IEEE Access
Multidisciplinary ⁝ Rapid Review ⁝ Open Access Journal

Received 21 February 2023, accepted 12 March 2023, date of publication 23 March 2023, date of current version 30 March 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3260980

APPLIED RESEARCH

Hybrid Vehicle-to-X Communication Network by Using ITS-G5 and LTE-V2X

JOCHEN STELLWAGEN[1], MATTHIAS DEEGENER[2], AND MICHAEL KUHN[3], (Member, IEEE)
[1]Frankfurt University of Applied Sciences, 60318 Frankfurt, Germany
[2]Department of Computer Science and Engineering, Frankfurt University of Applied Sciences, 60318 Frankfurt, Germany
[3]Department of Electrical Engineering, Darmstadt University of Applied Sciences, 64295 Darmstadt, Germany

Corresponding author: Jochen Stellwagen (jochen.stellwagen@fb2.fra-uas.de)

ABSTRACT Vehicle-to-X communication enables vehicles and other road users to exchange information in order to increase traffic efficiency and safety. All participants build a decentralized ad hoc network that can operate without the need for additional communication infrastructure. Two competing transmission technologies are available for this purpose. The WLAN-based approach ITS-G5 and the cellular-mobile-based LTE-V2X both enable the direct exchange of information between participants. Each of these technologies has individual advantages and disadvantages that recommend a specific technology for specific use cases. The hybrid usage of the two technologies in a common network can help to improve the reliability of transmissions for safety-critical applications by providing suitable transmission features for every use case, including dissemination range, latency, and channel throughput. The proposed hybrid V2X network approach provides participants with various options for selecting the transmission path to better adapt to the requirements of the specific use cases. The investigation is based on measurements of the transmission properties of ITS-G5 and LTE-V2X in real traffic environments as well as on simulations of hybrid V2X networks in a combined simulation environment for traffic and communication behavior. An important part of this investigation is the development of suitable dissemination models that describe the transmission behavior of both technologies. Initial results show that both technologies can be constructively combined to improve the reliability of communication for safety-critical applications in decentralized V2X networks.

INDEX TERMS Hybrid vehicle-to-X, ITS-G5, LTE-V2X, V2V, V2X, VANET.

I. INTRODUCTION TO VEHICLE-TO-VEHICLE COMMUNICATION

Vehicle-to-vehicle communication and communication between vehicles and stationary equipment as part of a communicative infrastructure offer the opportunity for information exchange that enables individual participants to complement and harmonize their individual knowledge [1]. On the vehicle side, this extension of the own sensor range enables an improvement in the perception of the environment. Conflicts with other road users can be detected earlier and resolved if necessary. The infrastructure that is connected to traffic control centers or traffic lights, for example, benefits from a more holistic perception of the traffic situation and consequently the possibility of more targeted traffic control [2].

Information generated by the vehicles goes far beyond the so-called "live traffic data" provided by map services. This traffic data is either based on the cell phones of the vehicle occupants or the location function of the route planning software used. This does enable trends, such as high traffic volumes, to be identified. While this is significantly better than the TMC system based on police reports, it cannot identify the causes of traffic incidents. By using vehicle data and special messages, causes (e.g., a broken-down vehicle) can also be transmitted.

Vehicle-to-Vehicle communication, or V2V for short, as well as Vehicle-to-Infrastructure communication, or V2I, use the same communication technologies and form a common network. Both aspects, Vehicle-to-Vehicle and Vehicle-to-Infrastructure, are therefore also denoted as Vehicle-to-X,

The associate editor coordinating the review of this manuscript and approving it for publication was Barbara Masini.

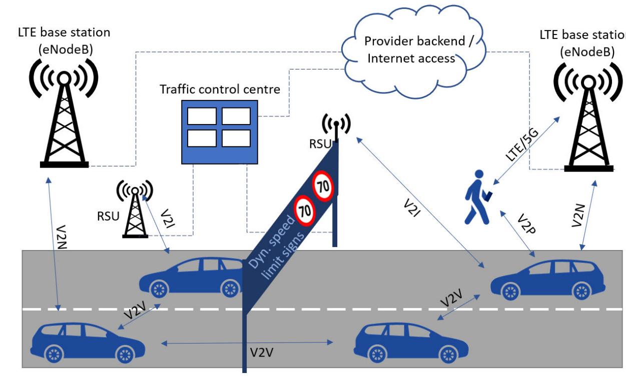


FIGURE 1. Overview about the V2X network structure.

or V2X for short [2]. In addition to the term V2X, the terms Car-to-X and C2X are also used in Europe [1].

Vehicles, as mobile participants, which represent the majority of the endpoints in the communication architecture, build a dynamic network that is characterized by permanently changing members. The mutual relevance for the exchange of information is time- and location-dependent and can therefore increase and decrease with the movement of the vehicles. The participants consequently form a dynamic ad hoc network, which is also known as Vehicular Ad hoc Network (VANET) [3](Figure 1).

The use case of data exchange between vehicles and between vehicles and infrastructure places certain requirements on the technologies to be used. In order to achieve a reliable exchange of information, which is particularly necessary when using the information for safety-critical driving functions, it is necessary to ensure, among other things, a sufficient communication range for an acceptable perception, a low delay for fast dissemination, and a sufficient data transmission rate for all participants [4], [5]. Safety-critical applications are those that have a direct impact on road safety. This includes collision avoidance by improving mutual perception as well as warning of local hazards such as obstacles on the road or accidents.

Furthermore, the functionality shall not be restricted even at higher vehicle velocities [5]. Security mechanisms, such as the signing and authenticating of messages, must ensure the integrity of the message content to prevent misuse [6], [7].

For Vehicle-to-X communication, there are two relevant communication technologies that can be used separately or in parallel and in different architectural approaches. One technology relies on WLAN-based direct communication between participants; the other approach uses a cellular mobile communication standard for data transmission. Both approaches are first presented in the following section, followed by a discussion of hybrid use.

A. WLAN-BASED V2X COMMUNICATION

The basis for reliable data exchange between road users and transport infrastructure in Europe is the ITS-G5 standard, which is based on the IEEE 802.11p WLAN standard. The standard describes the network access (OSI model layers 1 and 2) of the V2X systems in a local, dynamic ad hoc network [8]. The communication here takes place in a frequency range of 5.9 GHz, with seven radio channels available, each with a bandwidth of 10 MHz [9]. But not all of these channels are intended for safety-critical applications [10]. Three channels can be used for safety-related use cases, two for non-safety-related use cases, and another two for future use cases (Table 1).

TABLE 1. Usage of the V2X channels defined for Europe in ETSI EN 302 571.

Frequency range	Usage
5855 MHz to 5875 MHz	ITS non-safety applications
5875 MHz to 5905 MHz	ITS road safety
5905 MHz to 5925 MHz	Future ITS applications

The further structure of the communication technology as well as the structure of the messages and their processing are described for Europe by various standards of the European Telecommunications Standards Institute and the European Committee for Standardization [11].

Communication for the dissemination of warnings in dangerous traffic situations and conflicts is primarily organized as a spatially limited broadcast without addressing individual recipients. The transmitter of messages does not necessarily require information about the surrounding communication partners. Recipients receive all messages within their range and decide for themselves whether they are relevant to their own situation based on the content. Two types of messages form the basis of the information exchange: the Cooperative Awareness Message (CAM) and the Decentralized Environmental Notification Message (DENM) [12], [13].

The CAM is sent by each mobile participant cyclically at intervals of 1 to 10 Hz and informs the immediate environment of its presence. Due to the position and driving dynamics data contained in the CAM, applications such as collision avoidance warnings can already be realized with the CAM alone [14].

The DENM is an event-based message that is only transmitted when a specific and defined hazardous situation arises. The message is repeated as long as the corresponding situation exists and can be perceived by the detecting participant. This type of message may be forwarded by receiving participants to enable distribution beyond the direct radio range [13].

In addition, there were a number of other message types for special applications, such as the transmission of signal information from traffic light systems or road topology, for example, to the vehicle [2].

A direct addressing of individual participants in the form of a unicast is also possible and may be of interest for applications like maneuver coordination between highly automated vehicles, where the message content is only relevant for specific participants [1], [11].

The European ITS-G5 standard and the corresponding North American DSRC (Direct Short Range Communication) standard for WLAN-based communication have already been intensively investigated for the planned market launch in the countries concerned, supported by national and international research projects [15]. WLAN is characterized by low latency and sufficient availability at shorter ranges. Conversely, restrictions occur when there are longer distances between participants and when there is a high volume of communication on the channel [16], [17]. The respective quantitative characteristics are highly dependent on the respective application as well as the communicational and environmental conditions [5], [11], [17]. While, for example, the collision avoidance requires a low latency caused by the short distances between the vehicles, an event-based weather warning is, to a large extent, dependent on a large transmission range.

B. CELLULAR MOBILE COMMUNICATION

Communication via a cellular mobile data service is the second alternative to exchanging data. Current standards such as LTE 4G and 5G use mainly the Internet Protocol to transmit any content [1]. The required hardware is already often present in vehicles and integrated into the system architecture [3], [18]. The legal requirement to introduce eCall (emergency call) in all newly developed vehicles means that vehicles need to be connected to mobile cellular communication within the European Union [19].

However, the existing cellular mobile network does not support direct information exchange between individual vehicles in the immediate vicinity or to a neighboring infrastructure, such as a traffic light system. Participants are connected to the base stations of their respective providers and do not know the other participants in their environment, which means they are unable to address them directly. The use of a broadcast is not intended for individual participants here. In order to exchange information, participants would have to send their traffic and safety-related data to a central backend. Here, the incoming information is evaluated, summarized if necessary, and made available in a database. Other participants must now actively request all data for their current environments from this backend. In contrast to direct communication, the path from one vehicle via the infrastructure of the mobile network providers to a backend and back to another road user is significantly longer. The resulting latency is a problem, especially for time-critical applications. Since critical information has no priority during transmission and the communication path to the backend varies, the delay is also only predictable to a limited extent [11], [20]. Furthermore, there is a dependency on an infrastructure, which can also be owned by different providers.

Since 2015, however, another approach to mobile communications has been available. The 3rd Generation Partnership Project (3GPP) is a cooperation of national and international standardization institutes working on the further development of mobile communications standards [21]. Since Release 12 of the 3GPP, device-to-device communication has been introduced based on the LTE technology, which supports direct communication between participants even without the availability of base stations. In Release 14, among other things, the use case of direct data exchange between vehicles is considered [10], [22], [23], [24]. The term LTE-V2X describes the requirements and use cases for LTE-based V2X communication [23].

Two operating modes are available for LTE-V2X. In Mode 3, the vehicles are within the range of an LTE base station, which handles the resource management for the radio channels that are used. However, the data exchange between the participants takes place directly via the so-called sidelink [25].

In Mode 4, no base station is available as a central component. Vehicles have to select the resources for transmission from their own resource pool, which has been provided beforehand [26]. The resources are divided into Resource Blocks (RB) as usual for LTE, which subdivide the available channel by time and frequency range [27].

LTE-V2X provides the usage of broadcasts for information dissemination in security-critical applications, as is the case with ITS-G5 [28]. This enables the local dissemination of information in a direct way without having to know the addresses of the surrounding participants. The sidelink now also enables the realization of time-critical applications [22].

By enabling the targeted usage of individual RBs and providing more flexibility in choosing frequencies, bandwidths, and modulation methods, LTE-V2X has the potential to adjust the available resources of the radio channel more accurately and efficiently to the respective situation than is possible with ITS-G5 [29].

The higher layers of the communication stack, including the message types and services, are not specifically defined for LTE-V2X and can be adopted from the WLAN-based ITS-G5 approach [22].

The cellular mobile-based approach can be used as an alternative to ITS-G5 in the 5.9 GHz frequency range. Parallel operation with ITS-G5 on different channels in this frequency range is also conceivable [21].

However, it is also possible to locate the LTE-V2X communication in one of the defined LTE bands. This option can be used to exploit the benefits of lower carrier frequencies in terms of range and reflection behavior.

Previous research found that flexibility in channel resource allocation resulted in more efficient channel capacity utilization, allowing for higher data throughput than ITE-G5 [30], [31], [17]. A problem is the RB allocation procedure, which may struggle with the high mobility in the V2X network [32]. In addition, LTE-V2X enables more flexibility in the selection of modulation methods, channel bandwidths, and available channels [33]. ITS-G5, on the other hand, shows advantages in terms of communication latency within the mobile ad hoc network, where transmission delays for both technologies are strongly dependent on the utilization of the radio channel [31], [34].

With 5G, 3GPP has already standardized the next generation of mobile communications to follow LTE. It is already in the rollout phase and is already available to users [35]. Vehicle communication with 5G is provided in 3GPP Release

16 [36]. 5G-V2X does not replace the existing standards for LTE-V2X but rather extends the functionality to new applications, such as supporting automated driving functions [37].

II. STATUS QUO

At present, there are only a few vehicles on the market in Europe that can exchange information independently over a common communication standard [38]. For the vehicle manufacturers, however, such a communication standard is a fundamental requirement for the introduction of highly automated driving functions [11]. The exchange of information between vehicles is essential in this context, among other things, for the coordination of driving maneuvers [11]. Automated vehicles need to be able to coordinate their respective intentions with other road users in order to achieve an efficient traffic flow.

With the WLAN standard according to ITS-G5 and the related, standardized protocols, a technology for cross-manufacturer communication is already available, which has also been investigated and evaluated in numerous research projects [11], [15]. However, the investigations showed that a high market penetration and a high number of road users in a region e.g., in urban areas, may cause problems with congestion on the communication channel, which threatens the reliable transmission of information [39]. In addition, the transmission range of ITS-G5 at 5.9 GHz is not always sufficient to inform all requested receivers, depending on the application and the respective situation [24]. Nevertheless, due to its positive characteristics in terms of low latency and the independence of base stations and cellphone providers, WLAN-based communication is the central component of safety-critical close-range communication between road users in Europe [1], [11]. Road infrastructure systems are already using this technology. In several European countries, traffic control and construction site warning systems are already equipped with such radio systems [11].

However, it has also been shown that ITS-G5 alone cannot meet all the requirements of the V2X use cases [34]. This applies primarily to safety-critical applications and the support of automated driving functions, as this is where particularly high demands are placed on reliability. The problems here are not only the overload of the radio channels by a large number of participants but also the provided transmission ranges [24].

LTE-V2X is a competing technology to ITS-G5, which serves the same purpose. In several countries, it is under discussion to realize a V2X network based on this technology [23]. However, even LTE-V2X cannot meet all requirements on its own.

III. HYBRID V2X COMMUNICATION

In order to better meet the requirements of safety-critical applications in terms of reliability, range and latency, and also to take into account future applications such as highly automated driving functions, a hybrid deployment of both transmission technologies is proposed.

The use of both technologies in parallel should not only result in increased redundancy, which again improves transmission reliability. Each technology has certain features that can be combined constructively to improve the availability of safety-critical information. The concepts for dynamic and situation-adapted distribution of the data flow are designed to reliably disseminate information about danger spots and possible conflicts between road users in order to increase road safety.

Reliable information transmission and decentralized network organization are particular challenges in highly mobile ad hoc networks with constantly changing participants. Distributing the flow of information across different communication technologies to ensure reliable data transmission, for example in the event of congestion on one of the channels provided, increases the complexity.

Even before the introduction of LTE-V2X, heterogeneous network structures for V2X communication were investigated. In this case, however, the communication technologies were statically linked to specific use cases. ITS-G5 and DSRC, respectively, were used for direct and time-critical inter-vehicle communications, while applications of a more informative and non-time-critical nature were able to exchange data over a standard cellular mobile connection via the mobile phone provider's infrastructure and associated backend [40].

Since LTE-V2X provides a second way of direct communication between V2X participants, approaches are also being investigated that consider heterogeneous usage of transmission technologies in a hierarchical network structure. The focus here is on clustering the vehicles into dynamic groups with the goal of controlling the flow of messages in the existing ad hoc network. For this purpose, each cluster has a cluster head that organizes the cluster as a quasi-central subnetwork and acts as an interface to other clusters. Communication within a cluster can be handled via one transmission technology, while the hybrid cluster head connects to the network outside its own cluster via another technology, thus acting as a cross-technology gateway [41](Figure 2).

The advantage here is a network architecture that can be implemented with a manageable number of hybrid vehicles.

The main difficulty in clustering is finding suitable clusters and their cluster heads. Due to the high mobility of the participants, the clusters always represent only a temporary grouping that has to be restructured again and again [42]. The organization of the clusters requires additional communication between the participants, which makes the use of clustering reasonable only if the benefits of the information dissemination for the cluster outweigh the disadvantages of the additional communication effort. For this purpose, stable clusters must be found. There are numerous concepts that try to find suitable clusters of vehicles as well as suitable cluster heads [43], [44], [41], [42].

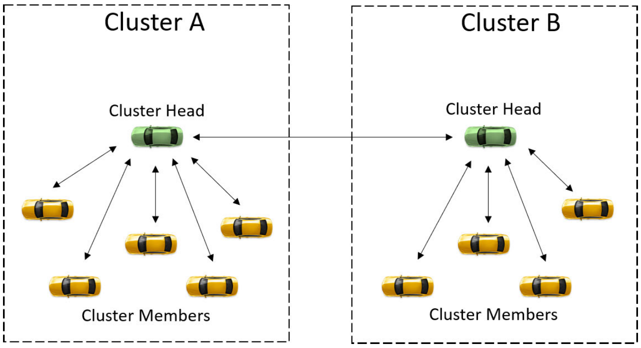


FIGURE 2. Example of Clustering in hybrid V2X network.

Another difficulty with this hierarchical approach is the shift from the previous broadcast approach of the two technologies to a targeted addressing of participants, which is now provided by the structure of the cluster. This means that the flow of information may have to follow the cluster structure over several steps, even if a more direct transfer between participants in different clusters would have been possible due to distance. This can become a problem due to the delays, especially in time- and safety-critical applications. In addition, the higher number of individual messages compared to the broadcast approach may also increase the local utilization of the radio channel.

IV. DIRECT COMPARISON BETWEEN ITS-G5 AND LTE-V2X

In the process of our investigations, measurements were made to determine the transmission properties of ITS-G5 and LTE-V2X in direct comparison. For this purpose, different locations in the real traffic area were selected, which represent different types of traffic and environmental conditions. These included different urban situations in inner cities and peripheral urban areas as well as scenarios on highways and rural roads.

The aim of this study was to determine and compare the environmental and situation-dependent transmission properties of the two technologies. In addition, the results should be used for the creation of transmission models to be used in subsequent simulations to investigate larger and more complex situations involving a large number of road users.

It is crucial that the measurements are not limited to the physical layer and link layer, but also include the overlapping technology-specific protocols. These have a direct influence on the transmission behavior of the systems in real traffic environments and must therefore be taken into account.

This approach makes it possible to compare the results of the measurements in terms of range and latency directly with the requirements of safety-critical applications. For hybrid stations that support several transmission technologies, it is crucial to be able to predict the characteristics of the individual technologies in the respective situation and to be able to compare them with the individual requirements of the active application case.

FIGURE 3. Measurement system with vehicle and stationary module.

TABLE 2. Properties of the V2X communication technologies for measurements.

Description	ITS-G5	LTE-V2X
Transmission frequency	5.9 GHz	5.9 GHz
Bandwidth per channel	10 MHz	10 MHz
Subcarrier-Modulation	OFDM	SC-FDMA
Modulation	QPSK	QPSK
Max. Transmission Power	23 dBm	23 dBm
Channel access	CSMA/CA	SB-SPS

Two radio systems per transmission technology were used for the measurements. One system was used stationary, while the second was installed in a vehicle (Figure 3). The vehicle was driven on roads in the vicinity of the stationary system. Both systems continuously sent CAM messages, including the position data of the systems. By recording the transmitted and received messages in both systems, position-dependent packet loss rates and latency times could be determined.

For the configuration of the systems, the parameters of both technologies were selected to be as comparable as possible. These are shown in Table 2.

As part of the measurement campaign, 29 measurement scenarios were carried out at 8 different locations. In total, more than 200000 transmitted messages were recorded during the measurements. Thus, a comprehensive database is available to compare the two technologies directly in different environments and under different system configurations.

Figures 4 and 5 show a direct comparison of the results for both technologies using the example of a scenario in the city center of Frankfurt, Germany. Here, as with the other scenarios, LTE-V2X already showed an advantage in terms of transmission range when used in the 5.9 GHz frequency range. In the area of line-of-sight communication, this range advantage was up to 200 meters. However, as the results of other studies already suggested, the latency of LTE-V2X was also significantly higher than that of ITS-G5. Here, the advantage of ITS-G5 was up to 30 milliseconds. The results were consistent across all measurements.

The results of the measurements regarding the location-dependent packet loss rates can be used to derive dissemination models for the two technologies. Two approaches were followed for the translation of the measurement data into a

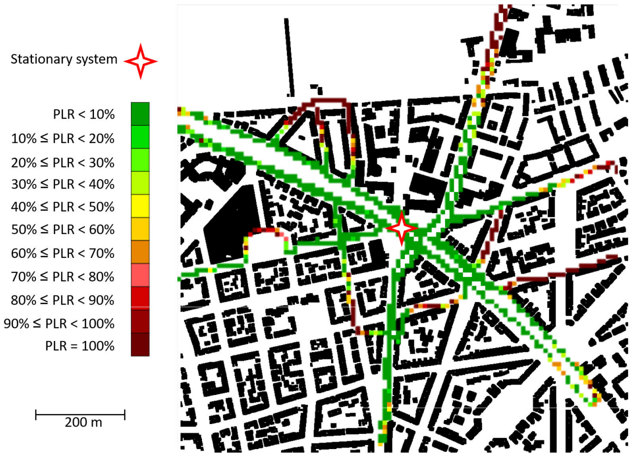


FIGURE 4. Measurement of ITS-G5 packet loss rates (PLR) in the city center of Frankfurt/Germany.

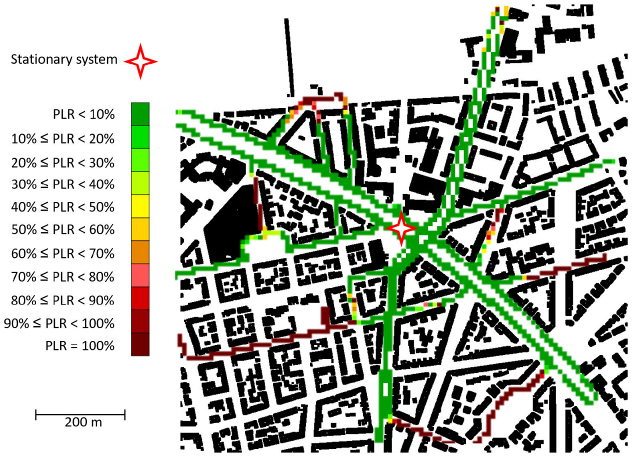


FIGURE 5. Measurement of LTE-V2X packet loss rates (PLR) in the city center of Frankfurt/Germany.

model, which can be used in a simulation to realize larger scenarios.

V. MODEL BUILDING

The desired channel models are to be characterized by parameters that can be directly compared with the requirements of V2X use cases, depending on the respective situation. The models should make it possible to determine the transfer behavior of the ITS-G5 and LTE-V2X technologies in specific situations and environmental conditions and thus to determine whether the respective technology meets the requirements of a use case. This should make it possible to select the appropriate transmission technology in a hybrid V2X network for each application and situation.

Established stochastic models do not take environmental conditions into account to the extent necessary for the representation of transmission characteristics in a hybrid network. Complex deterministic models, which would allow a more precise description of a concrete situation, are too computationally intensive to be used in real time in a subscriber system for the selection of the transmission path. In addition, mobile subscribers generally do not have comprehensive information about the surrounding situation.

Models are needed that can be used by subscribers in the hybrid network to select the best transmission path in a specific situation, with the limited information available to these subscribers. The models presented here are intended to fulfill this requirement.

The transmission behavior is determined by the respective situation and environment as well as by the system configurations of the transmitter and receiver. System parameters such as transmit power, modulation methods, radio channel, and antenna selection can be influenced by the station and are therefore not the focus of this investigation for the time being. The system configurations were initially kept static, as described in Table 2. For the modeling, the dynamic conditions of the respective situation are in the foreground.

The situation dependence that is to be taken into account in the modeling includes, on the one hand, the dynamics of the participating V2X stations, such as the speed of movement, the direction of movement, and the distance between the participants. In addition, there are environmental conditions, such as buildings, vegetation, or geography, that can have a significant influence on the transmission. Such obstacles lead to shading and reflections of the emitted signals and are decisive for the prediction of the transmission behavior.

Weather conditions and other road users in the vicinity can also influence the transmission. In the underlying measurements, however, these effects were so small that they could not be clearly identified or quantified, so they were not initially taken into account in the modeling.

A suitable value for characterization is the situation- and environment-dependent packet loss rate (PLR). It is a measure of the successful transfer of information between participants and can therefore be compared with the reliability requirements of the respective V2X applications. The packet loss rates are calculated here by comparing the stored sent and received messages of the two systems. Situation-dependent transmission ranges can also be recorded directly from the results of the measurements and the packet loss rates.

Another decisive value for the assessment of the respective transmission is the latency. However, the measurements showed that the latency is not significantly determined by the environmental situation in which the transmission takes place. The decisive components of the latency between the facility layers of the sender and the receiver arise during the creation of the message at the sender and during the processing on the receiving side. The modeling of a situation- and environment-dependent latency on the basis of these measurement results seems not possible, especially since the tolerances in the measurement process of the latency are much larger than the expected delay of the radio signal. A high utilization of the radio channel, which should have an influence on the latency, could not be realized in the measurements and therefore cannot be taken into account for the modeling.

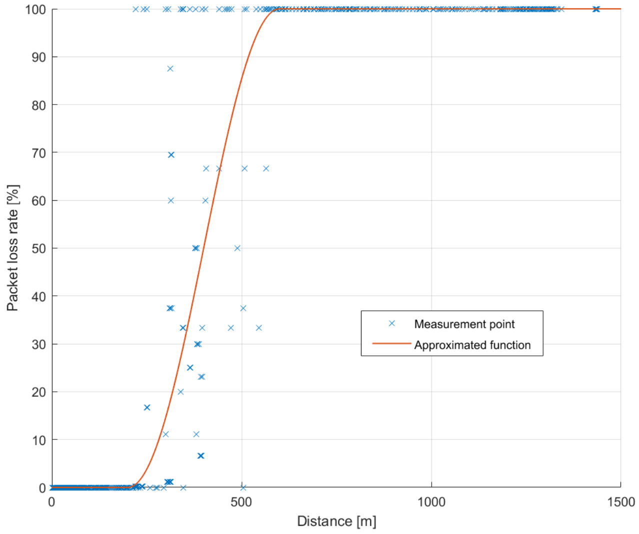


FIGURE 6. Distance-dependent packet loss rates in LOS situations for ITS-G5.

TABLE 3. Parameters to describe the approximated function for ITS-G5 and LTE-V2X.

	a	b	c	e
ITS-G5	50	π/408	225	50
LTE-V2X	50	π/196	-105	50

A. ANALYTIC APPROACH

In the analytic approach, the measurement results are first separated according to line-of-sight (LOS) and non-line-of-sight (NLOS) situations. The distribution of the measurement data according to certain parameters is possible since, during the execution of the measurements, it was ensured that only one parameter was changed between the individual measurement series. Thus, changes in the results of the measurements can be clearly attributed to certain parameter changes.

In LOS situations, the transmission is characterized by a non-covered main propagation path. Environmental conditions such as buildings and vegetation do not significantly influence the transmission. Thus, the transmission is primarily determined by the movement dynamics of the participants. In Figures 6 and 7, the packet loss rates of messages in LOS situations are displayed depending on the distance between the V2X systems.

In LOS situations, a curve can be approximated. This curve, again, can be represented in a mathematical function that describes the transmission behavior under the given conditions. The function can be parameterized for the respective technology (1). Table 3 shows the values that fit the measurement data best. The graphs for the respective functions are displayed as red lines in Figure 6 and Figure 7.

$$PLR(d) = \begin{cases} 100 & \text{if } d < c + b \\ a \cdot cos(b \cdot (d + c)) + e & \text{if } c \leq d \leq c + b \\ 0 & \text{if } d > c \end{cases} \tag{1}$$

In the case of NLOS, however, the transfer is largely determined by the nature and extent of the obstacles between the transmitter and the receiver. This applies both to the objects that block the direct line of sight and to the surrounding objects that allow the reflection of the signals. Figure 8 shows the distance-dependent packet loss rates for NLOS situations with LTE-V2X.

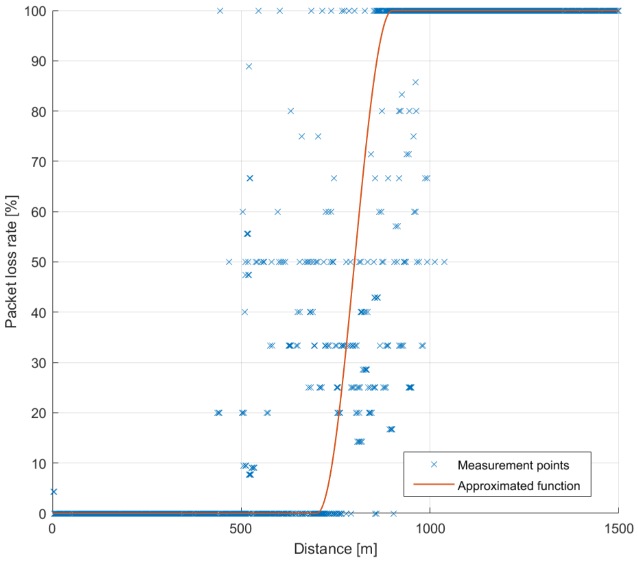


FIGURE 7. Distance-dependent packet loss rates in LOS situations for LTE-V2X.

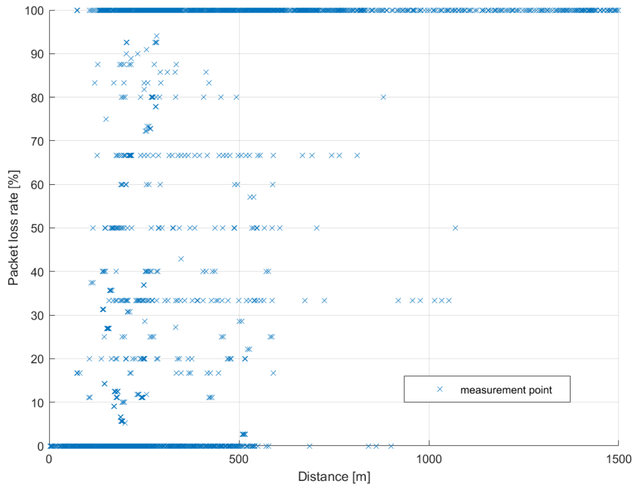


FIGURE 8. Distance-dependent packet loss rates in NLOS situations for ITS-G5.

It can be seen that no clear structure emerges without taking the environmental conditions into account. The data must be further sorted by the nature and extent of the surrounding conditions in order to obtain a more accurate representation, which can then be represented in a function.

This also demonstrates the drawbacks of using the WINNER model. This does not enable a more precise description of the environmental conditions for NLOS, which can lead to a significant mismatch between the calculated and measured values.

A challenge in modeling is to find a description of the environmental conditions that enables a sufficiently accurate representation of the transmission behavior, but is based only

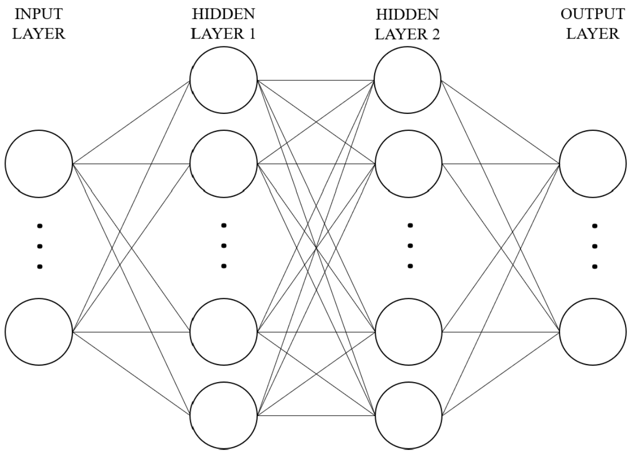


FIGURE 9. Structure of the neural network.

on data that is available to the participants. Only in this way can the models be used by the participants to determine the transmission behavior in the given situation and subsequently, to select a suitable transmission medium.

B. REPRESENTATION OF ENVIRONMENTAL CONDITIONS

The full complexity of the environmental conditions cannot be represented in the model. On the one hand, the information required for this is not available in this level of detail due to the constantly changing environment. On the other hand, a complex model of the environment would not enable real-time usage, which is made possible by the use of the stochastic approach.

The environmental conditions must therefore be represented by a model, which can be described with a very limited number of parameters. These parameters must be extractable from an available data set, such as a navigation map.

Such parameters are the general environmental situation, like urban or rural areas, the extent and nature of obstacles between the V2X stations, as well as expected dissemination paths around the obstacles.

C. NEURAL NETWORK

Another approach for determining suitable channel models is the use of neural networks (Figure 9). By preparing the measurement results into training data sets for neural networks, models can also be formed to describe the transmission behavior of the technologies in the respective situations. For this purpose, suitable input values have to be determined, which describe the respective situation with parameters for the transmission behavior. It must be taken into account that these parameters are also available to the subsequent target platform, such as a vehicle.

The parameters are composed of the environmental conditions, the movement dynamics, and the distance between the V2X stations. Here, also a suitable description of the static environmental conditions must be selected, which can be converted into input values for the neural network.

The neural network, which was used here, is intended to estimate the packet loss rate in a variety of traffic situations. The number of neurons in the input layer is based on the respective number of parameters. These differ in the various tests primarily due to different descriptions of the environmental conditions. The output layer consists of a number of neurons that are dependent on the requested resolution of the PLR. The neural network also consists of two hidden layers. Back propagation is used as a learning method, while the transfer function is realized with the Sigmoid function [45].

The data from the measurements in different environments was compiled to create an input data set. These records included both LOS and NLOS scenarios. The situation-dependent PLR is known for all the data. This data was used to train the networks.

Further measurement data, which was captured at other locations but also took into account a wide range of environmental conditions, was used as test data sets for the evaluation of the neural networks after the training phase.

D. RESULTS OF THE MODEL BUILDUNG

The aim of this investigation was to find a method to create a sufficiently accurate stochastic transmission model for the two technologies, ITS-G5 and LTE-V2X. These models are intended to enable a participant in a hybrid V2X network to determine the appropriate transmission technology for the transmission of its information. The results are evaluated against the measurement data from the real experiments as well as by comparing the analytic approach and the neural network.

In the analytic approach, it was possible to determine a mathematical description for the LOS situations of both transmission technologies, which can describe their respective behaviors. Since the transmission here is characterized by an uncovered main propagation pathway, it was possible to determine a function for each technology that enables a good approximation for all traffic areas.

By inserting the distance values from the measurements into the functions, PLR values were calculated, which again could be compared with the measured PLR values. For ITS-G5, the average deviation here was 3.56%. For LTE-V2X, the average deviation was 6.88%.

For the NLOS situations, it was not possible to define a mathematical description with a good approximation. By excluding the environmental conditions, the best approximations that could be achieved with a function had an average deviation of 29.98% for ITS-G5 and 33.29% for LTE-V2X.

Since the transmission in NLOS situations is determined by indirect propagation paths, characterized by reflections and shadowing, the environmental conditions play an important role here. The integration of these environmental conditions into a general function for each transmission technology was not possible on the basis of the measurement results.

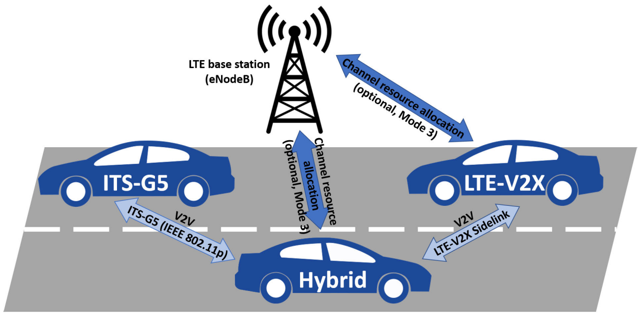


FIGURE 10. Hybrid non-hierarchic communication with ITS-G5 and LTE-V2X.

The determination of differentiated mathematical functions, which describe specific NLOS situations in different environmental conditions, is part of further investigations.

It was possible to create a common description for all situations for each technology by using neural networks to describe transmission behavior. By taking into account the environmental conditions, such as the nature and extent of the shadowing and possible reflection paths, a significantly improved description was achieved for the NLOS situations. For ITS-G5, the overall average deviation from the measured PLR values of the test data sets was only 5.17%, and for LTE-V2X, it was only 3.36%. The results included LOS and NLOS situations.

VI. INTRODUCED APPROACH FOR HYBRID V2X COMMUNICATION

The approach described here is based on a situation- and application-oriented dynamic usage of the two transmission technologies, ITS-G5 and LTE-V2X in a common network. The flat architecture of a decentralized ad hoc network already used by the individual technologies is to be preserved. In addition, broadcasting will continue to be used for the transmission of safety-critical information. This approach differs from previous approaches in terms of both its dynamics and its network structure (Figure 10).

The aim is to increase the reliability of information transmission by ensuring that messages are disseminated as widely and as quickly as necessary. On the other hand, the structure of the technologies used remains unchanged, which facilitates the expansion to hybrid communication.

Like the other hybrid approaches, this one depends on the number of participants that can support both technologies and thus act as an interface between them.

The choice of transmission path is determined by the availability of capacity on the radio channel in addition to the availability of the respective technologies for the transmitting and receiving vehicles. Furthermore, the requirements of the respective application are taken into account in terms of the required range and latency. The respective traffic and environmental situations must also be taken into account.

Table 4 shows some of the application-specific requirements that the respective transmission technology has to meet. Due to the different characteristics and performances of the technologies, a preferred technology can emerge depending on the application and situation. The relevant parameters to be derived from this are primarily the transmission ranges, the maximum permissible latency, the data rate, and the reliability of the data transmission as a resultant measure. The ETSI standards already provide limit values for individual groups of use cases [28], [46]. In addition to the requirements arising from the applications, there are also requirements in the area of data security, such as those regarding pseudonymization or authentication of messages, which are also already described in the standards [47].

TABLE 4. Examples of requirements for V2X use cases [37].

Use Case	Reliability	Max. Latency	Min. Range
Vehicle Platooning	99.99%	10ms	350m
Advanced Driving	99.999%	3ms	700m
Extended Sensors	99.999%	3ms	1000m
Remote Driving	99.999%	5ms	-

Another aspect that can be captured by this approach is the involvement of vulnerable groups away from vehicles, namely pedestrians and bicyclists. It is very unlikely that pedestrians will be on the road with an ITS-5G device in the foreseeable future, due to the lack of hardware support for the frequency range at 5.9 GHz. An LTE cell phone is currently used by over 80%, with the number of users steadily increasing [48]. By passing on position data and messages, vulnerable road users can both be detected by vehicles and warned by means of suitable apps. These apps can also support special scenarios and thus ensure an additional reduction of the hazard potential [49].

The objectives of this approach are summarized as follows:

- Avoidance of overload situations on the radio channel by splitting the communication over the available transmission technologies
- Improve the reliability of the transmission, particularly in safety-critical applications, by taking the requirements of the application and the specific situation of the participants into account
- Provision of redundancies and alternatives in the dissemination of information

The measurements also examined whether problems arise due to the coexistence of the two technologies in hybrid operation if they both operate in the same frequency range at 5.9 GHz. The usage of neighboring radio channels did not show any limitations or negative effects on the transmission behavior of the technologies. The interoperability of ITS-G5 and LTE-V2X in a hybrid network is thus given [50].

A joint use of both technologies on a common radio channel is excluded here, as the channel access procedures of ITS-G5 and LTE-V2X differ and a number of competing channel accesses can be expected. This increases the probability of message collisions, which in turn leads to higher packet loss rates. As the capacity of the concerned channel increases, it becomes increasingly difficult to find free resources and to use them successfully. For this reason, a joint use of a

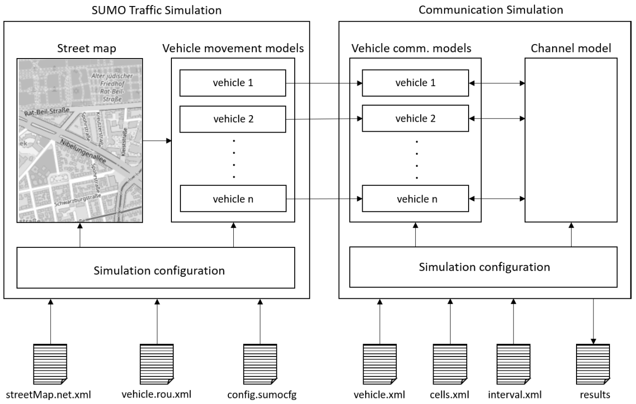


FIGURE 11. **Structure of the simulation environment.**

radio channel by both technologies at the same time is not considered here.

The two technologies therefore use different radio channels. The hybrid stations connect the two sub-networks and must support both technologies in parallel via different antennas.

A. IMPLEMENTATION OF THE SIMULATION

In contrast to the measurement of transmission properties described above, a comprehensive study of hybrid communication with a large number of participants in the real traffic environment is not possible in this investigation.

In order to test the feasibility of hybrid communication concepts and be able to assess their characteristics and behavior in the traffic environment, a suitable simulation environment was set up. This is able to represent a critical number of road users and their communication in a realistic manner. For this purpose, an individual simulation environment was built in order to be able to represent all required sub-aspects at the required level of detail.

For all studies, the DLR (German Aerospace Center) tool SUMO (Simulation of Urban MObility) was used to simulate realistic traffic behavior. This microscopic traffic simulator enables the representation of all considered road networks and mobility types.

The simulation of the communication volume was realized with the help of a Java application that implements both the required parts of the protocol stacks of the two technologies as well as the already mentioned transmission models (Figure 11).

The two parts of the simulation are connected by an interface, which allows an exchange of information in both directions and mutual influence.

B. INITIAL CONCEPT

An initial concept was created, which realizes a heterogeneous network with the two technologies ITS-G5 and LTE-V2X. The approach relies on ITS-G5 as the basic technology, with direct communication via LTE-V2X as a complement. Cellular mobile communications should be used dynamically and dependent on the situation. LTE-V2X is used at one channel in the 5.9 GHz frequency range and is intended to compensate for the range weaknesses of ITS-G5 transmission, which uses another channel also in the 5.9 GHz frequency range. The characteristics of a self-organized ad hoc network without hierarchical structures prevail. This means that both technologies, ITS-G5 and LTE-V2X, are used as described in the standards, without any specific extensions. The hybrid network uses only sidelink communication for the exchange of information between the participants. The decision on the transmission path to be used is made by each hybrid participant. The process for selecting the transmission technology in this approach is described in Figure 12.

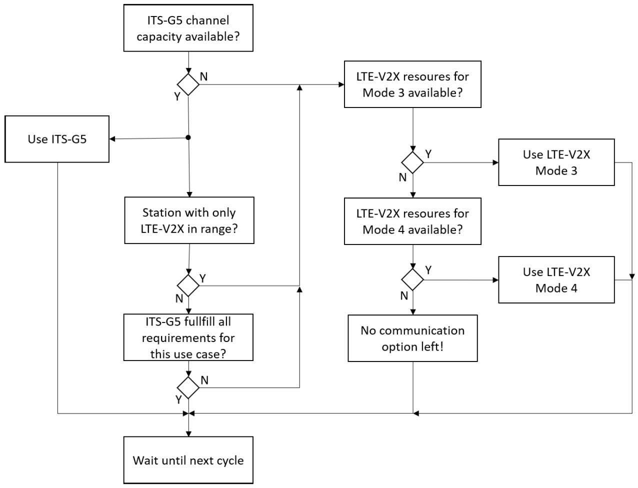


FIGURE 12. **Process of transmission technology selection in a hybrid V2X network with ITS-G5 as basic technology supported by LTE-V2X.**

It should be clarified how often and in which situations LTE-V2X resources should be used. This should show under what conditions a decentralized network approach, such as the basis for ITS-G5, can also be used in a hybrid operation.

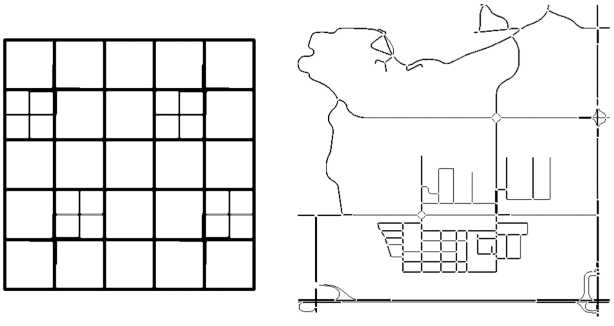
In addition, it should be determined for what reasons the additional usage of LTE-V2X occurs e.g., an overload of the ITS-G5 channels or a lack of transmission range.

A very decisive and interesting point in this investigation is the equipment rate of the participants with the respective technologies. In the real traffic environment, not all participants will be equipped with both transmission options with the respective technologies. Thus, the successful distribution of information will be strongly influenced by the selection of the right transmission method.

This investigation took into account both the availability of participants with appropriate transmission technology and the utilization of available radio channels.

The investigated use case was the Cooperative Awareness Service. This service enables the participants to perceive each other and thus represents the basic application of V2X communication. It is supported by both technologies, and both can use the CAM message for this purpose.

The requirements of the applications, which were also decisive in the choice of the technology, were taken into account, as the situation-dependent ranges and latency that



Urban road network

Combined road network

FIGURE 13. Simulated road networks.

are needed to transmit information in time are essential to avoiding suspected collisions and dangerous conflicts between road users.

Two scenarios were investigated in different traffic areas. One scenario describes a grid-shaped urban road network with an area of about 1000 by 1000 meters. The second scenario combines different road areas, such as country roads, motorways, and suburban regions, with a total area of 2000 by 2000 meters. In both scenarios, a total of 300 vehicles were simulated with V2X systems (Figure 13).

First, the communication behavior with pure ITS-G5 participants was considered in reference studies. For each transmission of a CAM message, it was checked whether the transmission occurred within the temporal and spatial requirements, which are defined in the respective situation by the use case of collision avoidance. The requirements are defined by whether information can reach an addressed recipient in time to be able to react to a situation without endangering it. The requirements are individual for each situation and depend primarily on the participants' speed and their distance from each other.

Following the baseline study, the number of hybrid participants gradually increased, while the number of pure ITS-G5 participants was reduced to the same extent. Thus, the total number of participants remained unchanged over the individual simulation runs. Simulations were performed with 30, 60 and 90 hybrid participants. The results for meeting the requirements of the participant collision avoidance application are shown in Figure 14.

The latency and range requirements have improved with the increasing number of hybrid participants. It should be noted that the difficulties in meeting the latency requirements are primarily due to the significant utilization of the radio channel. The effect of the hybrid participants here results from the additional usage of the LTE-V2X channel, which is only slightly utilized.

The simulations also showed that ITS-G5 at 5.9 GHz was not always able to meet the requirements of the range or the distribution area, especially in non-line-of-sight situations. This applies in particular to NLOS situations where, due to environmental conditions, a sufficient distribution area could not be reached to alert other participants in time of an imminent collision. Figure 15 shows the transmission ranges for the two scenarios, broken down by the technologies involved and by LOS and NLOS. LTE-V2X was actually able to provide useful support if the targeted participants had this technology at their disposal. However, it also turned out that only a few additional LTE-V2X resources had to be used for this application, as ITS-G5 was already able to successfully cover most of the communication.

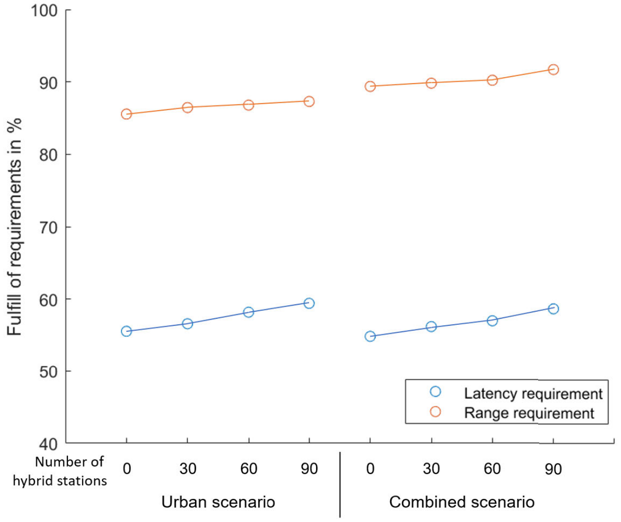


FIGURE 14. Fulfillment of the transmission requirements related to the number of hybrid stations.

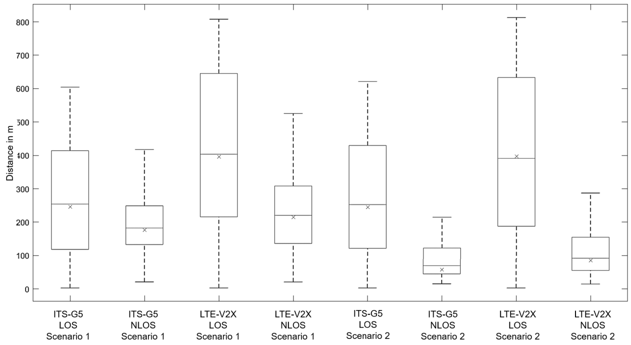


FIGURE 15. Simulated transmission ranges for ITS-G5 and LTE-V2X.

It was not possible to determine a fixed threshold for the number of required hybrid vehicles because this number depended heavily on the individual situation. Depending on the position of the hybrid vehicles in the simulated V2X network, an increase in the number of these vehicles in most cases brought with it an increase in successful message propagation and thereby, a rise in reliability.

VII. CONCLUSION

We were able to demonstrate that both technologies, ITS-G5 and LTE-V2X, despite sharing the same field of application and a very similar architecture in some respects, have their own advantages and disadvantages, which can have a decisive impact on the transmission of safety-critical messages and thus on the fulfillment of the requirements of the respective applications.

It has also been shown that a hybrid non-hierarchical approach, retaining the previous ITS-G5 and LTE-V2X network architectures, has the potential to increase the reliability of the transmission of safety-critical information.

By choosing the transmission path that is best suited to the specific situation, both the utilization of the radio channels and the requirements of the respective application cases can be better taken into account. The usage of broadcasts and connectionless transmissions, which do not require explicit routing of information and an additional communication volume for the organization of sub-networks (clusters),remains.

The additional cost of using two transmission technologies in hybrid vehicles is mitigated by the fact that the hardware required for cellular mobile communications is already widely available in the vehicle e.g., for Internet-based services or e-call [19].

In our view, the results justify further consideration of this hybrid approach. The two technologies should not be considered exclusively as competing technologies, which, if blended, could create interoperability problems. Rather, the potential for such joint usage should be further explored.

VIII. NEXT STEPS

However, this investigation was only a first step, looking at a single use case. Further use cases as well as the different forms of transmission need to be considered more extensively in order to create a complete picture of the capability of the hybrid approaches. Especially in the field of LTE-V2X, the flexibility in the choice of a frequency range and the allocation of resources offers possibilities for further investigations.

However, the structure of a hybrid network can also be considered in different ways. So far, the focus has been on supporting ITS-G5 with LTE-V2X, as ITS-G5 is established as the primary transfer technology in the European Union [11]. However, the approach of equally used technologies or a network primarily designed for LTE-V2X is still to be explored.

The algorithms for selecting a transmission technology from a participant's point of view can also be defined differently and based on different parameters. The investigation of such algorithms is also a very important part of the further considerations.

The next applications under investigation will be the event-based warnings of hazardous locations and situations that use the DENM message to distribute this safety-critical information. This group of applications places even higher demands on the transmission range, especially in large areas of danger, which should make using LTE-V2X even more important here.

Finally, the next generation of cellular mobile-based V2X communication has to be investigated in the context of hybrid usage. 5G-V2X is intended to extend LTE-V2X for use cases that require particularly high data rates and high reliability requirements. Highly and completely automated driving is critical for future safety-critical applications [37].

REFERENCES

[1] *CAR 2 CAR Communication Consortium Manifesto: Overview of the C2C-CC System*, 2007.

[2] H. Fuchs, F. Hofmann, H. Löhr, and G. Schaaf, "Car-2-x," in *Handbuch Fahrerassistenzsysteme*, H. Winner, S. Hakuli, F. Lotz, and C. Singer, Eds. Wiesbaden, Germany: Springer Vieweg, 2015, pp. 525–540.

[3] N. Lu, N. Cheng, N. Zhang, X. Shen, and J. W. Mark, "Connected vehicles: Solutions and challenges," *IEEE Internet Things J.*, vol. 1, no. 4, pp. 289–299, Aug. 2014.

[4] J. Thota, N. F. Abdullah, A. Doufexi, and S. Armour, "Performance of car to car safety broadcast using cellular V2 V and IEEE 802.11P," in *Proc. IEEE 87th Veh. Technol. Conf. (VTC Spring)*, Jun. 2018, pp. 1–5.

[5] M. Valta, M. Jutila, and J. Jamsa, "IEEE 802.11p and LTE as enablers of cognitive vehicle-to-infrastructure communication," in *Proc. 6th IEEE Int. Conf. Cognit. Infocommunications (CogInfoCom)*, Oct. 2015, pp. 71–76.

[6] L. Schnieder and R. S. Hosse, *Leitfaden Automot. Cybersecurity Engineering: Absicherung Vernetzter Fahrzeuge auf dem Weg zum Autonomen Fahren*. Wiesbaden Germany: Springer, 2018.

[7] B. Glas, O. Sander, D. K. Müller-Glaser, and J. Becker, "Echtzeitfähige car-to-X–kommunikationsabsicherung und E/E-architekturintegration," in *Vernetztes Automobil* (ATZ/MTZ-Fachbuch), W. Siebenpfeiffer, Ed. Wiesbaden, Germany: Springer Vieweg, 2014, pp. 70–81.

[8] D. Jiang and L. Delgrossi, "IEEE 802.11p: Towards an international standard for wireless access in vehicular environments," in *Proc. IEEE Veh. Technol. Conf. (VTC Spring)*, May 2008, pp. 2036–2040.

[9] European Telecommunications Standards Institute, *Intelligent Transport Systems (ITS); Cross Layer DCC Management Entity for Operation in the Its G5A and Its G5B Medium*, document Ts 103 175-v1.1.1, Jun. 2015.

[10] G. Cecchini, A. Bazzi, B. M. Masini, and A. Zanella, "Performance comparison between IEEE 802.11p and LTE-V2 V in-coverage and out-of-coverage for cooperative awareness," in *Proc. IEEE Veh. Netw. Conf. (VNC)*, Nov. 2017, pp. 109–114.

[11] A. Festag, "Standards for vehicular communication—From IEEE 802.11p to 5G," *E I Elektrotechnik und Informationstechnik*, vol. 132, no. 7, pp. 409–416, 2015.

[12] European Telecommunications Standards Institute, *Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service*, document En 302 637-2–v1.4.0, 2018.

[13] European Telecommunications Standards Institute, *Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 3: Specifications of Decentralized Environmental Notification Basic Service*, document En 302 637-3–v1.2.1, 2014.

[14] European Telecommunications Standards Institute, *Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service*, En 302 637-2–v 1.3.1, 2014.

[15] *Projekte Eict*.

[16] A. Bazzi, G. Cecchini, A. Zanella, and B. M. Masini, "Study of the impact of PHY and MAC parameters in 3GPP C-V2V mode 4," *IEEE Access*, vol. 6, pp. 71685–71698, 2018.

[17] X. Shen, J. Li, L. Chen, J. Chen, and S. He, "Heterogeneous LTE/DSRC approach to support real-time vehicular communications," in *Proc. 10th Int. Conf. Adv. Infocomm Technol. (ICAIT)*, Aug. 2018, pp. 122–127.

[18] S. Steglich and C. Fuhrhop, "Von der straße ins internet," in *Vernetztes Automobil* (ATZ/MTZ-Fachbuch), W. Siebenpfeiffer, Ed. Wiesbaden, Germany: Springer Vieweg, 2014, pp. 230–237.

[19] *Ecall: Leben Retten Auf Der Straße: 112-Ecall Wird für Neuwagen Verpflichtend—Deutschland—European Commission*, Europäische Kommission, 2018.

[20] A. Krini, *Zuverlässige Kommunikation für sichere Fahrerassistenzsysteme: Untersuchung zum GeoCast-Server für Fahrzeug zu Fahrzeug-Kommunikation mittels LTE für Fahrerassistenzsysteme*. Saarbrücken, Germany: AV Akademikerverlag, 2016.

[21] *3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; Study on LTE Support for V2X Services (Release 14)*, document 3GPP Tr 22.885-v1.0.0, 2015.

[22] A. Kousaridas, D. Medina, S. Ayaz, and C. Zhou, "Recent advances in 3GPP networks for vehicular communications," in *Proc. IEEE Conf. Standards Commun. Netw. (CSCN)*, Helsinki, Finland, Sep. 2017, pp. 91–97.

[23] S. Chen, J. Hu, Y. Shi, Y. Peng, J. Fang, R. Zhao, and L. Zhao, "Vehicle-to-everything (V2X) services supported by LTE-based systems and 5G," *IEEE Commun. Standards Mag.*, vol. 1, no. 2, pp. 70–76, 2017.

[24] A. Bazzi, M. Barbara Masini, A. Zanella, and I. Thibault, "On the performance of IEEE 802.11p and LTE-V2V for the cooperative awareness of connected vehicles," *IEEE Trans. Veh. Technol.*, vol. 66, no. 11, pp. 10419–10432, Nov. 2017.

[25] European Telecommunications Standards Institute, *LTE; Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall Description; Stage 2*, (document 3GPP TS 36.300 version 15.7.0 Release 15), document TS 136 300–v15.7.0, 2019.

[26] R. Molina-Masegosa and J. Gozalvez, "LTE-V for sidelink 5G V2X vehicular communications: A new 5G technology for short-range vehicle-to-everything communications," *IEEE Veh. Technol. Mag.*, vol. 12, no. 4, pp. 30–39, Dec. 2017.

[27] M. Gholibeigi, N. Sarrionandia, M. Karimzadeh, M. Baratchi, H. van den Berg, and G. Heijenk, "Reliable vehicular broadcast using 5G device-to-device communication," in *Proc. 10th IFIP Wireless Mobile Netw. Conf. (WMNC)*, Sep. 2017, pp. 1–8.

[28] European Telecommunications Standards Institute, *LTE; Service Requirements for V2X Services* (document 3GPP TS 22.185 version 15.0.0 Release 15), document TS 122 185–v15.0.0, 2018.

[29] S. Ucar, S. C. Ergen, and O. Ozkasap, "Multihop-cluster-based IEEE 802.11p and LTE hybrid architecture for VANET safety message dissemination," *IEEE Trans. Veh. Technol.*, vol. 65, no. 4, pp. 2621–2636, Apr. 2015.

[30] V. Mannoni, V. Berg, S. Sesia, and E. Perraud, "A comparison of the V2X communication systems: ITS-G5 and C-V2X," in *Proc. IEEE 89th Veh. Technol. Conf. (VTC-Spring)*, Apr. 2019, pp. 1–5.

[31] W. Anwar, K. Kulkarni, T. R. Augustin, N. Franchi, and G. Fettweis, "PHY abstraction techniques for IEEE 802.11p and LTE-V2 V: Applications and analysis," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2018, pp. 1–7.

[32] X. He, J. Lv, J. Zhao, X. Hou, and T. Luo, "Design and analysis of a short-term sensing-based resource selection scheme for C-V2X networks," *IEEE Internet Things J.*, vol. 7, no. 11, pp. 11209–11222, Nov. 2020.

[33] A. Abunei, C. R. Comsa, C. F. Caruntu, and I. Bogdan, "Redundancy based V2 V communication platform for vehicle platooning," in *Proc. Int. Symp. Signals, Circuits Syst. (ISSCS)*, Jul. 2019, pp. 1–4.

[34] S. Kuehlmorgen, P. Schmager, A. Festag, and G. Fettweis, "Simulation-based evaluation of ETSI ITS-G5 and cellular-VCS in a real-world road traffic scenario," in *Proc. IEEE 88th Veh. Technol. Conf. (VTC-Fall)*, Aug. 2018, pp. 1–6.

[35] M. Shafi, F. Andreas Molisch, J. Peter Smith, T. Haustein, P. Zhu, P. D. Silva, F. Tufvesson, A. Benjebbour, and G. Wunder, "5G: A tutorial overview of standards, trials, challenges, deployment, and practice," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 6, pp. 1201–1221, Jun. 2017.

[36] J. Lianghai, M. Liu, A. Weinand, and H. D. Schotten, "Direct vehicle-to-vehicle communication with infrastructure assistance in 5G network," in *Proc. 16th Annu. Medit. Ad Hoc Netw. Workshop (Med-Hoc-Net)*, Jun. 2017, pp. 1–5.

[37] European Telecommunications Standards Institute, *5g; Service Requirements for Enhanced V2X Scenarios*, (document 3GPP TS 22.186 version 15.4.0 release 15), document TS 122 186–v15.4.0, 2018.

[38] *Car2X: So Real IST Vernetztes Fahren*, 2019.

[39] H. Schumacher, "Netzlastabhängige dienstgütebewertung in fahrzeug-zu-fahrzeug-kommunikationsnetzen, Ph.D. dissertation, Leibniz Universität Hannover, Hanover, Germany, 2016.

[40] L. G. Baltar, M. Mucck, and D. Sabella, "Heterogeneous vehicular communications-multi-standard solutions to enable interoperability," in *Proc. IEEE Conf. Standards Commun. Netw. (CSCN)*, Oct. 2018, pp. 1–6.

[41] G. E. M. Zhioua, N. Tabbane, H. Labiod, and S. Tabbane, "A fuzzy multi-metric QoS-balancing gateway selection algorithm in a clustered VANET to LTE advanced hybrid cellular network," *IEEE Trans. Veh. Technol.*, vol. 64, no. 2, pp. 804–817, Feb. 2015.

[42] X. Bi, B. Guo, L. Shi, Y. Lu, L. Feng, and Z. Lyu, "A new affinity propagation clustering algorithm for V2V-supported VANETs," *IEEE Access*, vol. 8, pp. 71405–71421, 2020.

[43] Z. Khan and P. Fan, "A multi-hop moving zone (MMZ) clustering scheme based on cellular-V2X," *China Commun.*, vol. 15, no. 7, pp. 55–66, Jul. 2018.

[44] Z. Khan, P. Fan, F. Abbas, H. Chen, and S. Fang, "Two-level cluster based routing scheme for 5G V2X communication," *IEEE Access*, vol. 7, pp. 16194–16205, 2019.

[45] W. Ertel, "Grundkurs künstliche intelligenz: Eine praxisorientierte einführung," in *SpringerLink Bücher*. Wiesbaden, Germany: Springer Vieweg, 2016.

[46] European Telecommunications Standards Institute, *Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 1: Functional Requirements*, document TS 102 637-1–v1.1.1, 2010.

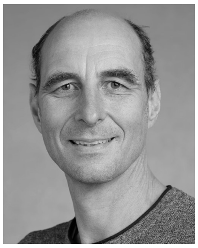
[47] European Telecommunications Standards Institute, *LTE; 5G; Security Aspect for LTE Support of Vehicle-to-Everything (V2X) Services* (document 3GPP TS 33.185 version 15.0.0 release 15), document TS 133 185–v15.0.0, 2018.

[48] *Mobile Statistics Report 2021–2025*.

[49] M. Deegener, "Einsatz der car-to-X technologie zur erhöhung der verkehrssicherheit von fußgängern und fahrradfahrern: Exploiting car2X technology to increase safety of pedestrians and bicycle drivers: Vdiberichte," in *Proc. 15. Internationaler Kongress Elektronik im Kraftfahrzeug*, 2011, pp. 677–678.

[50] K. Z. Ghafoor, M. Guizani, L. Kong, H. S. Maghdid, and K. F. Jasim, "Enabling efficient coexistence of DSRC and C-V2X in vehicular networks," *IEEE Wireless Commun.*, vol. 27, no. 2, pp. 134–140, Apr. 2020.

JOCHEN STELLWAGEN received the B.Eng. degree in electrical and information technology from the Darmstadt University of Applied Sciences, Darmstadt, Germany, in 2011, and the M.Sc. degree in mechatronic and robotics from the Frankfurt University of Applied Sciences, Frankfurt, Germany, in 2018. He is currently pursuing the Ph.D. degree with the Darmstadt University of Applied Sciences. From 2011 to 2018, he was an Engineer in the automotive industry and participated in several national and international car-to-car communication research projects.



MATTHIAS DEEGENER received the Diploma degree in computer science, in 1992, and the Ph.D. degree from the Technical University of Darmstadt, Germany, in 1998. From 1999 to 2009, he was a Project Engineer with Opel in the field of vehicle-to-vehicle communication. Since 2009, he has been a Professor with the Frankfurt University of Applied Sciences, with a focus on embedded systems. He is currently the Program Director of the Bachelor's Degree Program in computer science mobile applications and the Director of the Institute for Interdisciplinary Technology (IIT), Frankfurt University of Applied Sciences. He collaborated on several research projects on vehicle-to-vehicle communication. He is the coauthor of the *Car-2-Car Communication Manifesto*. He was a member of the Car-2-Car Communication Consortium.

MICHAEL KUHN (Member, IEEE) received the Dipl.-Ing. degree in electrical engineering in communication technology from the Technical University Darmstadt (TUD), Darmstadt, Germany, in 1998, and the Ph.D. degree from Saarland University, Saarbrücken, Germany, in 2002. He is currently a Professor of mobile communication with the Darmstadt University of Applied Sciences (h_da), Darmstadt. Before he joined h_da, in 2006, he was the Head of the Research and Development Department, Wavecom Elektronik AG, Switzerland, where he was in charge of hardware and software developments for software-defined radios. His research interests include cooperative wireless communications, mobile ad-hoc networks, and software-defined radios.

• • •