act in Europe, and the process in the US where the 5.9 GHz band was opened for other purposes than transport, both demonstrate that political actions on the issue of transport and communication are delicate. Understanding the "who, what, and why" within the policy domain is important for understanding the barriers and opportunities for policy change, as well as the stabilities of policies over time [9]. The rejection of the Delegated Act serves as a good illustration of this point. After the rejection, the policy domain has been filled with a vacuum within the EU system. There is also a strong need for standardization processes, which are necessary for avoiding proprietary national solutions, particularly in the EU where policies and solutions are addressed across national boundaries [24]. More technical testing is also needed to identify specification flaws, design flaws, and implementation defects in the life cycle of the technology, as well as evaluations of the security threats [8].

V. CONCLUDING REMARKS

In this paper, we have operationalized the concept of V2V communication through a series of controlled experiments involving measurements from onboard communication devices in moving vehicles. Turning to our first identified research gap, concerning whether ITS-G5 can be a reliable communication link for CAVs, we can conclude that although ITS-G5 has high risk of reduced radio link in non-LoS and radio shadowing traffic situations, the latency and operational range of radio links would be sufficient for safety critical services in LoS situations. The results indicate that the ITS-G5 technology has some limitations, especially for long range communication (>1500 m), and in cases with traffic shadowing. In non-LoS and radio shadowing traffic situations, a VANET integration of ITS-G5, possibly in a hybrid solution with other technologies, could provide a functional communication environment for the future transport sector.

Our second research gap aimed at describing what the implications of the results from the analysis are for policymakers and practitioners working with the future implementation of CAVs. Therefore, in addition to providing domain interpretation of domain specific radio communication experiments, we interpret the results in light of what the results imply for these stakeholder groups. We argue that the rejection of the Delegated Act in the EU system, and the split of the 5.9 GHz band in the US, highlight the need for practitioners to understand more about communication technologies such as ITS-G5. If not, it is challenging to know whether CAVs will deliver the promised positive societal impacts including safety and reduced emissions. Understanding the complex socio-technical system where communication for transport is located, an integrated approach for research may be needed. Transitioning the transport sector to zero-emission is another research field which has taken considerable steps towards an integrated approach where technology and social sciences meet, often referred to as socio-technical analysis [49]. This is an avenue that may be a promising approach also for research on the transition towards an automated and connected transport system.

Given the expected increase in complexity and diversity of vehicle communication, on the path to a future situation with full penetration of autonomous vehicles, framing experiments in realistic transport situations is another issue that should be highlighted. Although some contributions are provided in our study, a number of interesting follow-up studies could be mentioned. Firstly, we propose that the range limitations of ITS-G5 communication using roadside units should be investigated. A strategical placement of equipment at critical terrain shadowed spots or at low density traffic roads could mitigate the range limitations of ITS-G5. Secondly, experiments focusing on the impact of heavy vehicle shadows in more complex scenarios should be performed. Thirdly, more realistic experiments including VANET solutions utilizing different communications technologies should also be of high priority. These are all examples of contexts that are highly interesting for investigating the ability of ITS-G5 to be a successful communication technology alone or together with other technologies such as 5G solutions, and in particular the device-to-device communication functionality included in this emerging technology [50]. While communication in transport has been characterized by competing technologies, we argue that the larger benefit would only be realized when the technologies are not seen as competitors, but as supplements.

Although physical experiments are valuable for providing measurements, the increased cost and size when involving more complex situations will at some point favor desktop simulations. However, this require radio wave propagation models to be sufficiently accurate in high density traffic situations. Therefore, we encourage more research on this topic as well.

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