TECHNISCHE UNIVERSITÄT DARMSTADT

VEHICULAR COMMUNICATION *for* COOPERATIVE DRIVING

Relevance-Aware Data Dissemination Strategies for Adaptive Cooperative Driving

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DANIEL BISCHOFF, M.SC.

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Vorsitz: Prof. Dr. rer. nat. Markus Meinert
Referent: Prof. Dr.-Ing. Ralf Steinmetz
Korreferent: Prof. Dr.-Ing. Lars Wolf

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ABSTRACT

According to the EuroNCAP Roadmap 2025, vehicular communication is expected to play a decisive role in increasing traffic safety and efficiency. Vehicles can improve their environmental awareness, exchange driving intentions, and cooperate with other vehicles in their communication range. That way, vehicular communication enables the cooperative coordination of driving maneuvers to prevent traffic jams, increase traffic efficiency, and maintain safety on urban roads and highways, particularly in congested scenarios with high vehicle density.

Cooperative driving requires high communication quality to coordinate maneuvers safely and efficiently. Providing high communication quality in congested vehicular networks, specifically for vehicles coordinating a cooperative maneuver, poses a significant research challenge. Moreover, the context of cooperative driving continuously changes due to high vehicle mobility, which further complicates the provision of high communication quality for vehicles coordinating a cooperative maneuver.

Prioritizing information in congested vehicular networks improves the communication quality for vehicles coordinating a cooperative maneuver. If information prioritization is insufficient to provide high communication quality in heavily congested vehicular networks, the cooperative driving application must adapt to the available communication quality for maintaining traffic safety. The joint consideration of information prioritization from the application and congestion control from the network perspective to provide high communication quality for cooperative driving remains an open research challenge.

As our *first contribution*, we assess communication quality and information relevance for cooperative driving. Based on this, we present a relevance-aware resource allocation approach and an adaptive data dissemination strategy using heterogeneous vehicular access technologies to improve the communication quality in congested networks for vehicles coordinating a cooperative maneuver as our *second contribution*.

With our *third contribution*, we propose communication-aware cooperative driving. In scenarios with impaired communication quality, our approach reduces traffic efficiency to maintain safety. Thus, our approach can respond to unexpected events to avoid accidents, even in scenarios with impaired communication quality.

We use numerical analysis and our simulation framework CoDA.KOM with a prototypical implementation of the cooperative driving use case *left-turning at an intersection* to evaluate our contributions. Our evaluation demonstrates that relevance-aware resource allocation prioritizes information of vehicles coordinating a cooperative maneuver in scenarios with high vehicle density. Moreover, our adaptive data dissemination strategy with heterogeneous vehicular access technologies provides high communication quality to vehicles coordinating a cooperative maneuver. Overall, we increase traffic efficiency and maintain safety for cooperative driving by adapting to the vehicular communication quality.

KURZFASSUNG

Gemäß der Euro NCAP-Roadmap 2025 wird die Fahrzeugkommunikation eine entscheidende Rolle bei der Erhöhung der Sicherheit und Effizienz im Straßenverkehr einnehmen. Fahrzeuge können dadurch ihre Umgebungswahrnehmung steigern, zukünftige Fahrabsichten austauschen und mit anderen Fahrzeugen in ihrer Kommunikationsreichweite kooperieren. Somit ermöglicht Fahrzeugkommunikation die kooperative Koordinierung von Fahrmanövern, um Unfälle und Staus auf städtischen Straßen und Autobahnen, insbesondere in Szenarien mit hoher Verkehrsdichte, entscheidend zu reduzieren.

Kooperatives Fahren setzt eine hohe Kommunikationsqualität voraus, um Fahrmanöver sicher und effizient zu koordinieren. Die Bereitstellung einer hohen Kommunikationsqualität in stark belasteten Fahrzeugnetzwerken, insbesondere für Fahrzeuge, welche kooperative Fahrmanöver koordinieren, stellt eine entscheidende wissenschaftliche Herausforderung dar. Darüber hinaus ändert sich der Kontext von kooperativen Fahrmanövern aufgrund der hohen Fahrzeugmobilität fortwährend, was die Bereitstellung einer hohen Kommunikationsqualität für kooperativ agierende Fahrzeuge weiter erschwert.

Informationspriorisierung in stark belasteten Fahrzeugnetzwerken erhöht die Kommunikationsqualität von Fahrzeugen, welche kooperative Fahrmanöver koordinieren. Wenn Informationen für kooperative Fahrmanöver nicht ausreichend priorisiert werden können, muss die kooperative Fahrfunktion an die verfügbare Kommunikationsqualität adaptiert werden, um die Verkehrssicherheit weiterhin zu gewährleisten. Bislang bleibt die gemeinsame Betrachtung der Informationspriorisierung aus Applikations- und dem Entgegenwirken einer Netzwerküberlastung aus Netzwerksicht, um eine hohe Kommunikationsqualität für das kooperative Fahren bereitzustellen, ein offenes Forschungsthema.

In dieser Arbeit stellen wir einen Ansatz zur Bewertung der Kommunikationsqualität und Informationsrelevanz für das kooperative Fahren als unseren *ersten Beitrag* vor. Darauf aufbauend schlagen wir eine relevanzbasierte Ressourcenzuweisung und eine adaptive Verteilungsstrategie auf Basis heterogener Kommunikationstechnologien als unseren *zweiten Beitrag* vor. Somit können relevante Informationen für das kooperative Fahren mit einer hohen Kommunikationsqualität priorisiert werden. Als *dritten Beitrag* stellen wir einen kommunikationsberücksichtigenden Ansatz für das kooperative Fahren vor. Um die Verkehrssicherheit in Szenarien mit niedriger Kommunikationsqualität weiterhin zu gewährleisten, reduziert unser Ansatz die Verkehrseffizienz von kooperativen Fahrmanövern. Somit kann unser Ansatz auch bei niedriger Kommunikationsqualität auf unerwartete Ereignisse während eines kooperativen Fahrmanövers reagieren und Unfälle vermeiden.

Um unsere Beiträge zu bewerten, untersuchen wir diese zunächst mit numerischen Verfahren und verwenden im Anschluss unsere Simulationsumgebung CoDA.KOM,

welche eine prototypische Implementierung des kooperativen Fahrens im Anwendungsfall des *Linksabbiegens an einer Kreuzung* beinhaltet. Unsere Evaluation zeigt, dass eine relevanzbasierte Ressourcenzuweisung Informationen von Fahrzeugen, die kooperative Fahrmanöver koordinieren, in stark belasteten Netzwerken priorisiert. Darüber hinaus bietet unsere adaptive Verteilungsstrategie mit heterogenen Kommunikationstechnologien eine hohe Kommunikationsqualität für kooperierende Fahrzeuge. Insgesamt erhöhen wir die Verkehrseffizienz und -sicherheit von kooperativen Fahrmanövern durch Anpassungen an die Kommunikationsqualität von Fahrzeugen.

PREVIOUSLY PUBLISHED MATERIAL

The thesis at hand builds upon peer-reviewed material previously published in conference proceedings and journals. A summary of the previously published material with the corresponding journal or conference proceeding can be found in Appendix B. In this thesis, no texts and tables have been copied from the previously published material mentioned above. Algorithms for our concepts and figures, specifically used to illustrate our evaluation results, have been restructured, modified, and adapted to fit the scope of this thesis.

Scientific progress results from critical discussions, valuable feedback, and the development of new ideas in research teams. This thesis addresses interdisciplinary challenges in communication networks, computer science, and the automobile environment. Consequently, the contributions presented in this thesis are a collaborative result of research activities from computer and communication network scientists, mathematicians, and automobile researchers. With the pronoun "I", contributions of the thesis' author are highlighted. The mentioned pronoun will be exclusively used in this chapter. In the following, I will mention the contributions of my co-authors (related to the previously published material) and other contributors together with their respective affiliations used in the sections of this thesis, as depicted in Table 1. If a contributor or co-author is with the Multimedia Communication Lab of the TU Darmstadt, the respective affiliation is not stated. For the rest of this thesis, the pronoun "We" indicates the collaborative team effort in the mentioned research areas.

This thesis was written in collaboration with the Opel Automobile GmbH (Opel) and the Technical University of Darmstadt (TU Darmstadt). At the TU Darmstadt, all contributions and the thesis were subsequently supervised by Dr.-Ing. Björn Richerzhagen and Dr.-Ing. Tobias Meuser. At Opel, all contributions were subsequently supervised by Harald Berninger, Peter Andres, and Dr.-Ing. Dieter Schuller. From both organizations, the mentioned supervisors scientifically supported the entire thesis and contributions, discussing ideas and giving valuable feedback for the approaches. Further, all supervisors supported the evaluation towards the final state of the thesis.

Chapter 2, BACKGROUND AND RELATED WORK, organizes and summarizes related work for Vehicle-to-Everything (V2X) communication, network adaptations, and cooperative driving. I conducted a systematic literature review, where Dr.-Ing. Björn Richerzhagen and Dr.-Ing. Tobias Meuser, as well as Harald Berninger, assisted with the methodology, defining the research topic, selecting relevant areas, and identifying the research gap.

Based on this methodology, I reviewed V2X access technologies, which have been frequently used for traffic safety and efficiency V2X applications. Further, I researched communication requirements for traffic efficiency and safety V2X applications. Together with Dr.-Ing. Tobias Meuser and Florian Schiegg (Corporate Research, Robert

Section	[31]	[212]	[30]	[29]	[28]	[26]
Section 2.1: Vehicular Communication Networks	✓			✓		✓
Section 2.2: Cooperative Driving		✓		✓		
Section 2.3: Network Adaptations in Vehicular Networks	✓		✓			
Section 4.2: Numerical Model for Communication Quality Assessment		✓	✓	✓		
Section 4.3: Information Relevance for Cooperative Driving	✓					
Section 5.2: Relevance-Aware Resource Allocation	✓					
Section 5.3: Adaptive Data Dissemination Strategy for Cooperative Driving			✓			
Section 5.4: Communication-Aware Cooperative Driving		✓				
Section 6.2: Realistic Channel Modeling						✓
Section 6.3: Prototypical Realization of Cooperative Driving at an Intersection			✓		✓	
Section 7.2: Comparing the Numerical Model with Simulations	✓			✓		
Section 7.3: Resource Allocation in Decentralized Vehicular Networks	✓					
Section 7.4: Adaptive Data Dissemination Strategy for Cooperative Driving			✓			

Table 1: Peer-reviewed previously published material related to the sections of this thesis.

Bosch GmbH), we compared and discussed suitable V2X access technologies fitting the communication requirements of cooperative driving. For communication performance modeling and assessment, I categorized and collected radio propagation channel models. The analysis of different channel models was supported by Harald Berninger and Prof. Steffen Knapp (University of Applied Science HTW Saar), where we published our results in [26]. The medium access of the IEEE 802.11p has a significant impact on the communication quality performance. Together with Florian Schiegg, we examined different medium access models for IEEE 802.11p, partly published in [29, 31].

Cooperative driving uses V2X communication to coordinate and execute maneuvers with other vehicles for improving traffic efficiency. I researched different maneuver coordination protocols and discussed their applicability to large-scale V2X network simulations together with Harald Berninger, Peter Andres, Florian Schiegg, Prof. Steffen Knapp, and Viktor Lizenberg (Opel). We compared and reviewed them in our publication in [30]. Furthermore, traffic safety has been insufficiently studied for cooperative driving. In collaboration with Florian Schiegg, Dr.-Ing. Tobias Meuser, Ass.-Prof. Johan Thunberg, and Prof. Alexey Vinel (both from the University Halmstad, Sweden), we discussed, analyzed, and selected existing approaches to maintain traffic safety for cooperative driving considering the assessed communication quality in [212].

Resource allocation is required in V2X networks to counteract channel congestion in scenarios with a high vehicle density. With Florian Schiegg, we categorized resource allocation into content-agnostic, content-aware, and relevance-aware approaches. Jens Lemke assisted in the literature review of these approaches. Our literature review was partly published in [31]. Heterogeneous V2X communication adapts to the vehicle's context and transitions to the V2X access technology, offering the best communication quality. I conducted a literature review for the approaches in this area, targeting traffic safety and efficiency V2X applications, assisted by Jens Lemke. Based on the review, together with Dr.-Ing. Tobias Meuser, we analyzed and selected relevant approaches, which were partly summarized in [30].

Chapter 4, DATA ASSESSMENT FOR COOPERATIVE DRIVING, proposes the decentralized assessment of communication quality in V2X networks and information relevance for cooperative driving.

The assessment of communication quality for decentralized V2X networks has been studied in previous work using a Markov Chain Model for the representation of IEEE 802.11P Distributed Coordination Function (DCF) and Enhanced Distributed Channel Access (EDCA). However, by comparing the models with simulation results and assessing the assumptions of previous models, I found that currently no EDCA model focused on the specific communication setup considered for cooperative driving. I developed a suitable numerical model to assess the communication quality of our considered V2X network, published in [29, 31]. The definition of required assumptions for the numerical model was supported by Florian Schiegg, Dr.-Ing. Tobias Meuser, and Benjamin Becker. To describe the impact of communication quality on the performance of cooperative driving w. r. t. traffic efficiency and safety is not trivial. As a solution, I modeled communication quality as Age of Information (AoI) based on the proposed numerical model and developed a numerical framework to obtain the impact on the cooperation costs for different communication qualities. In collaboration with Florian Schiegg and Dr.-Ing. Tobias Meuser, we defined the evaluation of our framework to find a sweet spot between the communication range and cooperation costs to start a cooperative maneuver [29].

Information relevance assessment is the foundation of relevance-aware resource allocation. I researched existing approaches to assess the information relevance in V2X networks. For that, I developed an approach for resource allocation in cellular V2X networks for vehicles approaching an intersection in collaboration with Dr.-Ing. Tobias Meuser, published in [27]. With Florian Schiegg, we used the instantaneous approaching time of vehicles as a safety metric for the perceived quality of the V2X application collective perception. I extended the idea of the instantaneous approaching time to the continuous approaching time for trajectory-based information relevance assessment. With valuable feedback from Florian Schiegg and Dr.-Ing. Tobias Meuser, we obtained the perceived awareness over a trajectory's time horizon. We published our information relevance assessment for trajectory-based cooperative driving use cases in [31].

Chapter 5, RELEVANCE-AWARE ADAPTATIONS IN VEHICULAR NETWORKS, proposes relevance-aware resource allocation, heterogeneous data dissemination strategies, and communication-aware cooperative driving.

In scenarios with high vehicle density, the V2X channel can be congested, leading to impaired communication quality. In this context, the implementation of congestion control mechanisms reduces channel congestion and increases the communication quality from the network perspective. I developed the idea to formulate an optimization problem using information relevance and communication quality assessment. Assisted by Dr.-Ing. Tobias Meuser and Dr.-Ing. Dieter Schuller, we proposed the network's Accessible Information Relevance (AIR) to counteract channel congestion and increase the communication quality from the application perspective. Moreover, with Florian Schiegg, we extended the idea of Linear Message Rate Integrated Control (Limeric) [15] to allocate the vehicle-specific optimal message frequency in a decentralized V2X network, avoiding oscillation of the vehicles' message frequencies. Our relevance-aware resource allocation approach was published in [31].

Cooperative driving applications require high communication range. That way, vehicles can coordinate cooperative maneuvers early, decreasing cooperation costs for the vehicles offering cooperation. I developed a framework using heterogeneous V2X access technologies to improve communication quality for vehicles coordinating and executing a cooperative maneuver. Based on this framework, Jens Lemke and I investigated state adaptive heterogeneous radio access, which transitions to the V2X access technology offering the best communication quality for cooperative driving. Together with Dr.-Ing. Tobias Meuser and Dr.-Ing. Dieter Schuller, we extended the framework to the cooperative driving use case left-turning at an intersection in [30].

Although our approaches aim to offer high communication quality for vehicles coordinating and executing cooperative maneuvers, physical constraints can lead to impaired communication quality. I developed the idea for communication-aware cooperative driving. Vehicles decrease traffic efficiency to maintain safety in scenarios with impaired communication quality. In collaboration with Prof. Alexey Vinel and Ass.-Prof. Johan Thunberg and based on our results in [29], we investigated communication-aware cooperative driving. In [212], we proposed a framework to compute the reaction times of vehicle trajectories in a computationally efficient approach. The reaction time is compared with the assessed AoI for the cooperative maneuver to decide for efficient *and* safe trajectories, which we evaluated numerically. Based on the results, I developed a generic approach to obtain trajectory safety zones for each time step of received trajectories, depending on the assessed AoI.

Chapter 6, SIMULATION OF COOPERATIVE DRIVING IN VEHICULAR NETWORKS, presents our simulation framework CoDA.KOM. We explain our considered REALIS-

TIC channel model and detail our prototypical implementation of cooperative driving for left-turning at an intersection.

Radio propagation effects such as path loss and fading impair the communication quality. In recent work, these radio propagation effects have been modeled with different channel models for each V2X access technology. In this context, I developed a heterogeneous V2X channel model in the context of my master thesis with the title "Nachrichtenformate, Datenelemente und Strukturen für Hybride V2X Kommunikation am Beispiel Manöverabstimmung" at the University of Duisburg-Essen, supervised by Prof. Andreas Czylwik. This channel model is used in the evaluation framework of this thesis. With valuable feedback on the modeling approach from Harald Berninger and Prof. Steffen Knapp, we published the channel model in [26].

The proposed simulation framework CoDA.KOM implements the cooperative driving use case left-turning at an intersection and abstracts the application from the communication layer. Nicolas Himmelmann, Patrick Dworski, and Jonas Schulz contributed to implementing the GeoNetworking and Basic Transport Protocol layers in CoDA.KOM within the KOM Multimedia Communications Lab at the TU Darmstadt, based on the European Telecommunications Standards Institute (ETSI) specifications. Julian Dehner (Opel) implemented the cooperative awareness service, data elements, and data frames according to the ETSI Common Data Dictionary (CDD). Within the IMAGinE consortium, we discussed and developed approaches for decentralized cooperative driving and respective message protocols. Based on these approaches, I developed a framework for a cooperative driving approach with adaptations to significantly reduce the computational complexity in large-scale networks. In regular meetings, we discussed and improved the approach together with Prof. Steffen Knapp, Harald Berninger, Peter Andres, Viktor Lizenberg, and Bernd Büchs (all from Opel). In the KOM Multimedia Lab, I supervised Nils Dycke, who contributed to the map parsing and trajectory generation of CoDA.KOM. Our results were published in [28, 30].

Chapter 7, EVALUATION, presents the results of our contributions and compares them to reference approaches.

I assessed the communication quality with the proposed numerical model and compared the results with simulations. Furthermore, I discussed the results with Dr.-Ing. Tobias Meuser, Dr.-Ing. Dieter Schuller, and Florian Schiegg. Our results were presented in [29, 31]. I prepared and illustrated the evaluation for the numerical and simulation results, showing the convergence of the vehicles' message frequencies and the network's AIR. Together with Dr.-Ing. Tobias Meuser, we discussed the results for relevance-aware resource allocation. In this context, we developed the idea of representing the AoI as a probability of receiving at least one message. Our results were published in [31]. The evaluation of heterogeneous V2X communication concerned the communication quality and cooperative driving improvements. Together with Viktor Lizenberg, I supervised Youssef Haridy's master thesis, developing and evaluating performance metrics for the safety and efficiency of cooperative driving. Based on this work, I developed the evaluation of the adaptive data dissemination strategies with valuable feedback from Dr.-Ing. Tobias Meuser, Dr.-Ing. Dieter Schuller, and Florian Schiegg. The paper was published in [30].

CONTENTS

1 INTRODUCTION

Traffic jams in urban areas and on highways have increased from 189,000 km in 2011 to 723,000 km in 2017 [71]. The reason is that the vehicle density increases [64] while the road infrastructure remains the same [61, 63]. Traffic jams cause longer travel times and, moreover, constitute one of the main stress factors for human drivers [200], negatively impacting traffic safety and efficiency on the road.

From local environment perception ...

Today's Advanced Driver Assistant Systems (ADAS) aim to address and improve traffic safety for human drivers by processing information from other road participants perceived by the vehicle's local environment sensors. ADAS support safe driving by warning the human driver or even controlling the vehicle's movement to prevent accidents in dangerous situations [247] and constitute the first level of autonomous driving [186]. However, ADAS currently rely on the vehicle's local environment perception, which is limited to the vehicle's immediate surroundings and line of sight.

... to connected vehicles ...

In this context, connecting vehicles with Vehicle-to-Everything (V2X) communication to other road users and the infrastructure is a promising research area to extend the vehicle's environment perception [148, 209, 224]. Vehicles share their current positions, velocities, and headings with other road users in their communication range using V2X communication to create a cooperative awareness [96, 126, 241]. The vehicles' local environment perception can be further extended by sharing their perception with other vehicles to create a collective perception [80, 82], increasing awareness [70], efficiency [85], and safety [12, 189] on the road. Moreover, V2X communication enables *cooperative driving* by sharing the vehicle's future driving intentions to coordinate maneuvers cooperatively, further increasing traffic safety and efficiency [53, 142, 153]. Examples of cooperative driving use cases are platooning [79, 113, 188, 213], merging on highways [133, 159, 182], and turning at intersections [24, 36, 78].

... enabling cooperative driving.

V2X requirements

The cooperative coordination of driving maneuvers requires high communication quality [10, 32, 162]. In this context, a high communication range allows for early coordination. Moreover, reliable, low-latency communication avoids divergence between other vehicles' received and performed cooperative maneuvers. However, the demand for high communication quality, especially in congested channels, poses significant challenges to V2X networks [19, 141, 199]. Furthermore, the relevance to coordinate a maneuver depends on the vehicle's context. Hence, V2X network adaptations are required to satisfy the communication requirements of cooperating vehicles. Moreover, in scenarios with impaired communication quality, the cooperative driving application needs to adapt to the assessed communication quality [113, 213] to maintain traffic safety. In this thesis, we propose relevance-aware V2X network adaptations and communication-aware cooperative driving to address the mentioned challenges, enabling safe and efficient coordination of cooperative driving maneuvers.

Challenges for cooperative driving

1.1 MOTIVATION FOR RELEVANCE-AWARE VEHICULAR COMMUNICATION

In this work, we focus on V2X communication to enable safe and efficient cooperative driving in challenging environments. For applications with context-dependent communication requirements, *relevance-aware* communication provides high communication quality in networks with severely limited channel resources. Relevance-aware communication is a promising approach for cooperative driving because only a few vehicles coordinate a cooperative maneuver in a congested traffic scenario and, thus, require high communication quality.

History of V2X network adaptions

V2X communication is realized in decentralized and centralized topologies [11, 47]. On the one hand, decentralized V2X networks are infrastructure-independent, allowing vehicles to form Vehicular Adhoc Networks (VANETs) [72]. VANETs also provide low-latency communication because information is directly sent to other vehicles [52, 239]. On the other hand, centralized V2X networks provide reliable communication and high communication range [119, 123, 160]. However, decentralized and centralized V2X networks have limited channel resources. In this context, cooperative driving applications have a high demand for channel resources [32, 81], especially in scenarios with high vehicle density. Hence, V2X network adaptations are required to provide high communication quality [141].

Content-agnostic adaptation

Content-agnostic resource allocation and congestion control mechanisms have been recently proposed to improve the radio communication quality under congested channel conditions in V2X networks. Offloading information to other communication channels [179, 246], forming clusters [43, 187] and efficiently aggregating information locally [180, 216, 217], or reducing the message frequencies of all applications [18, 127, 141, 199] are promising approaches to counteract channel congestion. These mechanisms improve the radio communication quality and apply to any V2X application. However, content-agnostic approaches target a fair distribution of channel resources, where relevant information cannot be prioritized.

Content-aware adaptation

Content-aware resource allocation adaptations quantify the information relevance and allocate resources depending on the V2X application requirements. In this context, resource allocation for the Cooperative Awareness Message (CAM) based on the vehicle dynamics has been proposed and standardized in [96]. Resource allocation for the Collective Perception Message (CPM) considers the dynamics of the perceived vehicles [5, 48, 89, 208, 209]. The risk for collision [115] posed by different vehicles is used in [46, 114] to decide the optimal resource allocation strategy. The concept of Value of Information (VoI) offers excellent potential for V2X networks [50, 73, 75, 248] to generalize resource allocation for different V2X applications, e. g., for the CPM in [86]. In summary, content-aware adaptations satisfy the communication requirements from the application perspective but currently neglect channel congestion.

Identifying the limitations

As of today, V2X network adaptations either focus on the communication quality from the radio *or* application perspective. To counteract channel congestion and allocate resources depending on the application requirements simultaneously, content-agnostic and -aware approaches are interconnected [49, 81, 209]. In this combination, content-agnostic approaches hurt the application performance [195] because relevant information cannot be prioritized. Hence, approaches adapting to the assessed communication quality based on the application relevance are required to exploit the full potential of V2X networks.

V2X network limitations

However, physical constraints can prevent V2X network adaptations from providing the high communication quality required for cooperative driving [10, 32]. Assessing and adapting to low communication quality is required to coordinate maneuvers safely and efficiently [213], enabling communication-aware cooperative driving. Current approaches are limited to platooning and do not focus on the communication quality assessment [197, 214].

Relevance-aware cooperative driving

Therefore, *i)* assessing the communication quality and information relevance, *ii)* enabling relevance-aware V2X network adaptations, and *iii)* realizing communication-aware cooperative driving can increase safety and efficiency on the road.

1.2 RESEARCH CHALLENGES

Cooperative driving requires high communication quality in congested vehicular traffic scenarios, posing significant challenges on V2X networks. We identified the following research challenges that affect safe and efficient cooperative driving from the communication perspective.

Challenge: *Efficient usage of channel resources in vehicular networks.*

Cooperative driving improves traffic efficiency and safety in congested vehicular traffic scenarios but requires high communication quality to coordinate maneuvers early and monitor the cooperative maneuver. In V2X networks, channel resources are limited and channel congestion decreases the communication quality, negatively impacting the capability to coordinate and monitor cooperative maneuvers. In this context, efficiently using limited channel resources *and* providing high communication quality for relevant information is essential for cooperative driving and poses a significant research challenge. The challenge includes providing a sufficiently high communication range for early maneuver coordination *and* reliable, low-latency communication to monitor the cooperative maneuver coordination in congested, highly mobile V2X networks.

Challenge: *V2X application adaptation to communication quality.*

Communication quality is bound to physical constraints of the underlying access technologies. Hence, reliable, low-latency communication cannot be guaranteed in congested V2X networks. In scenarios with high traffic density, the channel resources are sparse and the communication quality can drop rapidly while performing a cooperative maneuver. Therefore, cooperative driving applications must assess and adapt to the communication quality. However, the strict communication requirements cannot be guaranteed in challenging scenarios with V2X network adaptations. Hence, cooperative driving must adapt traffic efficiency to maintain safety, i. e., providing larger margins between vehicles to account for outdated and uncertain information.

1.3 RESEARCH GOALS AND CONTRIBUTIONS

The main goal of this work is to propose *relevance-aware* V2X *network adaptations* and *communication-aware cooperative driving* to increase traffic efficiency and maintain safety. To tackle our stated challenges, we divided our research into the following goals.

Research Goal 1: *Assessment of communication quality and information relevance.*

Our first goal is to assess the communication quality in V2X networks and the information relevance of Maneuver Coordination Messages (MCMs), allowing for relevance-aware V2X network adaptations and communication-aware cooperative driving. Our contributions focus on two aspects for communication quality assessment: *i)* providing a model for decentralized communication quality assessment and *ii)* modeling communication quality as Age of Information (AoI). We propose a numerical communication quality model to assess the performance of different V2X network adaptation strategies for each vehicle depending on its current context. The AoI model considers reliability, latency, and message frequency and enables communication-aware cooperative driving. Moreover, we focus on information relevance assessment to abstract the communication requirements from the application perspective and allow for application-independent V2X network adaptations. We quantify information relevance for cooperative driving applications in a decentralized approach based on other vehicles' received cooperative maneuvers.

Research Goal 2: *Relevance-aware V2X network adaptation.*

Our goal is to allow for seamless monitoring of the cooperative maneuver from the communication perspective. Given the typical scenario of cooperative driving, the V2X network can be congested and the vehicles' mobility impairs the communication quality. In this work, we first focus on relevance-aware resource allocation to use channel resources efficiently, guarantee timely delivery of relevant information, and counteract channel congestion to avoid communication quality impairment. After that, we propose an adaptive data dissemination strategy using heterogeneous V2X access technologies to improve communication quality and extend the communication range for cooperative maneuvers.

Research Goal 3: *Communication-aware cooperative driving.*

Cooperative driving requires high communication quality to coordinate cooperative maneuvers safely and efficiently. However, the communication quality is physically constrained, where high communication quality cannot be guaranteed. Consequently, our goal is to adapt cooperative driving to the assessed communication quality. In scenarios with impaired communication quality, we reduce traffic efficiency to maintain safety. That way, cooperative driving can cope with higher reaction times to react to unexpected events. Reducing traffic efficiency is necessary because the information of other vehicles might be outdated. Hence, we increase the safety margins between vehicles if a high AoI is assessed while performing cooperative maneuvers.

In this thesis, we focus on V2X communication for cooperative driving. For this purpose, we concentrate on mechanisms to improve the communication quality in heterogeneous V2X networks and adapt cooperative driving to the available communication quality, increasing traffic efficiency and maintaining safety for vehicles.

Centralized cooperative driving [78, 133, 159, 170] is a promising research area because the traffic flow can be optimized considering all involved vehicles. However, we consider decentralized cooperative driving because it distributes the computation among vehicles, does not rely on infrastructure to decide for the cooperative maneuver, and preserves the driver's decision to cooperate.

Moreover, we assume that vehicles behave cooperatively and do not address cooperation fairness and incentives for individual vehicles to grant cooperation for improving the traffic efficiency, as considered in [62].

When coordinating cooperative maneuvers, vehicles must share their future intentions and trust other vehicles. Protecting the driver's privacy and future driving intentions [84, 156, 176] and securing cooperative driving from malicious data [7, 83, 84, 118, 130, 166, 231, 233] are relevant research areas. However, we do not contribute to these research areas in this thesis.

1.4 STRUCTURE OF THE THESIS

After introducing V2X communication for cooperative driving and discussing our research challenges and contributions, we provide necessary background information and classify the related work w. r. t. V2X access technologies, V2X network adaptations, and requirements for cooperative driving in Chapter 2. We formulate our problem in Chapter 3, focusing on communication quality in V2X networks and the impact of communication quality on the performance of cooperative driving.

Chapter 4 focuses on the communication quality and information relevance assessment in V2X networks. For this purpose, we propose a model for decentralized communication quality assessment, derive a numerical model to obtain the AoI in V2X networks, and define information relevance for cooperative driving. In Chapter 5, we propose relevance-aware resource allocation, introduce a data dissemination strategy for cooperative driving using heterogeneous V2X access technologies, and enable communication-aware cooperative driving based on our communication quality and information relevance assessment.

We outline our proposed simulation framework CoDA.KOM in Chapter 6, which implements a prototypical environment of the cooperative driving application *left-turning at an intersection*. CoDA.KOM is designed for large-scale simulations with a realistic representation of radio propagation effects and vehicular traffic flows. After that, we conduct numerical analysis and simulation evaluations of our core contributions in Chapter 7 to demonstrate the performance of our relevance-aware resource allocation, data dissemination strategy, and communication-aware cooperative driving. The conclusion of the thesis with a summary of our contributions and an outlook on potential future research directions is given in Chapter 8.

2 BACKGROUND AND RELATED WORK

In this chapter, we give background on Vehicle-to-Everything (V2X) communication and cooperative driving. We first elaborate on V2X networks in Section 2.1, explaining the communication architecture of Intelligent Transport Systems (ITS) and analyzing existing V2X access technologies. Further, we emphasize recent works on communication quality modeling and assessment approaches for V2X networks. After that, we explain the concept of cooperative driving in Section 2.2. More precisely, we focus on coordination approaches and message formats, summarize communication requirements for cooperative driving, and discuss the impact of impaired communication quality on traffic safety and efficiency. Section 2.3 presents recently proposed V2X network adaptations and data dissemination strategies for heterogeneous V2X access technologies. Finally, we summarize our findings and emphasize our identified research gap for this work in Section 2.4.

2.1 VEHICULAR COMMUNICATION NETWORKS

In the following, we briefly describe ITS in the context of V2X communication. For V2X communication, IEEE 802.11p and 3GPP LTE-V2X and its successor 3GPP 5G-NR are currently seen as the most promising technologies to connect vehicles in challenging environments [32]. Hence, we outline the communication architecture of IEEE 802.11p, focusing on ETSI ITS-G5. Furthermore, we briefly summarize the releases of 3GPP LTE-V2N, outline the different communication modes, and recap comparison efforts for both V2X access technologies w. r. t. communication quality. We conclude this section with an overview of communication quality modeling and assessment approaches for V2X networks.

2.1.1 *Intelligent Transport Systems*

ITS are expected to play a vital role in improving traffic comfort, efficiency, and safety. Vehicles communicate with other vehicles and the infrastructure [106]. ITS America started the standardization effort in 1997 and the Federal Communications Commission (FCC) allocated 75 MHz in the 5.9 GHz unlicensed spectrum in 1999, constituting the starting point of Dedicated Short Range Communication (DSRC) service in the USA [230]. The European Telecommunications Standards Institute (ETSI) allocated unlicensed spectrum between 5.855 GHz and 5.925 GHz, granted by the Electronic Communications Committee (ECC) in 2002 for ITS [59, 60, 100], constituting the starting point of ETSI ITS-G5 in Europe.

V2X *spectrum allocation*

The ETSI proposes a reference communication architecture for ITS in [93]. The reference communication architecture abstracts the applications from the underlying

Reference architecture

V2X access technologies and specifies an Open Systems Interconnection (OSI) protocol stack with a security and management entity. In the following, we discuss V2X access technologies to support cooperative driving.

2.1.2 *Access Technologies*

IEEE 802.11p and 3GPP LTE-V2X are the most promising access technologies for V2X applications, supporting cooperative awareness, collective perception, and cooperative driving [32]. In this work, we do not elaborate on Vehicular Visible Light Communication (VVLC) and mm-waves. These V2X access technologies are tailored to concrete use cases such as platooning and are not suited for most other cooperative driving applications such as left-turning at an intersection because of their limited communication range [32].

IEEE 802.11p

Distributed channel access

IEEE 802.11p is an adaptation of the IEEE 802.11a WiFi-based communication, where the reduced 10 MHz channel bandwidth (instead of 20 MHz for IEEE 802.11a) on the physical layer performs better in highly mobile environments [90]. On the Medium Access Control (MAC), IEEE 802.11p deploys Enhanced Distributed Channel Access (EDCA), which allows for Quality of Service (QoS) support and enables data traffic prioritization for V2X applications [103]. EDCA increases the queue length from applications with low priority data at the MAC, allowing for faster transmission of high priority messages under congested channel conditions. However, EDCA only prioritizes data traffic from relevant applications but cannot lower the channel load to counteract channel congestion. Therefore, the ETSI proposes Decentralized Congestion Control (DCC) [102] to counteract channel congestion and suggests three mechanisms: *i)* Transmission Rate Control (TRC), *ii)* Transmission Power Control (TPC), and *iii)* Transmission Data Rate Control (TDRC). We elaborate more on these DCC mechanisms in Section 2.3.

Congestion control

For ETSI ITS-G5 and according to the networking architecture in [99], the ETSI complements IEEE 802.11p with a GeoNetworking and Basic Transport Protocol (BTP) on the Networking and Transport Layer. ETSI GeoNetworking protocol provides mechanisms for geographical addressing in V2X networks and is divided into media-dependent and media-independent functionalities [105]. Currently, media-dependent functionalities cover ETSI ITS-G5 [107] and 3GPP LTE-V2X [108] technologies. ETSI GeoNetworking enables different addressing modes [98], using the location table created from received V2X messages. GeoUnicast (GUC) is used if a message needs to be transmitted to one vehicle at a specific location. Multi-hop communication (forwarding messages via multiple vehicles) is used until the destination at the specified location is reached. If the message needs to be transmitted to all vehicles in a specific location, GeoBroadcast (GBC) is used. In contrast, GeoAnycast (GAC) is used if the message only needs to be transmitted to at least one vehicle within a specific location. Topologically-Scoped Broadcast (TSB) reaches vehicles at the same location as the

Geo-Networking

transmitter vehicle. TSB leverages multi-hop communication to increase the dissemination area of the message. Single-Hop Broadcast (SHB) is a particular case of TSB, using only one-hop communication. In this work, we refer to Single-Hop Broadcast communication for Vehicle-to-Vehicle (V2V) communication unless otherwise stated.

Basic Transport Protocol

On the transport layer, BTP "provides an end-to-end, connection-less transport service in the ITS ad hoc network" [101] with minimum data overhead.

Using ETSI ITS-G5, vehicles exchange information with other vehicles and Roadside Units (RSUs). An RSU allows for an infrastructure-assisted V2X communication to improve traffic flows. For example, a traffic light RSU gives velocity advisories to vehicles close to an intersection to optimize the traffic flow [92].

3GPP LTE-V2X

Proximity service

V2N network mode

V2V/V2I direct mode

5G New Radio

In contrast to ETSI ITS-G5, cellular networks centrally coordinate channel access in the frequency and time domain of vehicles in their respective cells (spatial domain). In 3GPP LTE-V2X networks, mobile devices send data to the core network (cellular backend). The data is processed at the server offering the respective service. With Release 12, 3GPP LTE-V2X introduced the Proximity Service (ProSe), allowing mobile devices to communicate with each other directly [203]. In this mode, the cellular network only coordinates resource allocation and messages are sent directly to the receiver. V2X communication was first introduced in 3GPP LTE-V2X with Release 14 [204], offering two different communication modes: In the network mode, also referred to as Vehicle-to-Network (V2N), vehicles exchange messages with the cellular network. Here, the cellular network also coordinates the resource allocation in the time and frequency domain. The cellular network has different V2X application servers to process messages and send messages to respective vehicles. Based on the ProSe, 3GPP LTE-V2X also allows for a direct communication mode (Long Term Evolution (LTE)-PC5), where vehicles directly send messages via V2V or Vehicle-to-Infrastructure (V2I) communication. LTE-PC5 allows for two operation modes [203]: If vehicles have access to the core network, resource scheduling is managed centrally by the cellular network (in coverage), known as Mode 3. Without access to the Third Generation Partnership Project (3GPP) core network, vehicles schedule resources decentralized and distributed (out-of-coverage), known as Mode 4. With Release 15 [206], the 3GPP introduces 3GPP 5G-NR, enhancing the 3GPP LTE-V2X services. Release 15 provides, among others, carrier aggregation for Mode 4 (in addition to Mode 3) and reduces the message arrival time at Layer 1 to 10 ms [206]. The enhancements primarily target the extended set of considered V2X scenarios to support autonomous cooperative driving.

Vehicular Access Technology Comparison

IEEE 802.11p and 3GPP LTE-V2X are considered for V2X applications to support comfort, efficiency, and safety on the road [20, 160]. In [32], a qualitative assessment of V2X communication technologies for different V2X applications is provided.

In the following, we briefly summarize recent performance evaluations for both communication technologies to support V2X applications. We start with the comparison

11p vs. LTE-V2N

of IEEE 802.11p and 3GPP LTE-V2N. The author in [220] reveals in numerical analysis that, in contrast to IEEE 802.11p, 3GPP LTE-V2N cannot sufficiently support periodic message dissemination for V2X safety applications due to the lack of proper broadcasting support. Further, the field experiment in [235] shows higher reliability for IEEE 802.11p compared to 3GPP LTE-V2N. However, 3GPP LTE-V2N outperforms IEEE 802.11p w. r. t. throughput. In contrast, [135, 160, 161, 165, 225] show in simulations that 3GPP LTE-V2N provides better reliability performance in high vehicle density scenarios with high mobility compared to IEEE 802.11p. Especially under Non-Line of Sight (NLoS) conditions, i. e., obstacles block the direct wireless communication path causing signal attenuation, the reliability of IEEE 802.11p is impaired. However, [135, 225] show that the reliability and latency degrade for 3GPP LTE-V2N Unicast because of channel congestion in the downlink. The authors in [146] conclude that 3GPP LTE-V2N provides higher communication quality for a low vehicle density. In contrast, IEEE 802.11p shows better performance in congested scenarios with a high vehicle density.

11p vs. LTE-V2V

In the following, we provide a summary of communication quality comparisons for IEEE 802.11p and 3GPP LTE-V2V. The evaluation results in [20, 21] conclude that 3GPP LTE-V2V provides the same beacon periodicity performance as IEEE 802.11p with even fewer resources. In addition, better performance for IEEE 802.11p at close range (up to 300 m) and improved performance of 3GPP LTE-V2V at higher awareness ranges are shown. The evaluation in [169] shows that 3GPP LTE-V2V provides higher reliability for high communication ranges compared to IEEE 802.11p. Comparable results were shown in [37, 122] for 3GPP LTE-V2V in-coverage. However, the authors also show that IEEE 802.11p provides better latency performance than 3GPP LTE-V2V in out-of-coverage and better reliability for a communication range below 300 m.

Best V2X technology

In summary, the analyzed comparison studies conclude that the best V2X access technology depends on the specific V2X application and considered scenario. In general, IEEE 802.11p provides high reliability and low-latency communication in close-range scenarios up to 300 m. 3GPP LTE-V2V is best suited in low to mid-range scenarios up to 500 m, and cellular 3GPP LTE-V2N outperforms the other technologies in scenarios where a high communication range is required.

2.1.3 *Communication Performance Modeling and Assessment*

The comparison of V2X access technologies in the previous section has shown that the challenging vehicular environment impairs the communication quality in V2X networks. Numerical and simulation models describing the physical properties of V2X access technologies have been recently proposed to assess the communication quality in different scenarios [183, 221]. In the following, we summarize approaches to model and assess the medium access and radio propagation effects in V2X networks.

Channel Model

Much effort has been spent to correctly model and assess the radio propagation effects of V2X networks. The approaches are divided into Non-Geometry-based Stochastic (NGS), Geometry-based Stochastic (GBS), and Geometry-based Deterministic (GBD) approaches [150, 223]. A summary of V2X channel models is given in [183]. GBD models, such as proposed in [149], provide highly accurate results by explicitly modeling the scenario with high detail. However, the optical ray tracing of the radio propagation wave requires high computational resources. In contrast, NGS approaches, as proposed in [42, 120] solely rely on channel measurements to model object occurrence randomly. GBS approaches combine the accuracy of deterministic approaches and low computational complexity of stochastic approaches by providing a simplified scattering model, such as proposed in [121].

NGS, GBS, and GBD models

Medium Access Model

IEEE 802.11 Distributed Coordination Function (DCF) medium access has been modeled as a Markov Chain [25]. The extension provided in [243] allows analyzing DCF for heterogeneous vehicle message frequencies. The authors extended the Markov Chain model for EDCA with different access categories, considering the same message frequency for all vehicles. A Markov Chain for 3GPP LTE-V2V Mode 4 has been recently proposed in [229]. Using the Markov Chain model, reliability caused by message collisions, latency, and channel load for different vehicle densities and message frequencies can be analyzed.

Markov chain model

A performance and assessment model with lower computational complexity considering the communication range and channel load is provided for IEEE 802.11p [190] and 3GPP LTE-V2V Mode 4 [76]. Both models assess different message error types and the Channel Busy Ratio (CBR) from a system perspective.

2.2 COOPERATIVE DRIVING

In this section, we elaborate on different maneuver coordination protocols, i. e., centralized, decentralized, and hybrid approaches. Furthermore, we outline recently proposed message formats for cooperative driving, such as platooning [79, 113, 188, 213], merging on highways [133, 159, 182], and left-turning at an intersection [24, 36, 78]. After that, we summarize communication requirements for cooperative driving and describe the impact of impaired communication quality on traffic safety.

2.2.1 *Maneuver Coordination Protocols*

Cooperative driving can be organized in centralized, decentralized, and hybrid approaches, which we summarize in the following.

Centralized Cooperative Driving

Centralized coordination

Centralized cooperative driving aggregates traffic information such that a central controller optimizes the traffic flow. Centralized coordination of cooperative driving maneuvers is suggested in [159] for highway on-ramp merging using fuzzy logic. In their approach, a central entity optimizes the arrival times of vehicles at a merging point. The authors in [159] propose a central controller with reinforcement learning to coordinate cooperative maneuvers at an intersection with low computational costs, showing a significant increase in traffic efficiency.

Decentralized Cooperative Driving

V2X negotiation

Sense, model, plan, act

In contrast to centralized cooperative driving, decentralized approaches keep the decision of cooperation at the respective vehicle. Thus, they are independent of centralized infrastructure, and distribute the computation to coordinate cooperative maneuvers among the vehicles. In the following, we present decentralized cooperative driving approaches using V2X communication. In [36], a cooperative driving approach for intersections is suggested, where vehicles negotiate their velocities using V2X communication. A game-theoretic approach for cooperative coordination at an intersection is proposed in [133]. Vehicles coordinate cooperative driving maneuvers using game theory concepts to achieve a precise and optimal maneuver decision. The authors in [66] divide the cooperation process into *Sense*, *Model*, *Plan*, and *Act* states and introduce different message types to coordinate the maneuver depending on the current cooperation state. A trajectory-based approach was introduced in [57, 58], which is more flexible compared to state-dependent approaches and applies to different use cases. The trajectories are created from a set of target points, representing possible future positions of the vehicle. However, the authors concluded that the creation and selection of trajectories are computationally expensive [57].

Role-based negotiation

Generic, implicit cooperation

Challenges for cooperative maneuver planning and testing were summarized in [56]. A coordination approach for merging on highways using V2X communication is proposed in [182]. The authors show that cooperative driving reduces travel time and fuel consumption in their considered scenario. To be more robust to mixed traffic and impaired communication quality, [79] and [188] propose a role-based negotiation approach for platooning. However, both approaches are specific to the platooning use case and cannot be directly applied to other cooperative driving use cases like merging on highways or left-turning at an intersection. A generic approach for cooperative driving was proposed in [137], introducing a planned and optional desired trajectory. Vehicles always send a collision-free planned trajectory and implicitly ask for cooperation with an optional desired trajectory. The desired trajectory collides with at least another vehicle's planned trajectory and improves its traffic efficiency compared to its current planned trajectory. The generic cooperative driving approach in [137] was extended by [234], introducing explicit coordination to increase communication failure robustness. The approach was implemented in a simulation framework, considering a lightweight channel model. The authors in [24] decompose cooperative driving for non-signalized intersections in urban areas into observation, optimization, and control tracking. In the evaluation, the authors show that their approach achieves comparable performance to centralized coordination with slightly increased travel time.

Hybrid Cooperative Driving

A hybrid approach using centralized and decentralized coordination is suggested in [45], where vehicles coordinate cooperative driving maneuvers decentralized in the absence of supporting infrastructure and leverage central coordination if appropriate infrastructure is available. In [133], the authors combine a central coordination controller to predict traffic behavior at an intersection with a decentralized decision controller.

2.2.2 *Message Formats*

Vehicles coordinate cooperative maneuvers by exchanging driving intentions with each other. In the following, we summarize proposed message formats for cooperative driving, focusing on decentralized coordination.

One of the first message formats set for decentralized cooperative driving was proposed in [66], consisting of six different message types. The respective messages denote the vehicle cooperation state and divide it into request, offer, evaluation, accept, confirmation, and status messages. In [137], the authors suggest a more generic approach and propose the Maneuver Coordination Message (MCM). The MCM always contains the planned trajectory in Frenet frames, representing the vehicle's currently performed collision-free future path. A vehicle improves its traffic efficiency by sending an optional desired trajectory in addition to its planned trajectory. In [184], the MCM of [137] is adopted with its planned and optional desired trajectory. The MCM is extended with infrastructure-assisted capabilities to improve the coordination of driving maneuvers in different scenarios, e. g., RSU lane change advice. An extension to a trajectory-based message format of [137] is proposed in [142] and considered in the project IMAGinE (*Intelligent Maneuver Automation - cooperative hazard avoidance in realtime*) [91]. The proposed MCM consists of three containers, including the header, position, and trajectory containers. Information about the generation time and the vehicle's automation state is denoted in the header container. The position container refers to the current position of the vehicle. Finally, the trajectory container consists of a list of trajectories, including the reference trajectory, similar to the planned trajectory. The trajectory container may also include collision-free alternative trajectories. A vehicle asks for cooperation with one or multiple request trajectories, similar to the desired trajectory. Multiple alternative and requesting trajectories increase the message payload but can improve the cooperative driving coordination time and efficiency. The authors in [188] extend the coordination messages mentioned above with the Collaborative Maneuver Message (CMM) to account for impaired communication quality. The CMM increases the coordination capabilities such that vehicles differentiate between inform, request, and reply states, allowing for explicit coordination of cooperative driving maneuvers.

Trajectory-based message

Infrastructure assistance

Reference, request, alternative

Collaborative message

Application	Frequency [Hz]	Reliability [%]	Latency [ms]	Range [m]	Rate [kb/s]	Source	Derived From
Speed Management	$1-10$	N/A	>100 <300	>100	N/A	[162]	[92] [210]
Traffic Efficiency	N/A	99.999	<100	2,000	N/A	[8]	N/A
Advanced Driving	10	N/A	100	N/A	550–53,000	[44]	[1] [205]*
	N/A	90–99.999	$3-100$	N/A	960–53,000	[10]	[205]*
Cooperative Driving	N/A	>99	$<3-100$	<200–500	10–5,000	[32]	[205]*
Lane Merge	N/A	99.9	<30	>350	1,280	[10]	[65]
Platooning	N/A	High	Lowest	Medium	Medium	[74]	N/A
	N/A	>90–99.99	$<10-25$	N/A	N/A	[238]	[205]*

Table 2: Overview of V2X communication requirements for cooperative driving use cases. References marked with * may refer to different versions of the respective document.

However, the CMM does not explicitly account for impaired communication quality during the maneuver execution.

2.2.3 *Communication Requirements*

Cooperative driving has higher communication requirements than former V2X applications, e. g., cooperative awareness, because of the bidirectional maneuver coordination using V2X communication [87].

Table 2 summarizes recently proposed V2X communication requirements for cooperative driving. We categorize the communication requirements into message frequency, reliability, end-to-end latency, communication range, and data rate. In case the communication requirements were derived from a technical specification, it is also denoted in Table 2. We also mention the considered cooperative driving application.

V2X metrics

Interestingly, most of the work does not elaborate on the required message frequency for cooperative driving. The authors in [44, 162] suggest a message frequency between $1-10$ Hz. The reliability requirements are stringent and set above 90 % and up to 99.999 % [8, 10, 32, 238]. The currently available V2X access technologies cannot meet the upper requirements for reliability. The required minimum end-to-end latency depends on the cooperative driving use cases, where platooning requires the lowest latency below 30 ms [10, 238]. The latency requirements for other use cases are below 100 ms [8, 10, 32, 44, 162]. The required communication range to efficiently coordinate cooperative maneuvers is between 100 and 500 m [10, 32, 162], but it can also be as high as 2000 m [8]. The data rate requirements depend highly on the considered cooperative driving approach, where [205] suggests a data rate for cooperative driving between 10 to 53, 000 kbps. Most of the V2X communication requirements refer to [205].

In summary, cooperative driving requires reliable, low-latency communication with high data rate, communication range, and message frequency. According to our comparison analysis in Section 2.1, these strict communication requirements cannot be fulfilled with current V2X access technologies. Hence, we require V2X networks adaptations to provide a high communication quality for vehicles coordinating a cooperative maneuver. Furthermore, we need to adapt cooperative driving to the communication quality to maintain traffic safety if the communication quality is insufficient.

2.2.4 *Traffic Safety in Vehicular Networks*

In the following, we summarize recent work, which considered the safety aspect for impaired communication quality, i. e., if the communication requirements cannot be met before and while coordinating a cooperative maneuver.

Safety analysis

In [138], the authors perform a qualitative safety analysis of their proposed MCM in [137] and conclude that impaired communication quality does not introduce any additional safety risks. According to their analysis, impaired communication quality only lowers the traffic efficiency gain compared to the case without cooperative driving because a cooperative maneuver cannot be correctly coordinated with unreliable communication. However, the authors exclude unexpected events, e. g., emergency braking, during the maneuver execution *after* successfully coordinating a maneuver.

Adaptive cooperation

Safety analysis for platooning was performed in [213]. With the proposed parameter setup, the authors concluded that safe emergency braking is achieved. The authors in [177, 197] provide a framework to adapt the inter-platoon distance according to the available communication quality. If the communication quality is impaired, vehicles increase the inter-platoon distance to achieve a predefined crash probability. Hence, the frameworks trade traffic efficiency (increasing the inter-platoon distance) to achieve a target level of safety (crash probability). An extension for platooning in intelligent intersections for traffic safety considering impaired communication quality is provided in [214]. The authors compute the lower bound of safety margins between vehicles to avoid a potential crash in an intersection if vehicles sequentially pass the intersection.

2.3 NETWORK ADAPTATIONS IN VEHICULAR NETWORKS

In the previous section, the communication quality of recent V2X access technologies was summarized and we outlined requirements for cooperative driving. In this section, we recap V2X network adaptations to improve the V2X communication quality under challenging conditions, considering the physical limitations of V2X access technologies. We first summarize resource allocation mechanisms w. r. t. the vehicle's context. After that, we outline data dissemination strategies for V2X access technologies.

2.3.1 *Resource Allocation*

Resource allocation approaches adapt the message frequency to the vehicle's context to improve communication quality. In the following, we divide resource allocation into content-agnostic, content-aware, and relevance-aware approaches. Content-agnostic resource allocation adapts the message frequency to environmental conditions, such as channel and traffic congestion, or improves the Age of Information (AoI). Content-aware resource allocation focuses on the message content. If a V2X application requires more communication resources, it increases the message frequency. The approaches mentioned above purely focus on the own vehicles, thereby neglecting the communication requirements of other vehicles. Relevance-aware approaches assess the information relevance of the own and other vehicles to adapt the message frequency.

Content-Agnostic

In the following, we present content-agnostic resource allocation approaches and congestion control mechanisms for V2X networks.

A content-agnostic resource allocation approach was proposed in [88]. Vehicles adapt the message frequency to the number of perceived vehicles in the surroundings. *Channel load adaptation* One of the most popular approach for decentralized congestion control is presented in [15], called Linear Message Rate Integrated Control (Limeric), where vehicles linearly adapt their message frequency according to the currently perceived channel load. The approach was extended in [16], adapting to the vehicle dynamics, such as its velocity. Limeric was adopted in [102] for ETSI Adaptive Decentralized Congestion Control (A-DCC). ETSI DCC is analyzed and improvements are suggested in [128] to prevent under-utilization of available channel resources. Their evaluation reveals a significantly higher throughput, especially in high vehicle density scenarios. *Emergency exceptions* An extension for congestion control mechanisms in emergencies was proposed in [114]. The approach allows for temporary exceptions and higher message frequency if a vehicle is in an emergency. A heterogeneous resource allocation and power control mechanism is proposed in [194]. Vehicles adapt their message frequency and transmission power to the relative distance towards other vehicles for a lane change application. *Congestion and awareness control* In [193], the authors propose the Integration of congestion and awareness control (INTERN). The approach combines congestion control mechanisms with awareness control. The evaluation results show that INTERN prevents channel congestion and considers application requirements when allocating resources. INTERN was extended to Cross-layer Coordination of Multiple Vehicular Protocols (COMPASS) [191], which allows for cross-layer coordination, independent of the respective protocols. A game-theoretic approach for resource allocation in decentralized V2X networks was proposed in [38] and [240] with a cooperative and non-cooperative game model, respectively. The utility function of both approaches distributes the resources among the vehicles fairly.

Hidden terminals

Hidden terminal collisions severely impair the communication quality, especially in congested traffic conditions. The authors in [136] detect hidden terminals with bloom filters and adapt resource allocation based on the identified hidden terminals. The bloom filters are added to beacon messages such that receiving vehicles report the number of identified hidden terminals to the initial transmitter. [164] proposed a geo-based resource allocation to avoid hidden terminal collisions, where the cellular network provides information about the vehicles' positions to reduce message collisions caused by hidden terminals. A centralized congestion control using V2N communication to adjust beacon rates for IEEE 802.11p was proposed in [237]. The authors showed that event-driven messages are prioritized and the Packet Delivery Ratio (PDR) is reduced. Based on the position and heading of vehicles, the authors in [236] proposed a resource allocation approach to reduce message collisions in V2V networks, assisted by cellular infrastructure.

Cellular network assistance

Age of Information

In [124], the AoI in V2X networks was introduced, emphasizing the need for its minimization instead of optimizing MAC-related performance metrics. For example, reliability and latency have been analyzed in simulations in [227]. Decentralized resource allocation approaches are proposed in [3, 13, 14, 175] to provide a minimum AoI for V2X communication under congested channel conditions. The authors in [39–41, 117] propose resource allocation approaches to optimize the AoI using V2N networks.

Content-Aware

In the following, we present content-aware resource allocation approaches and specifically consider collective perception and cooperative driving applications.

Collective perception

The collective perception service is currently analyzed in conjunction with content-aware resource allocation approaches for standardization [104]. A comparison of different approaches was studied in [207], where the authors emphasize redundancy mitigation for the collective perception service. The same authors propose an improved algorithm in [208] to increase the V2X communication reliability and perception of vehicles. A combination of content-aware resource allocation approaches with ETSI DCC was performed in [209]. The authors revealed that ETSI DCC negatively impacts the performance of the collective perception service if not correctly configured. Different filtering schemes for the collective perception service to reduce the channel load were proposed and evaluated in [5, 48, 68, 89, 178]. The cellular channel load for diverse vehicular applications has also been studied in [155]. The authors used information relevance to increase the message frequency of important events.

Cooperative driving

A content-aware resource allocation method for the cooperative driving use case platooning was proposed in [226]. Based on the platoon state, the message frequency of the platoon members is adapted such that the channel load is minimized and platoon stability is guaranteed. The need for content-aware resource allocation was emphasized in [45] because it directly impacts the performance of the cooperative maneuver and channel congestion. In [46], a threshold-based Risk approach was introduced.

Relevance-Aware

Relevance assessment

Content-agnostic resource allocation approaches do not focus on specific V2X application requirements and content-aware approaches are highly specific to their respective application. In [73, 75], the authors propose a framework to assess the Value of Information (VoI) for V2X networks, allowing for novel resource allocation approaches. An early attempt to evaluate the information relevance for human drivers was made in [50], covering different information types. The authors in [115] estimate the collision probability of vehicles to allocate resources accordingly. Information relevance in combination with the information age was analyzed and evaluated in [158]. The authors showed that a relevance-aware approach improves the communication costs, leading to better decisions for the vehicles based on their perceived information.

Resource optimization

A first attempt to prioritize relevant information was studied in [125], where the authors introduced two different priority classes. Under congested channel conditions, high-priority messages are sent firstly. A similar approach was studied in [129], where the authors define high and low priority messages for different V2X applications or services. Vehicles with messages from lower priority services reduce their message frequency if another vehicle with a higher priority service requires to send messages, e. g., an emergency vehicle passing. In [157], the authors assess the relevance of certain events and reveal that a relevance-aware approach significantly reduces the communication overhead and simultaneously provides comparable performance results. An adaptive resource allocation approach based on QoS priority is proposed in [35]. The authors show an improved resource throughput and utilization in their evaluation. In [86], the authors used their VoI framework from [73, 75] and proposed a relevance-aware resource allocation approach for the collective perception service. The authors evaluate the VoI based on the message content and channel condition and reveal that relevance-aware resource allocation significantly improves the collective perception performance under high channel congestion.

2.3.2 *Heterogeneous Communication*

Cooperative driving requires high communication quality. However, a single access technology might be insufficient to fulfill the communication requirements at all times. Data dissemination strategies using heterogeneous V2X access technologies have been recently proposed to fulfill high communication requirements. In the following, we cover V2X clustering and offloading approaches.

Clustering

Clustering approaches locally aggregate communication resources by a cluster head with decentralized communication and forward them to other clusters using centralized communication. Due to frequent connection losses in decentralized V2X networks, much effort has been invested in forming stable clusters using a centralized network [43, 69, 151, 180]. Clustering approaches designed explicitly for safety-relevant data dissemination have been proposed in [196, 202, 216]. These approaches use the increased knowledge, extended communication range, and high reliability of V2N networks such that cluster changes are early recognized and cluster communication is improved. The aggregation of safety messages within a cluster reduces the communication overhead. Communication metric optimization using vehicle clustering is proposed in [4, 22, 144, 152, 232] to reduce latency and channel load and increase reliability, throughput, and communication range.

Offloading

Clustering approaches require aggregating information locally within the cluster before relaying it to other vehicles. The local message aggregation with decentralized communication introduces additional latency and messages are lost when aggregating *and* forwarding it to other clusters. Offloading approaches consider the best available V2X access technology to reliably transmit data with low latency [179, 246]. To improve communication quality, [2, 9, 54, 55, 110, 131, 132, 139, 140, 174, 185, 218, 242, 244, 245] use heterogeneous V2X communication technologies and adaptively select the most appropriate technology. Hence, the authors use machine learning, game theory, and probabilistic approaches based on the assessed radio performance metrics such as reliability, latency, AoI, and channel load. The mentioned approaches are content-agnostic and optimize the considered communication quality metrics, often referred to as QoS-balancing schemes. Based on the radio communication metrics *and* the application requirements, [77, 110, 155, 163, 192] perform vertical handovers, improving reliability, latency, and throughput.

QoS-balancing

Vertical handover

2.4 SUMMARY AND IDENTIFIED RESEARCH GAP

In this chapter, we provided background on V2X communication and cooperative driving and discussed related work for our introduced challenges in Section 1.2. In the following, we summarize key findings of the related work and emphasize the research gaps addressed by our contributions mentioned in Section 1.3.

How to assess the communication quality and relevance of information?

We have outlined comparison studies showing the performance of different V2X access technologies. Current V2X access technology cannot satisfy the high communication requirements of cooperative driving in different use cases and scenarios. The recent work studied communication quality assessment for each V2X access technology separately, focusing on either radio propagation or medium access effects. Further, the assessment of information relevance is currently limited to cooperative awareness and collective perception V2X applications. In our work, we provide a radio propagation and medium access model to assess the communication quality of messages in V2X networks. Furthermore, we assess the information relevance of MCMs based on the perceived maneuver coordination plan of other vehicles.

How to enable relevance-aware and adaptive V2X *communication for cooperative driving?*

Content-agnostic resource allocation approaches have been proposed to prevent channel congestion in scenarios with high vehicle density. In contrast, content-aware approaches currently focus on application communication requirements and relevance-aware approaches abstract resource allocation from the respective application. Data dissemination strategies presented in this chapter use heterogeneous V2X access technologies by locally clustering or offloading resources to other channels to improve the communication quality. However, these approaches are not designed for the specific communication requirements of cooperative driving, considering both the radio *and* application performance requirements. We propose a relevance-aware resource allocation and an adaptive data dissemination strategy with heterogeneous V2X access technologies. Relevance-aware resource allocation allocates resources based on the relevance to coordinate a cooperative maneuver. In addition, our adaptive data dissemination strategy extends the communication range to coordinate a cooperative maneuver early with high communication quality.

How to allow communication-aware safe and efficient cooperative driving?

Different maneuver coordination protocols have been proposed to increase traffic efficiency in congested scenarios. The impact of impaired communication quality on traffic safety when coordinating a cooperative maneuver has been discussed qualitatively and evaluated for platooning only. This work proposes a communication-aware approach to adapt the cooperative driving application to the assessed communication quality. Our approach adapts the safety margins of vehicles coordinating a cooperative maneuver to maintain traffic safety.

This chapter provided background on ITS, explicitly focusing on communication quality for IEEE 802.11p and 3GPP LTE-V2X access technologies. In the context of V2X communication, we surveyed approaches for the *i)* data assessment in Section 2.1, *ii)* communication-aware cooperative driving in Section 2.2, and *iii)* V2X network adaptation in Section 2.3. The related work does *not assess* the information relevance and communication quality for V2X networks to support relevance-aware resource allocation and adaptive data dissemination strategies for cooperative driving. Furthermore, the impact of communication quality on traffic safety for cooperative maneuvers has been studied insufficiently.

Traffic safety

In our work, we assess the communication quality for V2X networks and information relevance for cooperative driving in Chapter 4. We propose relevance-aware resource allocation and an adaptive data dissemination strategy for heterogeneous V2X access technologies in scenarios with high vehicle density to improve the communication quality for vehicles coordinating cooperative maneuvers in Chapter 5. Furthermore, we propose communication-aware cooperative driving to maintain traffic safety in scenarios with impaired communication quality.

3 COOPERATIVE DRIVING IN HIGH TRAFFIC DENSITIES

Cooperative driving requires high communication quality to coordinate maneuvers safely and efficiently [142, 213]. In the following, we discuss the communication quality of Vehicle-to-Everything (V2X) networks in high traffic density scenarios and the impact of impaired communication quality on the performance of cooperative driving in Section 3.1. Section 3.2 outlines our approach for a joint consideration of impaired communication quality for cooperative driving from the V2X network and cooperative driving perspective.

3.1 COMMUNICATION QUALITY IN VEHICULAR NETWORKS

In this section, we analyze the main factors impairing communication quality in V2X networks. Furthermore, we discuss how insufficient communication quality negatively affects cooperative driving from the traffic efficiency and safety perspective.

3.1.1 *Main Factors Impairing Communication Quality*

In the following, we analyze the impact of vehicle mobility, path loss, multi-path propagation, channel congestion, and message frequency on the communication quality in V2X networks.

Mobility

A key characteristic of V2X networks is the high mobility of vehicles in constrained road networks [223, 224, 239]. In wireless communication, the high velocity of vehicles may induce unreliable communication because of a frequency shift in the transmitted signal (Doppler effect) [23]. In addition, high vehicle velocities lead to frequent connection drops in decentralized V2X networks and require frequent cell handovers in centralized V2X networks.

Channel Attenuation

Wireless communication is prone to path loss, meaning that the attenuation of the transmitted signal power decreases over distance. According to the Friis model [67], the attenuation increases with the power of two with the communication distance. Furthermore, the attenuation is impacted by the message frequency of the carrier signal. As an additional effect, shadowing further increases the attenuation of the transmitted signal because of obstacles such as buildings or other vehicles [34]. Obstacles also induce reflection and scattering of the transmitted signal. The resulting multi-path propagation leads to constructive and destructive interference of the transmitted signal [23]. In summary, channel attenuation impairs the communication quality, affecting centralized and decentralized V2X networks. Hence, channel attenuation must be carefully considered in simulations to achieve a realistic representation of the communication quality in V2X networks [33].

Channel Congestion

The main factors for channel congestion are the number of vehicles sending messages, the message size, and message frequency [141]. In decentralized V2X networks, channel congestion causes message collisions because the probability that two vehicles send at the same time increases with the channel load. In addition, channel congestion also increases message latency because vehicles have to wait for the channel to become idle before sending messages [167]. In centralized networks, channel congestion also increases message latency and, in highly congested channels, messages may not even be scheduled and are dismissed [215].

Message Frequency

In V2X networks, messages are either sent periodically, e. g., the Cooperative Awareness Message (CAM) [96], or event-triggered, e. g., Decentralized Environmental Notification Message (DENM) [97]. A high message frequency allows for current information at the receivers, resulting in low tracking errors from the application perspective. As discussed before, the message frequency is one of the critical factors causing channel congestion. In V2X networks, the maximum message frequency is limited for applications [96] and can be further limited by congestion control mechanisms to improve the reliability and latency of the channel. However, a low message frequency impairs the communication quality from the application perspective because the Age of Information (AoI) of messages increases, inducing tracking errors.

3.1.2 *Impact of Communication Quality on Cooperative Driving*

Chapter 2 discussed the strict communication requirements for cooperative driving [32], including communication range, bandwidth, reliability, and latency. In the following, we qualitatively discuss the performance of cooperative driving if the required communication quality cannot be satisfied.

Early coordination

Before coordinating a cooperative maneuver, e. g., merging on highways or left-turning at an intersection, vehicles must recognize a cooperation conflict by exchanging their future driving intention with V2X communication. A high communication range allows for early conflict detection and increases the time to coordinate a cooperative maneuver. Early coordination and agreement on a cooperative maneuver are essential to decrease the cooperation cost for the vehicle offering cooperation. If the maneuver is coordinated early, the vehicle offering cooperation has more time to cooperate, requiring less deceleration. Hence, early maneuver coordination increases traffic efficiency of vehicles coordinating cooperative maneuvers.

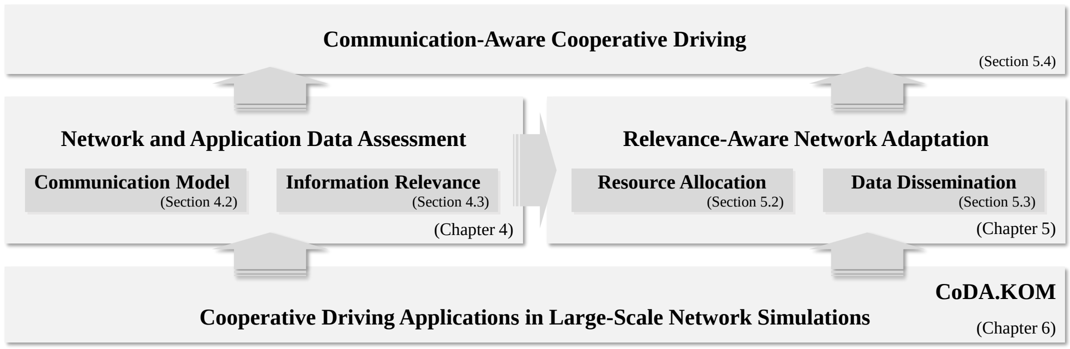


Figure 1: Concept of data assessment and V2X network adaptations for communication-aware cooperative driving.

After coordinating a cooperative maneuver and starting its execution, one could argue that there is no need for vehicles to exchange further messages with their cooperation partners as long as the vehicles can follow their agreed maneuvers. However, monitoring the cooperation partner to track the agreed maneuver is essential to maintain traffic safety. In this context, cooperative driving requires high communication quality to closely monitor the maneuver execution because the vehicle's environmental sensors might not recognize unexpected events in time due to obstructions and their limited perception range. If the V2X network cannot provide sufficient communication quality, the tracking errors of cooperation partners increase, impeding close monitoring of the cooperative maneuver. Consequently, vehicles cannot react to unexpected events in time, negatively impacting traffic safety.

Maneuver monitoring

Tracking error

3.2 TOWARDS COMMUNICATION-AWARE COOPERATIVE DRIVING

Figure 1 depicts our concept to address impaired communication quality for cooperative driving. In this thesis, we propose network and application data assessment in Chapter 4. Vehicles coordinating and executing cooperative maneuvers assess the communication quality and information relevance in the V2X network. The network and application data assessment and the cooperative driving application provide the input for relevance-aware V2X network adaptions. In Chapter 5, we focus on relevance-aware resource allocation and an adaptive data dissemination strategy to provide high communication quality for vehicles coordinating cooperative maneuvers. Finally, we complement the relevance-aware V2X network adaptations with communication-aware cooperative driving to adapt the cooperative maneuver to the assessed communication quality. Our simulation framework CoDA.KOM, which we introduce in Chapter 6, is used to evaluate the contributions of this thesis. CoDA.KOM enables cooperative driving and offers heterogeneous V2X access technologies in a large-scale network. In the following, we elaborate more on the challenges and approaches for network and application data assessment, relevance-aware V2X network adaptations, and communication-aware cooperative driving.

3.2.1 *Network and Application Data Assessment*

Network and application data assessment constitutes the fundamental for relevance-aware V2X network adaptation and communication-aware cooperative driving, as depicted in Figure 1. Cooperating vehicles must have a common understanding of the upcoming cooperative maneuver before agreeing to it, including knowledge about the expected communication quality during the maneuver. Cooperative driving enables the prediction of communication quality and information relevance using trajectories.

V2X quality

During the execution of a cooperative maneuver, the communication distance between the cooperation partners changes, affecting the communication quality during a cooperative maneuver. We address this problem with the communication quality assessment based on the vehicles' future paths. Hence, we predict the communication quality at different communication distances for the time of the cooperative maneuver.

Information relevance

Additionally, channel resources are limited and the relevance to coordinate a cooperative maneuver differs for vehicles in the same scenario. Vehicles must assess the information relevance to coordinate a cooperative maneuver. Messages required to coordinate a cooperative maneuver and solve an immediate collision conflict must be delivered in time to the cooperation partner to allow fast coordination and avoid a potential collision. In this context, information assessment must reflect the relevance of safety-critical situations and the necessity to coordinate a cooperative maneuver.

Decentralized assessment

Centralized data quality and relevance assessment have already been studied for V2X networks [154]. In this thesis, we focus on decentralized cooperative driving. Consequently, we present a decentralized approach to assess the communication quality and information relevance for cooperative driving such that vehicles remain independent of central infrastructure.

3.2.2 *Relevance-Aware V2X Network Adaptations*

Providing high communication quality in scenarios with high vehicle density constitutes a significant research challenge. Cooperative driving requires high communication range and reliable, low-latency communication to coordinate a cooperative maneuver timely and reliably. Strict communication requirements are addressed with relevance-aware V2X network adaptations based on the communication quality and information relevance assessment.

Resource allocation

Vehicles perceive the current channel congestion and predict the communication quality for different resource allocation strategies in a decentralized V2X network. Information relevance and communication quality assessment enable relevance-aware resource allocation to optimize resource allocation, providing high communication quality for cooperative driving, even in challenging vehicular traffic scenarios. For example, in a congested scenario, vehicles with highly relevant information allocate more resources than vehicles with less relevant information to send critical information to other vehicles in time. Hence, we address impaired communication quality because of channel congestion and low message frequency with relevance-aware resource allocation. Additionally, an adaptive data dissemination strategy with heterogeneous V2X access technologies improves the communication range, reliability, and latency by using the V2X access technology, which is expected to satisfy the required communication quality for a cooperative maneuver. Hence, we address impaired communication quality because of channel attenuation and congestion with our adaptive data dissemination strategy for vehicles coordinating a cooperative maneuver.

Data dissemination strategies

3.2.3 *Communication-Aware Cooperative Driving*

High communication quality cannot be guaranteed in V2X networks, especially in scenarios with high vehicle density because of physical constraints.

Need for adaptation

If V2X network adaptations cannot satisfy the communication quality requirements of cooperative driving, vehicles must adapt the cooperative maneuver to the assessed communication quality. For example, for left-turning at an intersection, cooperative driving opens a sufficiently large cooperation gap for a requesting vehicle to turn left in an intersection. The size of the cooperation gap has a significant impact on the traffic efficiency of cooperative driving: Increasing the gap for the left-turning vehicle increases the cost for the vehicle offering cooperation. From a traffic efficiency perspective, the provided cooperation gap should be as small as possible. After coordination, the vehicles monitor the cooperative maneuver by periodically exchanging Maneuver Coordination Messages (MCMs). That way, vehicles can react to unexpected events and, if required, abort the cooperation to maintain safety if the cooperation gap is insufficient to turn left safely in the intersection. However, insufficient communication quality induces tracking errors and vehicles might not be informed about unexpected events to abort the cooperative maneuver.

Monitoring maneuver coordination

V2X awareness

Consequently, we address impaired communication quality because of mobility, channel attenuation and congestion from the application perspective with communication-aware cooperative driving. We fully exploit the traffic efficiency gain of cooperative driving if high communication quality is available, allowing vehicles to monitor and track a cooperative maneuver accurately. In scenarios with impaired communication quality, communication-aware cooperative driving decreases traffic efficiency to maintain safety by increasing the safety margins between vehicles or denying cooperation according to the assessed communication quality.

In this chapter, we have discussed the challenges of V2X communication for cooperative driving. For this purpose, we outlined the factors impairing communication quality in V2X networks. We discussed how these communication effects decrease the traffic efficiency and safety performance of cooperative driving. Based on the identified challenges, we proposed our approach to provide high communication quality for cooperative driving and enable communication-aware cooperative driving. In the following chapters, we describe our approach in detail. We first focus on data assessment for cooperative driving in Chapter 4 and present relevance-aware V2X network adaptations and communication-aware cooperative driving in Chapter 5.

4 DATA ASSESSMENT FOR COOPERATIVE DRIVING

In this chapter, we present communication quality and information relevance assessment for cooperative driving in decentralized Vehicle-to-Everything (V2X) networks. In Chapter 2, we have outlined that cooperative driving requires high communication quality, which cannot be fulfilled with current V2X access technologies. Communication quality and information relevance assessment is required to enable relevance-aware resource allocation, adaptive data dissemination strategies, and communication-aware cooperative driving, as focused in this thesis. In this context, we focus on a decentralized approach to assess the vehicle's communication quality and information relevance independent from additional infrastructure [31].

V2X quality

In this chapter, we derive a communication model to assess radio propagation and medium access effects in V2X networks. Additionally, we extend the concept of the Age of Information (AoI) in V2X networks [29, 30]. The AoI allows to track the communication quality in one metric and not separately as Packet Delivery Ratio (PDR), latency, and message frequency. We propose two assessment models for the AoI: *i)* A measurement-based assessment from past observations allows to adapt the data dissemination strategy to the actual perceived AoI of other vehicles. Additionally, *ii)* a model-based assessment allows to obtain the AoI for the upcoming maneuver based on the vehicles' driving intentions. The model-based AoI assessment enables communication-aware cooperative driving. Lastly, we present information relevance assessment for cooperative driving. Communication quality and information relevance assessment are the fundamentals of relevance-aware resource allocation.

Information relevance

In this chapter, we first overview data assessment for cooperative driving use cases, focusing on the considered scenario and introducing the concept of trajectory-based data assessment in Section 4.1. In Section 4.2, we present our numerical model for communication quality assessment in a decentralized V2X network. Finally, in Section 4.3, we focus on information relevance assessment for cooperative driving.

4.1 OVERVIEW AND CONCEPT

In this section, we outline our scenario and discuss our concept of trajectory-based data assessment.

4.1.1 *Scenario*

Figure 2 depicts our considered scenario, where two vehicles coordinate a cooperative driving maneuver with V2X communication. For illustration, we consider an intersection scenario, where the cooperative driving application left-turning at an intersection

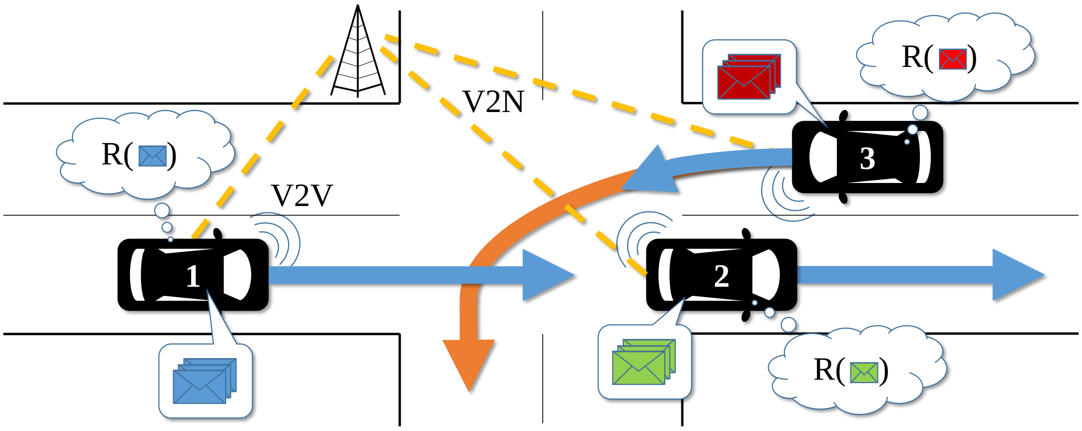


Figure 2: Data assessment in the cooperative driving use case scenario left-turning at an intersection with heterogeneous V2X access technologies.

improves traffic efficiency. Notably, our communication quality and information relevance assessment approach is not limited to a specific cooperative driving use case.

V2X data dissemination

The vehicles in the scenario inform other vehicles about their driving intentions by disseminating Maneuver Coordination Messages (MCMs) via V2X communication. All vehicles have access to the Vehicle-to-Vehicle (V2V) and Vehicle-to-Network (V2N) communication. In Figure 2, colored messages illustrate the dissemination of MCMs. We depict messages from vehicle 1 as blue, vehicle 2 as green, and vehicle 3 as red. Furthermore, vehicles obtain the information relevance of their current message w. r. t. their context and the message content.

Decentralized cooperative driving

In this thesis, we focus on a generic cooperative driving approach, where a vehicle's driving intention is sent to other vehicles using trajectories [137, 142]. For the rest of this thesis, we refer to the generic cooperative driving approach suggested in [137], where vehicles send planned and optional desired trajectories. The planned trajectory represents the vehicle's performed maneuver, illustrated as a blue arrow in Figure 2. A vehicle requests cooperation by sending an additional desired trajectory, depicted as an orange arrow. The desired trajectory conflicts with at least one other planned trajectory and increases the vehicle's traffic efficiency compared to its current planned trajectory. In Figure 2, vehicle 3 sends a collision-free planned trajectory and requests cooperation with an additional desired trajectory to avoid stopping in the intersection.

Assumptions

For our data assessment approach presented in this section, we assume that all vehicles are equipped with V2X communication and coordinate maneuvers with the mentioned cooperative driving approach. Hence, all vehicles continuously disseminate their planned and optional desired trajectories. Our data assessment obtains the communication quality and information relevance from the vehicle's own and received trajectories of other vehicles. Notably, our trajectory-based data assessment also applies to vehicles without V2X communication or a cooperative driving application. For unequipped vehicles, a mechanism to approximate their trajectories based on the road topology and past driving behavior is required. However, the estimation of driving intentions is not in the scope of this thesis.

4.1.2 *Objective and Concept*

In the following, we outline the objective of data assessment for cooperative driving in decentralized V2X networks. After that, we introduce our concept of trajectory-based data assessment for cooperative driving.

Data Assessment Requirements for Cooperative Driving

In this thesis, we focus on cooperative driving, where vehicles coordinate and decide on cooperative maneuvers autonomously without relying on additional infrastructure. Consequently, we present a decentralized approach to assess the vehicles' communication quality and information relevance to remain independent of infrastructure.

V2X quality

Each vehicle assesses the communication quality of each V2X access technology from other vehicles separately. For centralized V2N communication, a vehicle assesses the communication quality to the connected base station. For decentralized V2V access technologies, a vehicle assesses the communication quality to all vehicles in its communication range. According to Figure 2, vehicle 1 assesses the communication quality to vehicles 2 and 3. In this chapter, we derive a numerical model to obtain the PDR and latency for decentralized V2X communication. Based on the PDR and latency assessment, we propose a model-based AoI assessment approach to obtain the AoI for different communication distances, vehicle densities, and message frequencies. Further, we present a measurement-based assessment approach to capture the perceived AoI of other vehicles.

Information relevance

In this thesis, the information relevance quantifies the need to coordinate a cooperative maneuver and resolve a cooperation conflict. For cooperative driving, we assign more relevance to immediate conflicts in contrast to conflicts with sufficient coordination time. In Figure 2, vehicles 1 and 3 recognize a trajectory conflict in the intersection, assuming that both vehicles have received messages from each other. While approaching the intersection, the message relevance of vehicles 1 and 3 increases as long as the cooperation conflict exists, i. e., the relevance of the conflict increases. In contrast, vehicle 2 has no conflict with another vehicle in this intersection and, therefore, has a low information relevance. We denote the information relevance of a vehicle n as r_n, where $n \in \{1, 2, ..., N\}$ and N denotes the number of vehicles in the considered scenario. Vehicles continuously determine the information relevance of their MCMs based on received MCMs from other vehicles in their communication range. Furthermore, vehicles share their assessed information relevance with other vehicles by attaching it to their MCMs.

Computational complexity

The communication quality and information relevance assessment must have low computational complexity to enable efficient V2X network adaptations and communication-aware adaptive cooperative driving. In this context, we require that the data assessment computation time does not exceed the maximum message frequency λ_{MAX} of MCMs to allow for fast adaptations from the communication and application perspective. In this thesis, we consider a maximum message frequency of 10 Hz, resulting in a maximum computation time of 100 ms.

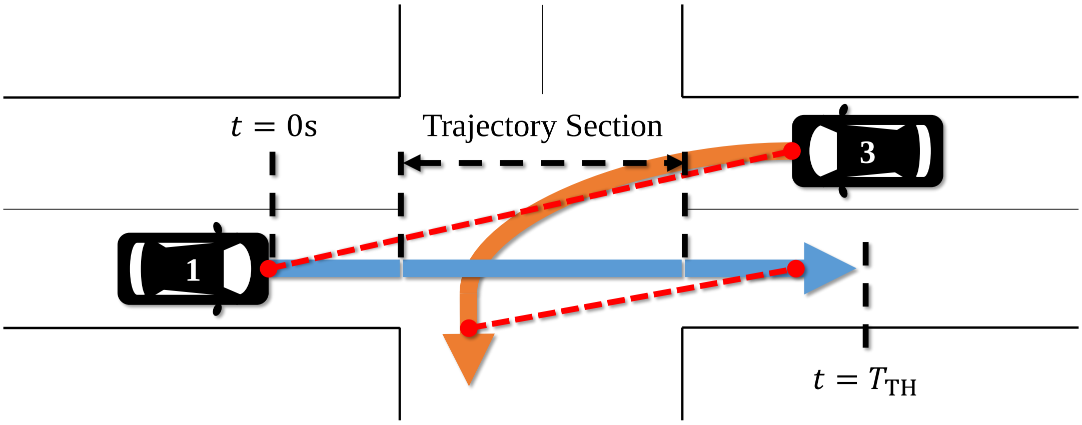


Figure 3: Trajectory-based data assessment in V2X networks.

The assessed communication quality and information relevance allow for relevance-aware V2X network adaptations and communication-aware cooperative driving, which we focus on in Chapter 5.

Concept of Trajectory-Based Data Assessment

Trajectory notation

Cooperative driving allows coordinating maneuvers in the near future by sharing driving intentions with other vehicles using trajectories. We use the following notation for trajectories, adapted from [137]. A trajectory describes a vehicle's position in Frenet coordinates as a function of time t and consists of one or multiple trajectory sections. In the time domain, the trajectory length is limited by the trajectory's time horizon T_{TH}. In the spatial domain, each trajectory section covers exactly one lane segment (lane of a road or an intersection). In Figure 3, the planned trajectory of vehicle 1 consists of three trajectory sections, covering the lane to the left, the intersection lane, and a part of the lane to the right. Each trajectory section has a specific validity time. The validity times of all sections represent the trajectory's time horizon. For example, the first trajectory section of vehicle 1 in Figure 3 starts at the current time and the third section ends at $t = T_{TH}$. Each trajectory section represents the vehicle's position, velocity, and acceleration at different time steps, described with longitudinal and lateral polynomials. The longitudinal polynomial is a function of time and the lateral polynomial is a function of the longitudinal polynomial. We obtain a vehicle's position, velocity, and acceleration for a given trajectory at any given point in time t within the trajectory's validity time $0 \leqslant t \leqslant T_{TH}$.

Data assessment

According to [137, 142], vehicles coordinate and agree on cooperative maneuvers based on the knowledge of other vehicles' future driving intentions obtained from the received MCMs. That is, cooperative driving resolves trajectory conflicts of vehicles. In the current research, the decision to agree on a cooperative maneuver is limited to the vehicles' driving intentions. We suggest that cooperative driving also considers the assessed communication quality and information relevance to coordinate cooperative maneuvers. On the one side, a vehicle measures the communication quality within a limited time interval to adapt its data dissemination strategy accordingly. On the other side, using trajectories, a vehicle also assesses the communication quality and information relevance for the upcoming maneuver within the trajectory's time horizon to enable communication-aware cooperative driving.

A vehicle improves the communication quality for the cooperative maneuver with relevance-aware resource allocation and adaptive data dissemination strategies. If impaired communication quality is assessed because of physical constraints in the V2X network, the cooperative maneuver is adapted to the available communication quality. We obtain the relative position, velocity, and acceleration for a pair of two vehicles' trajectories to assess the communication quality and information relevance at different time steps t and coordinate the upcoming maneuver in conjunction with the vehicles' shared driving intentions.

4.2 NUMERICAL MODEL FOR COMMUNICATION QUALITY ASSESSMENT

In the following, we present our numerical model to assess radio propagation and medium access effects. After that, we describe communication quality as the AoI in V2X networks, focusing on a measurement- and model-based approach, where the latter builds upon our numerical communication model.

4.2.1 *Radio Propagation and Medium Access in Vehicular Networks*

Communication quality is primarily prone to radio propagation (path loss and fading) and medium access effects, leading to unreliable communication [145, 183]. In the following, we provide a numerical communication model for vehicles to assess the communication quality as PDR and latency given the communication distance, number of vehicles, and message load. For this purpose, we briefly recap the well-known log-normal shadowing radio propagation model, which extends the Friis path loss model [67] and considers large-scale fading with random scatters. We obtain the PDR from the log-normal model to obtain the communication quality at different communication distances. The effects of medium access on the communication quality in V2X networks highly depend on the considered V2X access technology. In this thesis, we derive a medium access model for safety BROADCAST messages considering the IEEE 802.11P Enhanced Distributed Channel Access (EDCA) mechanism, which we have previously published in [31]. Medium access models for other V2X access technologies are left for future work. After that, we discuss the computational complexity of our medium access model. Finally, we derive an approximate model for addressing the computational complexity of our numerical communication model.

Communication Model

The Non-Geometry-based Stochastic (NGS) log-normal shadowing model has a significantly lower computational complexity compared to Geometry-based Stochastic (GBS) and Geometry-based Deterministic (GBD) radio propagation models [183]. In a high vehicle density scenario, a low computational complexity is decisive as the communication quality to all vehicles in the communication range has to be assessed simultaneously. Additionally, NGS models apply to different scenarios by adapting their parameters. In contrast, GBS and GBD require detailed environment knowledge. We obtain the reception power $P_{R,dBm}(d)$ in dBm at distance d as

Radio propagation

$$P_{R,dBm}(d) = P_{R,dBm}(d_o) - 10\gamma \cdot \log\left(\frac{d}{d_o}\right) + X_\sigma, \tag{1}$$

where $P_{R,dBm}(d_o)$ is the reception power at the reference distance d_o, γ is the path loss exponent, and X_σ is a zero-mean normally distributed random variable with standard deviation σ. The parameters γ and σ depend on the considered scenario and are obtained from measurement studies, such as performed in [42].

We obtain the PDR from path loss and random large-scale fading by integrating over Equation 1 with the minimum threshold power $P_{TH,dBm}$ required to decode a message successfully as

$$\rho_{PL}(d) = P(x \geqslant P_{TH,dBm}) = \int_{P_{TH,dBm}}^{\infty} \mathcal{N}(\mu(d), \sigma)\,dx. \tag{2}$$

$\mathcal{N}(\mu(d), \sigma)$ denotes the normal distribution with mean $\mu(d)$ at distance d and standard deviation σ. The mean is obtained from the first two summands of Equation 1, giving $\mu(d) = P_{dBm}(d_o) - 10\gamma \cdot \log\left(\frac{d}{d_o}\right)$. Using Equation 2, we assess the PDR for path loss and fading ρ_{PL} at any distance d.

Medium access

The medium access performance highly depends on the considered V2X access technology. In the following, we propose a numerical model to capture the effects of the IEEE 802.11p EDCA mechanism, considered on the access layer of ETSI ITS-G5 [102]. EDCA extends the Distributed Coordination Function (DCF) mechanism used for message scheduling in decentralized V2X networks to avoid message collisions. The communication quality decreases if two or more vehicles simultaneously send a message (access the medium), causing their messages to collide. In the following, we only consider message collisions of vehicles in communication range and neglect hidden node collisions. The estimation of hidden nodes is analyzed in [136]. Our proposed EDCA model allows assessing the communication quality for different vehicles' message frequencies and depends on the number of connected vehicles. As discussed in Section 2.1, the medium access for IEEE 802.11p has been modeled as a time-discrete Markov Chain [25]. However, an EDCA model for heterogeneous message frequencies for safety Broadcast messages with the highest access category has not been proposed yet. In IEEE 802.11p, messages are slotted in the time domain [90].

Figure 4 depicts the Markov Chain, representing the EDCA backoff mechanism for safety Broadcast messages of the highest access category. The Markov Chain is based on the IEEE 802.11 DCF model from [145] and follows the specification of EDCA from [90] and [103]. In the following, we derive the probability τ_n that a message of vehicle n is sent in a randomly chosen time slot. A message is sent if the message arrives at the backoff stage b_{-1}.

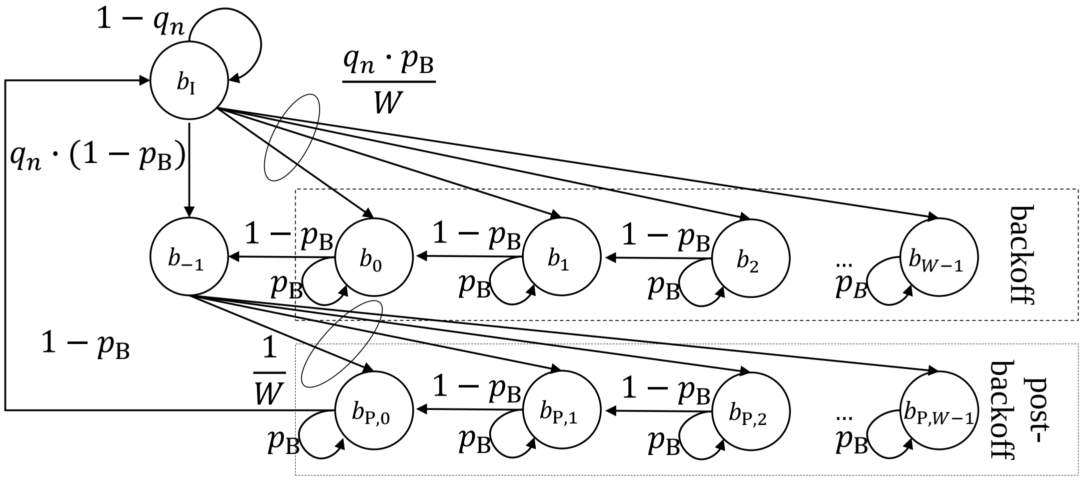


Figure 4: Markov Chain representing the IEEE 802.11P EDCA backoff mechanism with a backoff and post-backoff stage from the perspective of a vehicle, adapted from [31].

After sending a message, EDCA initiates a post-backoff stage to avoid sending a message immediately after the last message has been sent. We leave the post-backoff stage if we are in the post-backoff stage $b_{P,0}$ and the channel is not busy. The probability that the channel is busy, i. e., at least one other vehicle occupies the channel, is denoted as p_B. Further, the probability that a message from a V2X application of vehicle n arrives at the Medium Access Control (MAC) is denoted as q_n. EDCA remains in the idle stage b_I if no message arrives at the MAC. Hence, we obtain the transition probability for the idle stage as

Idle stage

$$\begin{aligned} P(b_I|b_{P,0}) &= 1 - p_B, \\ P(b_I|b_I) &= 1 - q_n. \end{aligned} \tag{3}$$

From the idle stage, we transition to the backoff stage if a message can be sent and the channel is busy. We randomly transition to one of W backoff stages b_k, where W depends on the respective Quality of Service (QoS) access category. $k \in \{0, 1, ..., W-1\}$ denotes our current backoff stage. The QoS access category depends on the considered V2X application of the respective message. Following [90], W is not increased in Single-Hop Broadcast (SHB) mode if the channel is busy. We remain in the current backoff stage if the channel is busy and transition to the next backoff stage b_{k-1} if the channel is idle. We write the transition probabilities for the backoff stages as

Backoff stage

$$\begin{aligned} P(b_k|b_I) &= \tfrac{q_n \cdot p_B}{W}, & k &\in \{0, ..., W-1\}, \\ P(b_k|b_k) &= p_B, & k &\in \{0, ..., W-1\}, \\ P(b_k|b_{k+1}) &= 1 - p_B, & k &\in \{0, ..., W-2\}. \end{aligned} \tag{4}$$

Post-backoff stage

After sending a message in stage b_{-1}, i. e., we have finished the backoff stage or transitioned from the idle stage, we randomly transition to one of W post-backoff stages. Similar to the backoff stage, we transition to the next post-backoff stage $b_{P,k-1}$ if the channel is idle. We remain in the current post-backoff stage if the channel is busy. Hence, the transition probabilities for the post-backoff stages are

$$\begin{aligned} P(b_{P,k}|b_{-1}) &= \tfrac{1}{W}, & \\ P(b_{P,k}|b_{P,k}) &= p_B, & k \in \{0, ..., W-1\}, \\ P(b_{P,k}|b_{P,k+1}) &= 1 - p_B, & k \in \{0, ..., W-2\}. \end{aligned} \tag{5}$$

Stationary state

Now, we obtain the stationary state of the Markov Chain as

$$1 = b_I + b_{-1} + \sum_{k=0}^{W-1} b_k + \sum_{k=0}^{W-1} b_{P,k}. \tag{6}$$

Using the transition probabilities for the idle, backoff, and post-backoff stages in Equation 6, we get

$$1 = \frac{b_{-1}}{q_n} + b_{-1} + \sum_{k=0}^{W-1} \frac{W-k}{W} \frac{p_B}{1-p_B} b_{-1} + \sum_{k=0}^{W-1} \frac{W-k}{W} \frac{1}{1-p_B} b_{-1}. \tag{7}$$

We solve Equation 7 for b_{-1} and get

$$b_{-1} = \tau_n = \frac{2q_n \cdot (1-p_B)}{2(1+q_n) \cdot (1-p_B) + q_n \cdot (1+p_B) \cdot (W+1)}. \tag{8}$$

For a randomly chosen time slot, Equation 8 denotes the probability of a vehicle n to send a message. Considering N vehicles, we obtain the probability that the channel is idle as the probability that no vehicle sends in a randomly chosen time lost, giving

$$p_I = \prod_{n=1}^{N} (1 - \tau_n). \tag{9}$$

Load equation

The probability that the channel is busy is then given as $p_B = 1 - p_I$. According to [25], there is always a message available at the MAC, giving $q_n = 1$ for the load equation. A more realistic approach was proposed in [145], assuming a Poisson distribution for the message arrival rate at the MAC, giving

$$q_n = 1 - \exp\left(-\lambda_n \cdot T_{VS}\right), \tag{10}$$

where T_{VS} is the duration of a virtual time slot and λ_n is the message frequency of vehicle n. An expression for the duration of the virtual time slot is given in [25], denoting the duration where the channel is idle or busy with either a successful or collision transmission. We modified T_{VS} such that the channel is idle for the Arbitration Inter-Frame Spacing (AIFS) time T_{AIFS} [90] *and* the channel slot time $T_{CH,S}$. After the channel was sensed busy, EDCA first waits for the AIFS time T_{AIFS} *and* the channel slot time $T_{CH,S}$ before sending the next message. Hence the virtual time slot is given as

$$T_{VS} = p_I \cdot (T_{AIFS} + T_{CH,S}) + p_S \cdot T_S + p_C \cdot T_C. \tag{11}$$

According to [145], the probability of a successful transmission is given by

$$p_S = \sum_{n=1}^{N} \tau_n \cdot \left[\prod_{j \neq n} (1 - \tau_j) \right]. \tag{12}$$

In SHB mode, we have the same duration for a successful or collision transmission, denoted as T_S and T_C, respectively. We do not wait for an acknowledgment message after sending a message. The duration of a frame T_{FD} denotes the temporal message expansion, which is influenced by the message size M. T_{FD} is also constrained by the bits per Orthogonal Frequency-Division Multiplexing (OFDM) symbol B_{OFDM}. Furthermore, messages must be scheduled in the time slots $T_{CH,S}$ of IEEE 802.11P. Moreover, we wait for the AIFS time T_{AIFS} before sending a message and consider the propagation delay T_{PD}, giving

Transmission duration

$$T_S = T_C = \left\lceil \frac{T_{FD} + T_{AIFS} + T_{PD}}{T_{CH,S}} \right\rceil \cdot T_{CH,S}. \tag{13}$$

The frame duration T_{FD} is given in [90] as

$$T_{FD} = T_{PRE} + T_{SIG} + T_{OFDM} \left\lceil \frac{M + 6\,\text{bits} + 16\,\text{bits}}{B_{OFDM}} \right\rceil, \tag{14}$$

where T_{PRE} and T_{SIG} are the durations' of the preamble and signal headers of the physical layer in IEEE 802.11P, respectively. T_{OFDM} is the length of an OFDM symbol. According to [90], the tail and service bits are also considered in Equation 14 with 6 bits and 16 bits, respectively.

Reliability

Finally, we obtain the PDR as the probability that no other vehicle j is sending a message [25], giving

$$\rho_{n,MA} = \prod_{j \neq n} (1 - \tau_j). \tag{15}$$

Notably, Equation 15 does not consider the case that more than two vehicles send messages simultaneously.

Throughput

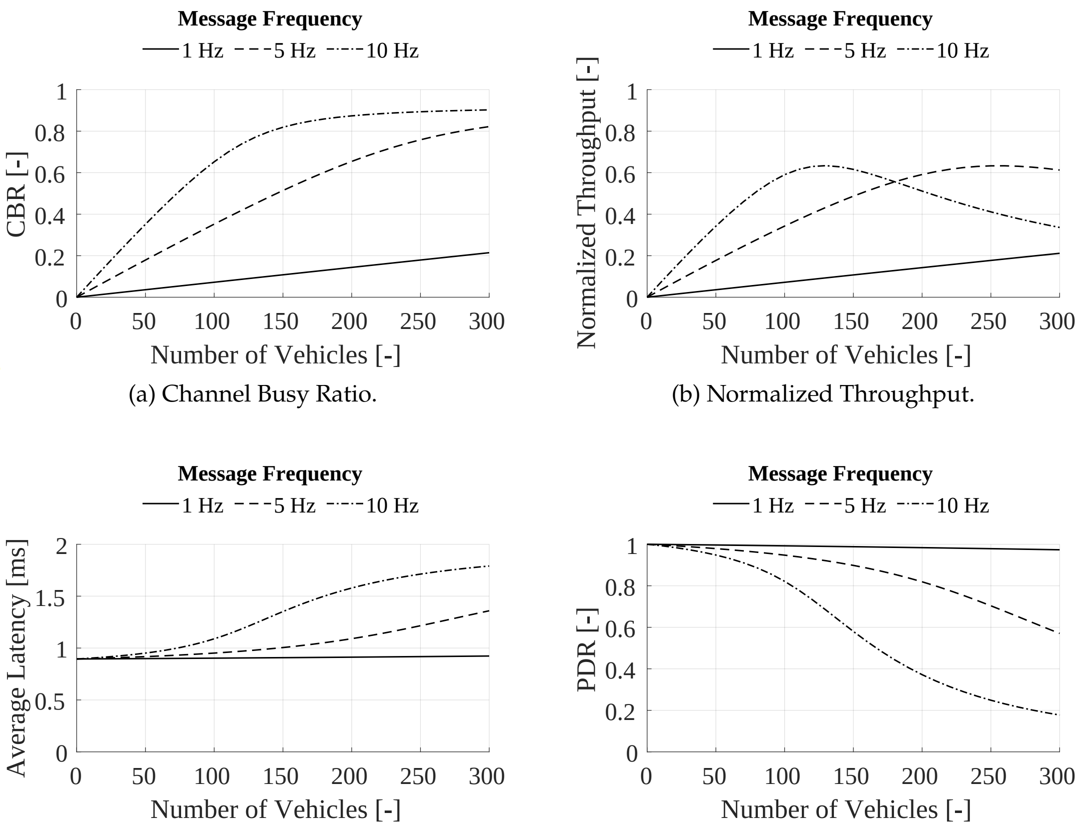
The normalized throughput is given in [25] by the time messages are successfully sent in the channel $p_S \cdot T_{FD}$ divided by the virtual duration of a time slot T_{VS}, giving

$$S = \frac{p_S \cdot T_{FD}}{T_{VS}}. \tag{16}$$

We also derive an expression for the Channel Busy Ratio (CBR) C, which is frequently used as a V2X communication metric, especially for European Telecommunications Standards Institute (ETSI) Decentralized Congestion Control (DCC) [102]. The channel is busy if we either have a successful or collision transmission. The transmission duration is given by the frame duration T_{FD} in Equation 14. Hence, we obtain the CBR as the fraction of time where the channel is busy and the virtual duration of a time slot, giving

Channel busy ratio

$$C = \frac{(p_S + p_C) \cdot T_{FD}}{T_{VS}}. \tag{17}$$



(a) Channel Busy Ratio.

(b) Normalized Throughput.

(c) Average Latency.

(d) Packet Delivery Ratio.

Figure 5: Assessment of communication quality depending on the number of vehicles and message frequency in a numerical IEEE 802.11p network model.

Latency In a congested scenario, it is expected that the medium access cannot immediately send a message. In [6], a message arriving at the MAC is expected to complete $0.5 \cdot (W-1)$ backoff stages before being sent, where a backoff stage is completed in a virtual time duration T_{VS}. Hence, the average latency is given as

$$L = \frac{0.5T_{VS} \cdot (W-1)}{1 - 0.5(W-1) \cdot \lambda_n \cdot T_{VS}}. \tag{18}$$

We use our derived communication model to assess the communication quality for vehicles in a scenario. For illustration in Figure 5, we consider the parameters used for the log-normal shadowing model in [29] and the parameters for the IEEE 802.11p EDCA model from [31].

Figure 5 depicts the CBR, normalized throughput, average latency, and PDR obtained from our communication model derived in this section for different numbers of vehicles. Note that the channel load is impacted by the number of vehicles. Hence, we can also obtain the communication quality for 0 vehicles. For simplicity, all vehicles have the same message frequency. However, our communication model allows us to obtain the communication quality for different message frequencies, i. e., each vehicle

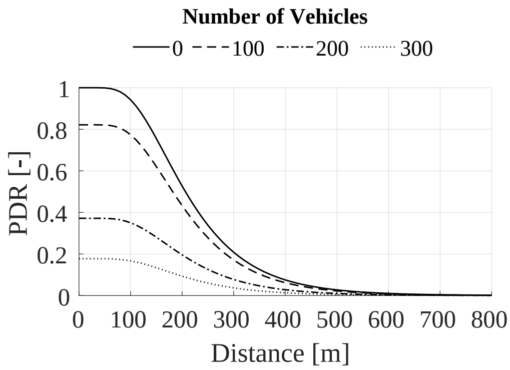


Figure 6: PDR assessment for a message frequency of 10 Hz and different number of vehicles in a numerical IEEE 802.11p network model.

can have an individual message frequency. Figure 5a depicts the CBR obtained from Equation 17 for different numbers of vehicles, where the vehicles have a message frequency of 1 Hz, 5 Hz, and 10 Hz. According to [102], the channel is considered relaxed below a CBR of 0.3 and congested above a CBR of 0.6. If all vehicles have a message frequency of 10 Hz, the channel is considered congested for more than 80 vehicles in the scenario. For 5 Hz, the channel is congested for more than 175 vehicles in the scenario. For 1 Hz, the channel is not congested even with 300 vehicles in the scenario. The normalized throughput of the V2X network is depicted in Figure 5b. Interestingly, the normalized throughput increases for an increasing number of vehicles and decreases again for more than 130 and 260 vehicles considering a message frequency of 10 Hz and 5 Hz, respectively. Few vehicles cannot use all communication resources of the respective channel. For 5 Hz and 10 Hz, the normalized throughput reaches its maximum at 0.63 for 130 and 260 vehicles, respectively. Figure 5c depicts the average latency depending on the number of vehicles and the message frequency. The average latency does not exceed 1.8 ms, even if the channel is congested and does not decrease below 0.9 ms for a relaxed channel. In Figure 5d, we depict the PDR as a function of the number of vehicles for different message frequencies. With a message frequency of 10 Hz, the PDR is below 0.5 for more than 160 vehicles.

Channel busy ratio

Normalized throughput

Average latency

Packet delivery ratio

Figure 6 depicts the PDR as a function of the communication distance obtained from our communication model for a message frequency of 10 Hz and different numbers of vehicles. We assume that the PDR for path loss and medium access is independent of each other, such that $\rho_n(d) = \rho_{n,MA} \cdot \rho_{PL}(d)$ holds. The PDR without medium access effects is obtained from Figure 5d for 0 vehicles. From Figure 6, we see that the PDR is severely impaired because of the medium access if the channel is congested. The PDR is below 0.8 for 100 vehicles. The PDR also severely decreases with an increasing communication distance and is, independent from the congestion state, below 0.2 for a communication distance higher than 300 m. Next, we discuss the computational complexity of our proposed IEEE 802.11p EDCA model.

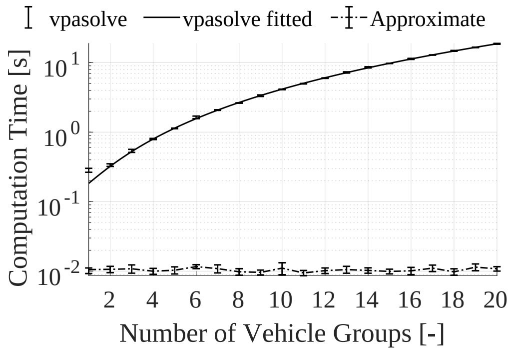


Figure 7: Computation time for the numerical and approximate IEEE 802.11p EDCA model measured with commodity hardware, taken from [31].

Computational Complexity

Our proposed numerical EDCA model assesses the PDR, CBR, normalized throughput, and average latency by solving Equation 8, which recursively depends on q_n and p_B. Each vehicle n can have a different load q_n, leading to N coupled non-linear equations τ_n. A numerical solver is required to solve the coupled non-linear equations.

However, the vehicles' message frequency is lower- and upper-bounded with a minimum and maximum message frequency [102], λ_{MIN} and λ_{MAX}, respectively. Furthermore, the vehicles' message frequencies can be discretized in message frequency steps λ_S, such that we get N_G vehicles groups with the same message frequency as

$$N_G = \left\lceil \frac{1}{\lambda_S} \cdot (\lambda_{MAX} - \lambda_{MIN}) + 1 \right\rceil . \tag{19}$$

Considering the assumptions mentioned above, the number of coupled non-linear equations reduces to N_G. For example, with a message frequency between 1 Hz and 10 Hz and a message step size of 0.5 Hz, we get 19 vehicles groups.

In the following, we obtain the computational complexity of our numerical EDCA model by measuring the computation time to solve Equation 8 for different numbers of vehicle groups. As an example, we use MatlabR2020b vpasolve to solve Equation 8 for up to 20 vehicle groups.

Figure 7 depicts the computation time for different vehicle groups, showing the confidence interval of vpasolve for a series of 30 simulation runs on a logarithmic scale. Figure 7 shows that the computation time exceeds 20 s to obtain the PDR for 20 vehicle groups. We fit the computation time of our numerical EDCA model with a second-degree polynomial. Hence, we approximate the computational complexity as $\mathcal{O}(N_G^2)$.

In this chapter, our goal is to derive a communication model that allows for V2X network adaptations and communication-aware cooperative driving. In this context, a computation time of up to 20 s to obtain the PDR of vehicles in the V2X network does not allow for timely V2X network and cooperative driving adaptations. In the following, we propose an approximate model with a constant computation time below

0.02 s, measured with commodity hardware, based on our derived IEEE 802.11p EDCA model. The computation time also fulfills our requirement of less than 100 ms.

Approximate PDR Model

Our proposed numerical IEEE 802.11p EDCA model considers the message frequency and obtains the PDR for each vehicle separately. In the following, we assume that the vehicles' message frequencies λ_n are bounded between a minimum and maximum message frequency, giving $\lambda_{MIN} \leqslant \lambda_n \leqslant \lambda_{MAX}$. Furthermore, we assume that the maximum message frequency λ_{MAX} is significantly lower than the theoretical maximum message frequency in the respective channel, i. e., $\lambda_{MAX} \ll \lambda_{CH,MAX}$. *Assumptions*

We address the computational complexity by reducing the number of coupled non-linear equations. Let us assume that our vehicle n with the message frequency λ_n has perceived the message frequency of $N-1$ vehicles j with the message frequency λ_j. Vehicle n obtains the network's average message frequency from its perspective as

$$\bar{\lambda}(\lambda_n) = \frac{1}{N} \cdot \left[\lambda_n + \sum_{j \neq n} \lambda_j \right]. \tag{20}$$

Considering a network's average message frequency $\bar{\lambda}$, we obtain an approximate network load as *Average load*

$$\tilde{q} = 1 - \exp\left(-\bar{\lambda} \cdot T_{VS}\right). \tag{21}$$

Equation 21 is a sufficiently accurate approximation if $\lambda_{MAX} \ll \lambda_{CH,MAX}$ and $\lambda_{MIN} \leqslant \lambda_n \leqslant \lambda_{MAX}$ because of the exponential function in Equation 10.

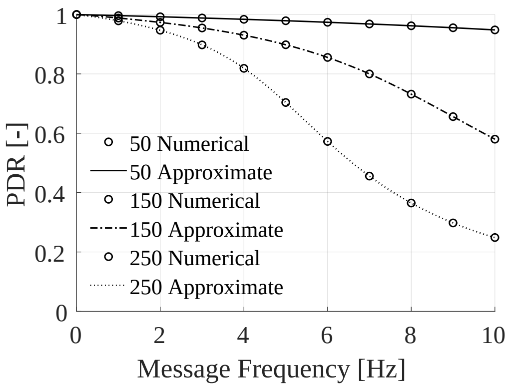
From Equation 15, it is evident that $\rho_{n,MA} \approx \tilde{\rho}_{MA}$ if $q_n \approx \tilde{q}$, meaning that all vehicles are assumed to experience the same PDR $\tilde{\rho}_{MA}$. Consequently, we obtain the approximated PDR experienced by all vehicles in the network as

$$\tilde{\rho}_{MA} = (1 - \tilde{\tau})^{N-1}. \tag{22}$$

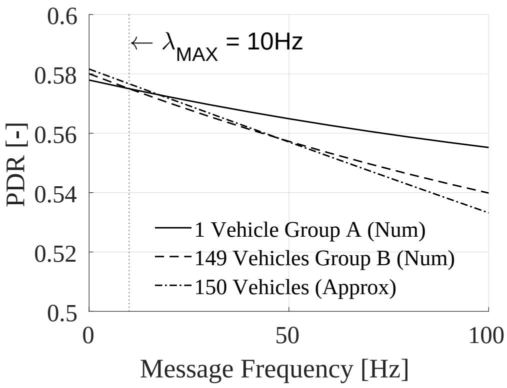
Equation 22 requires a numerical solver to obtain $\tilde{\tau}$ for $\tilde{q}$ but only considers one vehicle group. As depicted in Figure 7, the computation time significantly reduces but is still higher than the required computation time of 100 ms. *Approximate model*

To avoid a numerical solver for communication quality assessment and further decrease the computation time, we approximate the PDR for a set of vehicles as a function of the network's average message frequency.

Therefore, we obtain the PDR for different numbers of vehicles in the minimum and maximum message frequency range using our numerical communication model. Figure 8a depicts the PDR for 50, 150, and 250 vehicles with a message frequency between 0 and 10 Hz. We use the non-linear least square method to approximate the PDR of our numerical EDCA model with a Gaussian exponential function. Each Gaussian exponential function represents a specific number of perceived vehicles in the V2X network. A vehicle assesses the number of vehicles N and obtains the network's average message frequency $\bar{\lambda}$ in its communication range. Then, we obtain *PDR assessment*



(a) Comparison.



(b) Edge case analysis.

Figure 8: PDR as a function of the message frequency for the numerical and approximate model, taken from [31].

the PDR from the Gaussian exponential function. Moreover, a vehicle n can assess the impact of different message frequency strategies on the PDR of the V2X network, which we require for relevance-aware resource allocation in Section 5.2. In Figure 7, the approximate PDR model significantly reduces the computation time to 0.02 s.

The approximate EDCA model assumes that the message load of vehicles is comparable for all vehicles, i. e., $q_n \approx \tilde{q}$. The vehicles' message frequencies are all reflected in the network's average message frequency and, by changing the message frequency of a vehicle, we slightly impact the network's average message frequency.

However, assuming a comparable load $\tilde{q}$ for all vehicles also implies that all vehicles have the same PDR. According to Equation 15, the same PDR for vehicles with different message frequencies cannot correctly reflect the numerical EDCA model, especially if the network's average message frequency does not reflect the individual vehicle's message frequency.

Numerical V2X model

For this purpose, we consider that $N - 1$ vehicles send with a message frequency of 10 Hz and 1 vehicle varies its message frequency. Figure 8b compares the PDR for the numerical and approximate models. In the scenario, we consider 1 vehicle, referred to as Group A, with a message frequency between 0 and 100 Hz and 149 vehicles (referred to as Group B) sending with a message frequency of 10 Hz. Notably, the approximate model does not differentiate between vehicles with different message frequencies and obtains the same PDR for all vehicles. Interestingly, the PDR in the numerical model is higher for vehicles with a higher message frequency than vehicles with a lower message frequency. A vehicle with a high message frequency has a higher share of messages sent in the channel. However, messages can only collide with messages from other vehicles. Therefore, the probability of a message collision is lower with a high share of sent messages compared to a lower message share. Furthermore, the PDR is equal if all vehicles send with the same message frequency of 10 Hz. The PDR decreases for all vehicles if the vehicle from Group A increases its message frequency for all models because the channel load increases. However, the PDR decreases faster

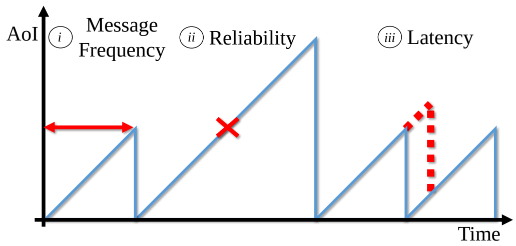


Figure 9: Evolution of the AoI over time, qualitatively showing the effects of message frequency, reliability, and latency.

for the vehicles from Group B because of the lower message frequency compared to the vehicle from group A.

We see that our approximate model obtains comparable results for $\lambda_{MAX} \leqslant 10\,\text{Hz}$, which confirms our assumption that $\lambda_{MAX} \ll \lambda_{CH,MAX}$. Suppose the vehicle from Group A further increases its message frequency. In that case, the approximate model cannot correctly reflect the message frequency of vehicles with the network's average message frequency, leading to a deviation in the PDR compared to the numerical model. For a message frequency of 100 Hz, the PDR deviates by less than 10 % and 1 % compared to the numerical model for the vehicle from Group A and B, respectively.

Approximate V2X model

4.2.2 *Age of Information*

In the following, we present a model to describe the AoI in V2X networks. The AoI describes how current the information is at the receiver. When a vehicle receives a message, its information gets outdated until a subsequent message is received. We identified three communication effects impairing the freshness of information. As depicted in Figure 9, these effects are *i)* message frequency, *ii)* reliability, and *iii)* latency. In the following, we provide an approach for measurement-based and model-based assessment of the AoI. The measurement-based approach, which we previously presented in [30], assesses the perceived peak AoI from current and past observations of a specific vehicle and is used in Section 5.3 to transition to the V2X access technology providing the required communication quality for cooperative driving. The model-based approach, which we previously presented in [29], allows assessing the peak AoI at different time steps of the vehicles' trajectories, enabling communication-aware cooperative driving, which we discuss in Section 5.4.

Measurement-Based Assessment

In the following, we propose our measurement-based assessment of the peak AoI. A vehicle n obtains the AoI $\Delta_{n,j}$ from a message of vehicle j at the current time t_0 as $t_0 - t_{j,msg}^{last}$, where $t_{j,msg}^{last}$ is the time when the last received message of vehicle j at vehicle n was created. $\Delta_{n,j}$ increases over time until the next message of vehicle j arrives at vehicle n. Hence, the AoI depends on the time when we assess the information. In the same scenario, the AoI is high if we assess the AoI before receiving the next message and low if we just received a new message and then assess the AoI.

Peak AoI

Recent work proposes a continuous observation of the AoI for each vehicle and message service by integrating it over time [17]. A more efficient method is to obtain the AoI from the creation time of a vehicle's last and previous message. That way, we only update the AoI of a vehicle if a new message is received.

Lifetime

V2X messages have a lifetime T_{LT} [96] and the message content is considered outdated if the lifetime expires, i. e., $t_0 - t^{last}_{j,msg} > T_{LT}$. Hence, we consider the message lifetime T_{LT} as the peak AoI if the last received message of vehicle j is outdated or we have not received two subsequent messages from vehicle j.

Exponential smoothing

However, only considering the difference between a pair of subsequent messages leads to a high fluctuation of the peak AoI. The resulting peak AoI is too optimistic if we assess it after successfully receiving two subsequent messages but have not received previous ones. In contrast, the peak AoI is too pessimistic if we just missed one message of vehicle j but received all previous ones. Therefore, we introduce an exponential smoothing function for the peak AoI to consider the last and previous observations denoted as $\hat{\Delta}^{last}_{n,j}$ and $\hat{\Delta}^{prev}_{n,j}$, respectively. An exponential smoothing function has been previously used to assess the CBR in decentralized V2X networks [102]. If vehicle n receives a new message from vehicle j, we obtain $\hat{\Delta}^{last}_{n,j}$ as

$$\hat{\Delta}^{last}_{n,j} = \begin{cases} \alpha_\Delta \cdot \left(t^{last}_{j,msg} - t^{prev}_{j,msg}\right) + (1 - \alpha_\Delta) \cdot \hat{\Delta}^{prev}_{n,j}, & \text{if } t_0 - t^{last}_{j,msg} < T_{LT}, \\ T_{LT}, & \text{else.} \end{cases} \tag{23}$$

where α_Δ is the exponential weighting factor for the peak AoI.

Continuous assessment

Equation 23 is only updated if we receive a message from vehicle j. Consider a scenario where we first receive messages from vehicle j with high reliability, leading to a low peak AoI. If the communication link suddenly disconnects, e. g., because of shadowing, the peak AoI in Equation 23 remains low until the last received message exceeds its lifetime T_{LT}.

To assess the peak AoI $\hat{\Delta}^{t_0}_{n,j}$ at the current time t_0, we consider the difference between the current time and the creation time of the previous message of vehicle j if it is larger than the last obtained peak AoI, i. e., $t_0 - t^{last}_{j,msg} > \hat{\Delta}^{last}_{n,j}$, and get

$$\hat{\Delta}^{t_0}_{n,j} = \begin{cases} \alpha_\Delta \cdot \left(t_0 - t^{last}_{j,msg}\right) + (1 - \alpha_\Delta) \cdot \hat{\Delta}^{last}_{n,j}, & \text{if } t_0 - t^{last}_{j,msg} > \hat{\Delta}^{last}_{n,j}, \\ \hat{\Delta}^{last}_{n,j}, & \text{else.} \end{cases} \tag{24}$$

Hence, using Equation 24, a vehicle n obtains a measurement-based assessment of the peak AoI at the current time t_0 for any perceived vehicle j.

Model-Based Assessment

In the following, we present our model-based assessment of the peak AoI. In contrast to the measurement-based assessment, which relies on past observations of a specific vehicle, the model-based approach allows obtaining the peak AoI independent of a concrete vehicle for different communication distances, message frequencies, and vehicle densities. For this purpose, we use our derived numerical communication model to obtain the communication quality as reliability and latency for a given distance and traffic density. Our model-based approach for peak AoI assessment considers the effects of message frequency, reliability, and latency, which we describe separately in the following.

Message frequency

A vehicle n sends messages with the message frequency λ_n. The time a vehicle waits for new information decreases for a high message frequency and vice versa. However, the freshness of the information depends on the time when evaluating the information. More precisely, if we evaluate the information from a message we just received, the information will not be outdated. In contrast, if we evaluate the information before receiving the subsequent message, the information is aged by a full message cycle. The latter case describes the peak AoI, which we consider as

$$\hat{\Delta}_F(\lambda) = \frac{1}{\lambda}. \tag{25}$$

Reliability

In the previous section, we discussed that radio propagation and medium access lead to unreliable communication, i. e., the message cannot be decoded at the receiver. If a message is not successfully delivered, the receiver assesses outdated information. The probability p to receive at least one of i messages with a PDR ρ from another vehicle is expressed as

$$p = 1 - (1 - \rho)^i. \tag{26}$$

We obtain the PDR from Equation 2 for path loss and from Equation 15 for medium access effects. Assuming that path loss and medium access effects are independent of each other, we get $\rho = \rho_{PL}(d) \cdot \rho_{n,MA}$. Equation 26 is used to obtain the number of messages required to receive at least one message with the probability p and the PDR ρ. In other words, with the probability p and PDR ρ, we get the peak AoI induced by reliability as

$$\hat{\Delta}_R(\rho) = \frac{1}{\lambda} \cdot \frac{\ln(1-p)}{\ln(1-\rho)}. \tag{27}$$

Latency

In communication systems, the content of a message arriving at the receiver is outdated because of latency. We consider the frame duration T_{FD} of a message, as defined in Equation 14, the propagation delay T_{PD}, and the latency induced by medium access L, as defined in Equation 18, causing messages to arrive late at the receiver. Hence, we obtain the AoI induced by latency as

$$\hat{\Delta}_L(L) = T_{FD} + T_{PD} + L. \tag{28}$$

Finally, by considering the effects of message frequency, reliability, and latency to be independent of each other, we obtain the model for the peak AoI as

$$\hat{\Delta}(\lambda, \rho, L) = \hat{\Delta}_F(\lambda) + \hat{\Delta}_R(\rho) + \hat{\Delta}_L(L). \tag{29}$$

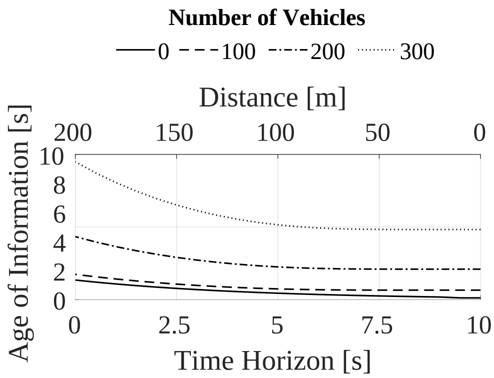


Figure 10: Model-based peak AoI as a function of the communication distance and time in a numerical IEEE 802.11p network model, assuming that two vehicles approach each other with a message frequency of 10 Hz. The number of vehicles is varied and a probability of $p = 0.9999$ to receive at least one message is assumed.

Note that $\hat{\Delta}$ from Equation 29 is a model-based assessment approach for the peak AoI considering the current scenario for different parameter sets. For example, we can vary the vehicle's message frequency, evaluate the peak AoI for different distances, or consider a different number of vehicles impacting the reliability and latency.

Figure 10 shows the model-based peak AoI assessment using Equation 29. In the illustration, we assume that two vehicles approach each other with a constant velocity of 10 m/s each, reducing their communication distance from 200 m to 0 m in 10 s. Figure 10 shows that the peak AoI is at 9.5 s for 300 vehicles, depicted as a dotted line, and 200 m communication distance and does not fall below 4.8 s. The lowest peak AoI is at 0.15 s for 0 vehicles, depicted as the solid line, with a message frequency of 10 Hz. Hence, we see that the peak AoI is lower bounded by the number of vehicles, causing severe message collisions above 100 vehicles. Additionally, the communication distance between both vehicles severely impacts the peak AoI above 100 m because of unreliable message transmission.

In summary, we proposed a numerical model to assess the communication quality in decentralized V2X networks for path loss and medium access effects. We analyzed the computational complexity of our numerical model and, subsequently, proposed an approximate model, providing comparable results like our numerical model with significantly less computation time. Finally, we proposed a measurement- and model-based AoI assessment approach for communication quality assessment. The measurement-based model assesses the AoI of each perceived vehicle. The model-based AoI assessment builds upon our numerical model for communication quality assessment and allows obtaining the AoI depending on the considered communication distance, message frequency, and vehicle density.

4.3 INFORMATION RELEVANCE FOR COOPERATIVE DRIVING

Cooperative driving continuously broadcasts MCMs with the vehicle's driving intentions as trajectories to other vehicles in the communication range [137, 142]. That way, the awareness of the current position and future driving intentions increases. Furthermore, the exchange of driving intentions allows to coordinate cooperative driving maneuvers. However, not all MCMs are equally relevant. For example, messages of vehicles coordinating a cooperative maneuver are more relevant than messages of vehicles without the need to coordinate a maneuver. Moreover, MCMs informing about an emergency are more relevant than MCMs coordinating a cooperative maneuver for increasing traffic efficiency. Assessing the information relevance of MCMs is specifically important when considering the limited channel resources of V2X networks [75, 157]. The goal of information relevance assessment is to enable relevance-aware resource allocation, where relevant information is prioritized over less relevant information in a congested V2X network. Relevance-aware resource allocation is specifically challenging in decentralized V2X networks because vehicles have incomplete knowledge about the channel state and the information relevance of other vehicles.

Generic information relevance assessment

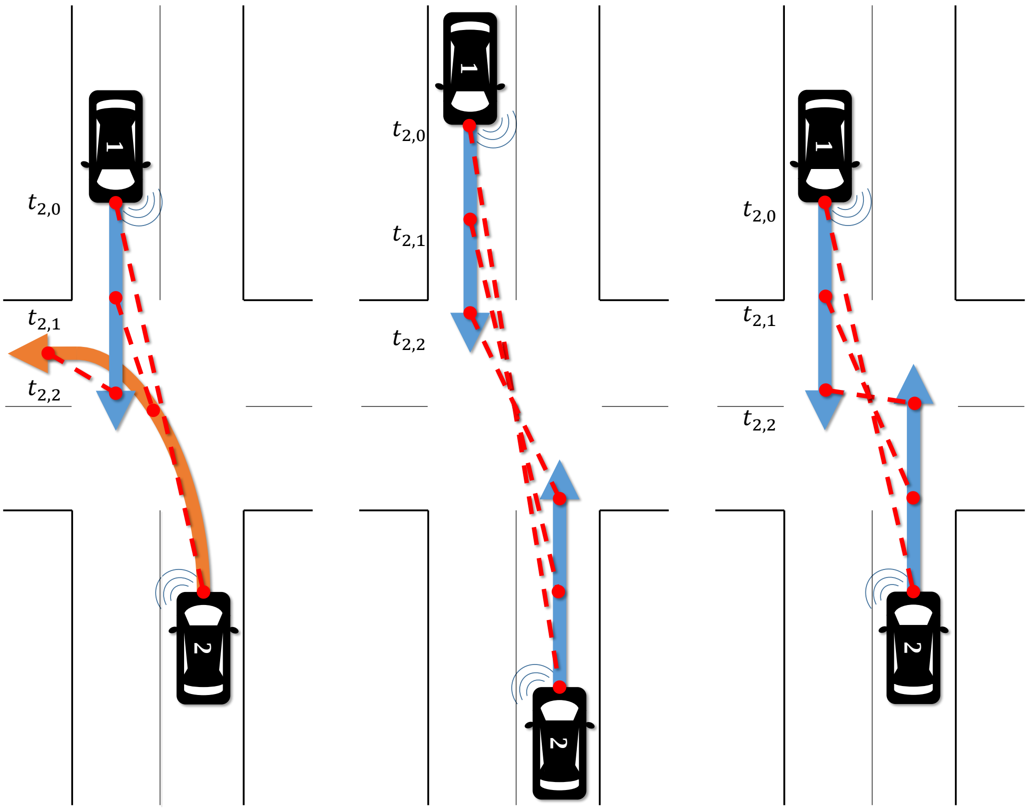
In the following, we present a generic model to assess the information relevance of MCMs used for cooperative driving. The information relevance is obtained by each vehicle independently, based on its current maneuver plan and perceived MCMs of other vehicles. A high information relevance implies that the vehicle identified an immediate conflict with another vehicle. In contrast, a low information relevance implies that the vehicle is unaware of any conflicts. We set the information relevance value range of a vehicle n to $r_n \in [0, 1]$. In the following, we first formalize the approaching time of trajectories, obtain the Perceived Awareness over Time Horizon (PATH) based on the approaching time, and then link the PATH to the information relevance of an MCM.

4.3.1 *Continuous Approaching Time*

In our previous work in [189], we defined the Environmental Risk Awareness (ERA) to obtain a safety metric for collective perception. A vehicle n evaluates its perceived ERA θ_p by evaluating the instantaneous approaching times $t_{j,0}$ of all vehicles j in its communication range as

$$\theta_p = \sum_{t_{j,0}>0;j} \frac{\mu_j}{t_{j,0} + u(t_{j,0})}, \tag{30}$$

where μ_j is the collision risk posed by vehicle j, depending on, e.g., the tolerated safety time, its weight, or dimension. We select a more conservative collision risk μ_j for vehicles close to our tolerated safety time. Furthermore, we select a conservative collision risk for vehicles with high weight or large dimensions. That way, the ERA adequately represents the potential severity of a vehicle collision. $u(t_{j,0})$ denotes the uncertainties of the states vectors induced by inaccurate local environment sensor measurements of vehicle n. Notably, Equation 30 only considers positive approaching



(a) Conflicting trajectories. (b) Approaching trajectories. (c) Passing trajectories.

Figure 11: Assessment of continuous approaching time at different time steps.

Instantaneous approaching time

times, i. e., only vehicles approaching our vehicle n. The instantaneous approaching time is obtained by solving the motion equation as

$$d_t + \dot{d}_t \cdot t_{j,0} + 0.5\ddot{d}_t \cdot t_{j,0}^2 = 0, \tag{31}$$

where d_t, $\dot{d}_t$, and $\ddot{d}_t$ denote the distance, relative velocity, and acceleration at time t between vehicle n and j. Solving Equation 31 for $t_{j,0}$ yields the instantaneous approaching time of the vehicles. For $t_{j,0} < 0$, both vehicles drive away from each other. However, Equation 31 is limited to the instantaneous approaching time, whereas trajectories allow to obtain future driving intentions from other vehicles.

Trajectories

In [137, 142], the authors propose cooperative driving approaches and use trajectories to represent the future driving intentions of the vehicle. The planned trajectory (or reference) is the performed maneuver and the desired trajectory indicates the need for cooperation. In both approaches, the trajectories have a validity time t, where $0 \leqslant t \leqslant T_{TH}$ and T_{TH} is the trajectory's time horizon. Using trajectories, we can obtain the approaching time for a pair of trajectories within their validity time [46], which we refer to as continuous approaching time $t_{j,t}$ in the following. According to Figure 11a, vehicle 1 obtains the continuous approaching time for the trajectory received from vehicle 2 at different time steps t, denoted as $t_{2,t}$, for the trajectories' validity

Continuous approaching time

times. The distances at different time steps for a pair of trajectories are depicted as red dashed lines. The continuous approaching time yields a positive value if both vehicles approach each other. In the considered scenario of Figure 11a, $t_{2,0}$ yields a high positive value because both vehicles are far away from each other. For $t_{2,1}$, the continuous approaching time yields a small positive value because both vehicles will approach the intersection simultaneously and the relative distance is small. For $t_{2,2}$, the continuous approaching time yields a negative value, indicating that the vehicles drive away from each other.

In the following, we derive the perceived awareness for a pair of two trajectories using the described continuous approaching time.

4.3.2 *Perceived Awareness over Time Horizon (PATH)*

In [46], the authors propose the RISK approach, where a vehicle obtains the minimum approaching time at any trajectory time step for all perceived trajectories. The vehicle generates a message if $t_{j,t} + t \leqslant T_{SG}$, where T_{SG} denotes the tolerated safety time. The proposed message generation highly depends on the parameter T_{SG}. A small safety time only generates messages in critical situations but cannot allocate resources for cooperative driving. That is, a cooperative maneuver should be planned as early as possible. In this context, selecting a high safety time increases the message frequencies for all vehicles and the channel congestion in dense traffic scenarios. The authors showed that 95 % of all vehicles send with the highest message frequency [46] using the RISK approach. In addition, RISK does not differentiate between vehicles passing each other or having a conflict in, e. g., an intersection.

PATH properties

In the following, we propose the PATH to overcome the drawbacks of a threshold-based approach. The PATH denotes the perceived awareness for a given trajectory towards another trajectory in the range 0 to 1 at each time step t. The PATH is 0 for vehicles driving away from each other. For vehicles approaching each other, we check if the trajectories conflict in the time *and* spatial domain. In Figure 11b, two vehicles approach each other, but their trajectories cannot overlap because they are too far away from each other. In this case, we obtain the continuous approaching time because we do not know if the trajectories will collide in the future. In Figure 11c, the trajectories indicate that the vehicles will pass each other without any conflict. Hence, the PATH of both vehicle trajectories is 0. If the continuous approaching time is negative at any time step *and* the trajectories have no conflict, the PATH is 0.

Trajectory relevance

Let us define the trajectories of vehicle n and j as χ_n and χ_j, respectively. Algorithm 1 checks if the trajectories approach each other and can overlap in the future. We first set the output $\zeta_{n,j}$ to **True** in line 1. From lines 2 to 7, we iterate over the trajectories' time horizons in discrete time steps from 0 to T_{TH}. At each time step t, we check if the vehicles approach each other using `isApproaching()` and if the trajectories conflict in the spatial and time domain using `hasCollision()`. The function `isApproaching()` checks if the continuous approaching time at the respective time step is positive and `hasCollision()` checks the trajectories for collision. The collision check is retrieved from the maneuver planning module of the cooperative driving application. If the

Algorithm 1 : The algorithm checks if the trajectories χ_n and χ_j of vehicle n and j, respectively, can conflict in the future, taken from [31].

Result: $\zeta_{n,j}$

1: $\zeta_{n,j} \leftarrow$ **True** ;
2: **for** $t = 0$ **to** T_{TH} **do**
3:     **if not** `isApproaching` $(\chi_n(t), \chi_j(t))$ **and not** `hasCollision` (χ_n, χ_j) **then**
4:         $\zeta_{n,j} \leftarrow$ **False** ;
5:         **break** ;
6:     **end if**
7: **end for**

vehicles are not approaching and have no trajectory collision, we assume that both trajectories cannot overlap in the future. Hence, we set $\zeta_{n,j}$ to **False** and break the loop in lines 4 and 5, respectively. Algorithm 1 returns **True** for the scenario in Figure 11a and Figure 11b. Furthermore, Algorithm 1 returns **False** for the scenario in Figure 11c. A vehicle n executes Algorithm 1 for each of its considered trajectories (planned or desired) and each received trajectory from other vehicles.

Perceived awareness

The PATH extends our previously introduced ERA in Equation 30. For readability, we only consider one trajectory of each vehicle and we obtain the PATH of vehicle n towards vehicle j. Hence, we define the PATH as

$$\Phi(t)_{n,j} = \begin{cases} 0 & \text{if } \textbf{not } \zeta_{n,j}, \\ 1 & \text{else if } t_{j,t} + t \leqslant T_{SG}, \\ \frac{T_{SG}}{t_{j,t}+t} & \text{else,} \end{cases} \tag{32}$$

where $\Phi(t)_{n,j} \in [0, 1]$ and $0 \leqslant t \leqslant T_{TH}$.

For the PATH, we aggregate the risk for each vehicle and trajectory separately and consider the safety time T_{SG} for the collision risk μ_j because we might not have access to the other vehicle's weight or dimension. In contrast to the ERA, we also do not consider the uncertainty vectors induced by measurements. The continuous approaching time is obtained at different time steps along the time horizon of a trajectories' pair. For $t > 0$, we add t to the continuous approaching time, meaning we have more time to react to a potential collision. The PATH is 0 if Algorithm 1 returns **False**, which means that both trajectories are not approaching and colliding with each other. Equation 32 yields 1 if $t_{j,t} + t \leqslant T_{SG}$, i. e., the other vehicle is already within our safety time and has an imminent collision risk. Furthermore, we obtain the PATH between 0 and 1 if $\zeta_{n,j}$ is **True** and $t_{j,t} + t > T_{SG}$.

A vehicle obtains the PATH for each perceived vehicle in its communication range. In the following, we link the PATH to the information relevance.

4.3.3 *Information Relevance*

According to the cooperative driving approach suggested in [75, 157], an MCM contains a planned and optional desired trajectory (or reference and optionally request and alternative trajectories). Our goal is to assess the information relevance of the MCM using the PATH. The PATH is defined for pairs of trajectories and is a function of time.

Maximum PATH

We first obtain the maximum PATH within the time horizon for all possible pairs of trajectories. A trajectory pair consists of one of our generated trajectories and a received trajectory from another vehicle. After that, we obtain the maximum PATH among all pairs of trajectories. The trajectory pair with the highest PATH is considered the most relevant trajectory conflict and determines the information relevance of the MCMs. We define the information relevance r_n of vehicle n for the current MCM as

$$r_n = \max_{t \in [0, T_{TH}]; j} (\Phi(t)_{n,j}). \tag{33}$$

We obtain the maximum PATH for each trajectory over its time horizon and each vehicle j. We obtain a low information relevance and have no risk for a collision, i.e., $r_n \to 0$, if the PATH is low for all time steps and perceived vehicles. In this case, there is no need to coordinate a cooperative maneuver. For $0 < r_n \ll 1$, there is a potential cooperation conflict in the future, where cooperative driving can resolve the conflict upfront and, therefore, increase traffic efficiency. In contrast, for $r_n \to 1$, the information relevance is high and we have an imminent collision risk. In this case, immediate action is required to mitigate a potential collision. In Section A.2, we evaluate the cumulative distribution of the information relevance in a cooperative driving scenario.

Cooperation conflict

In this section, we have discussed the information relevance assessment for cooperative driving using trajectories. Our presented approach obtains the approaching time for a pair of trajectories and information relevance from the vehicle's most critical trajectory conflict. Our approach ensures that the information relevance of safety-critical scenarios is higher than the information relevance of traffic efficiency scenarios.

In this chapter, we have derived communication quality and information relevance assessment for cooperative driving in decentralized V2X networks. Our first contribution provides a numerical model to assess the communication quality of the IEEE 802.11p EDCA mechanism. Based on the analysis of the computational complexity of the numerical model, we proposed an approximate model, providing comparable results with significantly less computational time. Further, we extended the AoI assessment in decentralized V2X networks, providing a measurement- and model-based approach. As our second contribution, we proposed the information relevance assessment for cooperative driving. Vehicles assess the continuous approaching times of other vehicles using trajectories and derive the PATH from the continuous approaching time. The information relevance of MCMs is then defined as the maximum PATH for the trajectories being sent in the respective message. In the following, we build upon assessing information relevance and communication quality to enable V2X network adaptations and communication-aware cooperative driving.

5 RELEVANCE-AWARE ADAPTATIONS IN VEHICULAR NETWORKS

Communication quality and information relevance assessment presented in the previous chapter enables relevance-aware adaptations in decentralized Vehicle-to-Everything (V2X) networks. Hence, in this chapter, we improve the communication quality with relevance-aware resource allocation and an adaptive data dissemination strategy for cooperative driving. Furthermore, we present communication-aware cooperative driving for increasing traffic efficiency and safety by adapting to the assessed communication quality.

Network and application adaptations

On the communication side, previous research proposed mechanisms to either improve the communication quality, e. g., counteract channel congestion, or fulfill application-specific communication requirements, e. g., message frequency. On the application side, previous research for cooperative driving primarily focused on efficient coordination of cooperative driving maneuvers without explicitly considering the communication quality (cf. Chapter 2).

Providing high V2X quality

Cooperative driving specifically increases traffic efficiency in scenarios with a high vehicle density, where only a subset of vehicles in the V2X network coordinates cooperative maneuvers. However, cooperating vehicles require high communication quality to enable early coordination for improving traffic efficiency and highly accurate monitoring of vehicles involved in the cooperative maneuver for maintaining traffic safety. However, providing high communication quality specifically for vehicles coordinating cooperative maneuvers in scenarios with a high vehicle density constitutes a significant research challenge.

In this chapter, we address the mentioned challenges from the V2X network *and* application perspective. In the following, we provide an overview of the concept proposed in this thesis, highlight the contributions of this chapter, and link them to the other contributions presented in this thesis.

5.1 OVERVIEW AND CONCEPT

In this section, we briefly describe V2X communication for cooperative driving. After that, we explain our concept of relevance-aware adaptations in V2X networks for communication-aware cooperative driving based on the data assessment presented in Chapter 4.

5.1.1 *V2X Communication for Cooperative Driving*

This thesis builds upon the generic cooperative driving approach presented in [137] to coordinate cooperative maneuvers. Vehicles share their planned and optional desired trajectories with other vehicles in the communication range using V2X communication. The planned trajectory describes a vehicle's future driving intention in a limited time period. The desired trajectory is sent in addition to the planned trajectory if a vehicle requires cooperation to increase its traffic efficiency, e. g., left-turning at an intersection.

Single vs. multi-hop broadcast

We assume that all vehicles are equipped with V2X communication, having access to decentralized Vehicle-to-Vehicle (V2V) and centralized Vehicle-to-Network (V2N) access technologies. For V2V communication, we use the Single-Hop Broadcast (SHB) transmission mode to send Maneuver Coordination Messages (MCMs). Multi-hop communication allows extending the communication range of vehicles to increase their awareness in an emergency, i. e., increasing the probability of message reception by relaying the same message via multiple vehicles [143]. However, multi-hop communication is susceptible to severe channel congestion, impairing the communication quality, especially in scenarios with high vehicle density.

Unicast vs. multicast

For V2N communication, each vehicle is connected to a base station and we use the UNICAST transmission mode in the up- and downlink to offer Ultra-Reliable Low-Latency Communication (URLLC). In 3GPP LTE-V2N networks, the MULTICAST and BROADCAST transmission modes require a time-intensive session setup before sending messages to vehicles of interest. Due to the high vehicles' mobility, continuous session setups are required to capture all vehicles of interest. Therefore, MULTICAST and BROADCAST transmission in 3GPP LTE-V2N networks currently cannot fulfill the communication requirements of safety-relevant V2X applications [147].

Data dissemination for cooperative driving

For cooperative driving, we use V2V communication as the default V2X access technology. V2V communication does not rely on additional infrastructure and, hence, is well suited for the considered generic cooperative driving approach in [137]. Vehicles also have access to V2N networks. As channel resources are limited and also used for other V2X applications, each V2X access technology only has access to a single channel to send MCMs, i. e., Single-Channel Operation (SCO).

In this thesis, vehicles solely operate on the cooperative driving application and periodically send MCMs to other vehicles. The message frequency of the cooperative driving application is limited between λ_{MIN} and λ_{MAX}. The relevance-aware resource allocation approach proposed in this chapter optimizes the vehicle's message frequency for cooperative driving. The presented approach is not limited to the cooperative driving application and also applies to other V2X applications, e. g., collective perception. However, our relevance-aware resource allocation approach requires assessing the application-specific information relevance, which is not within the scope of this thesis.

Trajectory-based data assessment

In the following, we outline our concept of decentralized adaptation in V2X networks for cooperative driving based on our trajectory-based communication quality and information relevance assessment.

5.1.2 *Decentralized Adaptations in Vehicular Networks for Cooperative Driving*

In this chapter, we present *relevance-aware adaptations* in V2X networks and *communication-aware cooperative driving* to improve communication quality and robustness for safe

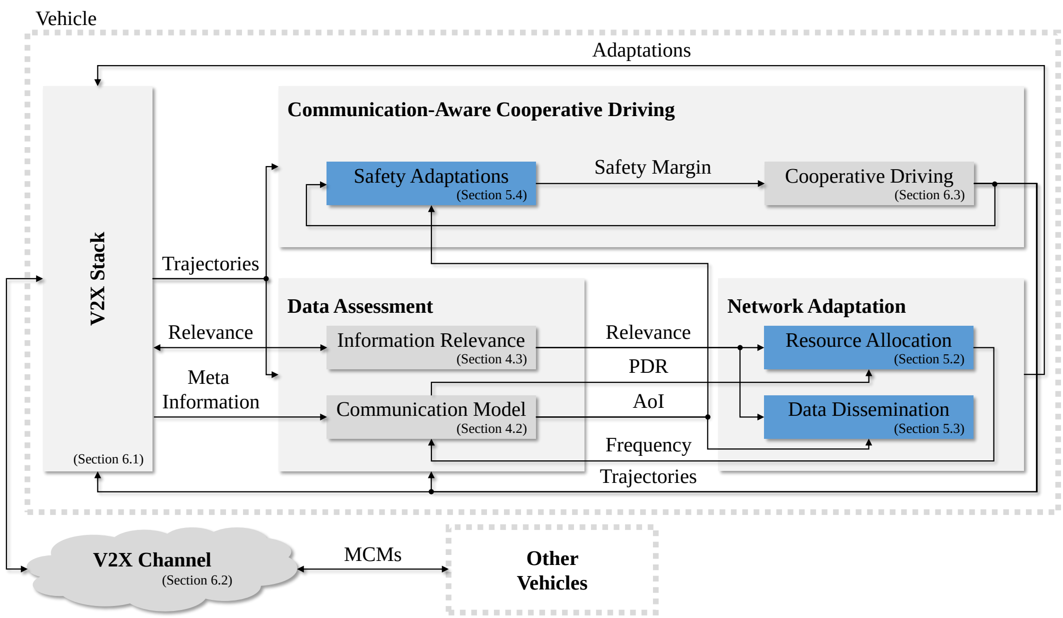


Figure 12: Concept overview for relevance-aware adaptations in V2X networks for communication-aware cooperative driving based on data assessment.

and efficient cooperative driving. The concept focused on in this thesis is illustrated in Figure 12. The components presented in this chapter are highlighted in blue.

V2X stack

In V2X networks, vehicles send MCMs to coordinate cooperative maneuvers with other vehicles. Our considered V2X communication stack offers access to heterogeneous V2X access technologies and connects vehicles in the V2X network. Received MCMs are decoded and other vehicles' trajectories are forwarded to the data assessment and communication-aware cooperative driving modules. Additionally, the communication model of the data assessment module retrieves meta information from the V2X stack, such as the number of vehicles in the communication range, their message frequencies, and the timestamp of MCMs. The trajectories created by the cooperative driving application are forwarded to the V2X stack to create and send MCMs.

Data assessment

The data assessment presented in Chapter 4 consists of the communication quality and information relevance assessment. The information relevance of an MCM is obtained based on the vehicle's current context and derived from the own and received trajectories. The assessed information relevance is attached to the MCM and, then, forwarded to the V2X stack. The model-based communication quality assessment requires the number of vehicles in the communication range and the message frequency of the own and other vehicles. Relevance-aware resource allocation presented in this chapter adapts the vehicle's message frequency based on the assessed communication quality and information relevance. The measurement-based approach assesses the Age of Information (AoI) of other vehicles, derived from the timestamps of received MCMs and is required for our adaptive data dissemination strategy.

V2X network adaptations

In this chapter, we propose relevance-aware resource allocation in Section 5.2 to use the available channel resources efficiently, counteract channel congestion, and prioritize relevant information in decentralized V2X networks. Furthermore, we present an adaptive data dissemination strategy with heterogeneous V2X access technologies in Section 5.3 to increase the communication range and quality of V2X communication for vehicles coordinating cooperative maneuvers. The dissemination of MCMs is extended to V2N communication, providing a high communication range and URLLC with UNICAST transmission for vehicles performing cooperative maneuvers. V2N communication is only used by vehicles coordinating cooperative maneuvers because UNICAST transmissions lead to channel congestion in the downlink if used by all vehicles. Relevance-aware V2X network adaptations improve the communication quality for cooperative driving. However, the communication quality can be insufficient to coordinate cooperative maneuvers. We use our model-based AoI assessment to predict the communication quality of other vehicles derived from their trajectories. On this basis, we adapt the safety margin to other vehicles for safe and efficient cooperative driving in Section 5.4.

Adaptations for cooperative driving

5.2 RELEVANCE-AWARE RESOURCE ALLOCATION

Channel congestion severely impairs the communication quality in decentralized V2X networks, causing unreliable communication. Channel congestion occurs if the channel capacity is insufficient for the messages sent by vehicles in the same V2X channel. The probability that two vehicles sense the channel idle and send messages simultaneously increases with the channel load. Channel congestion can be prevented by either decreasing the number of sent messages or the transmission power. The results of our numerical communication model in Section 4.2.1 show that decreasing the number of messages, i. e., the number of attempts to access the channel, has a significant impact on the reliability of V2X communication. In contrast, a transmission power reduction further limits the communication range required for cooperative driving.

Transmission rate and power control

Relevance-aware resource allocation adapts the vehicle's message frequency depending on its information relevance, the information relevance of other vehicles, and the assessed V2X channel congestion. According to our approach in Section 4.3, a vehicle obtains its current information relevance and attaches it to the respective MCM. Hence, a vehicle can obtain the information relevance of other vehicles from the received MCMs. Each message allocated to the channel increases the probability of message collision, decreasing the V2X communication reliability of vehicles in the V2X network. A vehicle can decrease its message frequency to improve the reliability of the V2X network. However, with a low message frequency, a vehicle cannot provide relevant messages to other vehicles in time.

Information relevance assessment

We address the mentioned problem by deriving an optimization problem, aiming to maximize the Accessible Information Relevance (AIR) in a decentralized V2X network. For this purpose, we define the network's AIR as the sum of information relevance successfully provided by vehicles in the V2X network. A vehicle adapts its message frequency based on its information relevance, the assessed channel congestion, and the information relevance of other vehicles. For example, in a scenario with a low channel load, all vehicles increase their message frequencies to increase the network's AIR,

Accessible information relevance

i. e., the channel resources are sufficient for all vehicles. However, in a scenario with a high channel load, vehicles with low information relevance decrease their message frequencies to decrease channel congestion and, therewith, increase the reliability in the V2X network. In contrast, vehicles with relevant information will not decrease their message frequency because their information increases the network's AIR. That way, messages with high information relevance are prioritized because their reception probability increases without decreasing their message frequency.

In this section, we define the network's AIR and derive an algorithm for optimizing the network's AIR from the perspective of each vehicle. After that, we derive a model to converge to the optimized message frequency in a decentralized V2X network.

5.2.1 *Accessible Information Relevance*

Abstracting from the V2X application

In our scenario, we consider N vehicles. A vehicle $n \in \{1, 2, ..., N\}$ obtains the information relevance r_n of its current message, where $r_n \in [0, 1]$. Vehicles can have multiple V2X applications, where each application creates messages with a different information relevance. Our relevance-aware approach abstracts resource allocation from specific V2X applications. Hence, we only refer to r_n as the information relevance of the current message of vehicle n, independent of the respective V2X application. In this context, the information relevance of a message varies over time because the message content ages and, therefore, becomes less relevant over time. However, we assume that the information relevance r_n remains constant for the short lifetime considered for V2X messages. For example, the Cooperative Awareness Message (CAM) lifetime is set to 1 s [96].

Creating and sending messages

In this section, our goal is to obtain the message frequency λ_n of a vehicle n, where $\lambda_n \in [\lambda_{MIN}, \lambda_{MAX}]$. λ_{MIN} and λ_{MAX} denote the minimum and maximum message frequency for the respective V2X application. Let i_n denote the index of the current message of vehicle n and suppose that vehicle n sent a message $i_n - 1$ at time t. When the message i_n is created, vehicle n obtains the information relevance r_n based on the content of the message i_n and the message frequency λ_n. Vehicle n waits for the time $t + \lambda_n^{-1}$ to send the message i_n, depending on the obtained message frequency. Assume that a subsequent message $i_n + 1$ was created by a V2X application *before* the message i_n was sent. In that case, the message i_n is discarded and vehicle n updates the information relevance r_n and message frequency λ_n and sends the message $i_n + 1$ at time $t + \lambda_n^{-1}$.

Provided information relevance

Vehicle n increases the information relevance provided to other vehicles in the same channel by increasing its message frequency λ_n if $r_n > 0$. We define the provided information relevance by vehicle n as $\lambda_n \cdot r_n$. However, the Packet Delivery Ratio (PDR) of messages sent by vehicle n decreases in a congested channel. Therefore, other vehicles will not receive *all* messages sent by vehicle n, decreasing the information relevance provided by vehicle n. Consequently, we define the information relevance Λ_n, which can be perceived by other vehicles in the same channel from vehicle n as

$$\Lambda_n = \lambda_n \cdot r_n \cdot \rho_{n,MA}. \tag{34}$$

Medium access and path loss

Note that $\rho_{n,\text{MA}}$ refers to the PDR caused by medium access effects, derived in Equation 15. Propagation loss and hidden node collisions also negatively impair the PDR (cf. Section 4.2). We can derive a location-specific AIR optimization problem by considering the PDR $\rho_{\text{PL}}(d)$ of path loss. However, our goal is to address relevance-aware resource allocation to improve communication quality in the V2X network and counteract channel congestion. In this context, a location-specific AIR does not improve the communication quality and counteract channel congestion in a decentralized V2X network. Furthermore, mitigating hidden message collisions requires estimating hidden nodes, which is not trivial [136]. We leave the integration of hidden node estimation in our relevance-aware resource allocation approach for future work to limit the model's complexity. However, we carefully analyze the impact of path loss and hidden message collisions on the performance of our approach in Chapter 7.

Hidden nodes

Accessible Information Relevance

We define the network's AIR as the sum of the information relevance, message frequency, and PDR of each vehicle n and get

$$\Lambda = \sum_{n=1}^{N} \lambda_n \cdot r_n \cdot \rho_{n,\text{MA}}. \tag{35}$$

Incomplete knowledge

Each vehicle n obtains the network's AIR by assessing the other vehicles' information relevance and message frequency and obtaining the PDR from Equation 15. However, each vehicle only approximates the network's AIR: *i)* The message frequency of other vehicles is approximated by the inverse of the model-based assessed AoI of other vehicles. Consequently, we denote the message frequency approximated for a vehicle n as $\tilde{\lambda}_n$; *ii)* the information relevance of other vehicles obtained from received MCMs can be outdated because of unreliable communication, latency, and propagation delay. Hence, we denote the assessed information relevance obtained from a received MCM of vehicle n as $\tilde{r}_n$; *iii)* the assessed PDR relies on a model and can be inaccurate. We denote the assessed PDR for a vehicle n as $\tilde{\rho}_{n,\text{MA}}$. In summary, each vehicle has an incomplete knowledge of the network's AIR since we consider a decentralized V2X network.

Channel load impact

According to Equation 35, each vehicle n impacts the network's AIR by adapting its message frequency. We define the channel load λ_L as the sum of all vehicles' message frequencies, giving

$$\lambda_L = \sum_{n=1}^{N} \lambda_n. \tag{36}$$

It is evident that the channel load in Equation 36 changes if a vehicle n adapts its message frequency. However, the difference in the channel load for a single vehicle adapting its message frequency seems negligible for $\lambda_L \gg \lambda_{\text{MAX}} \geqslant \lambda_n$, which holds for a congested channel. Hence, one could argue that a single vehicle cannot noticeably impact the reliability of the V2X network. However, by adapting its message frequency, a vehicle marginally impacts the PDR in the V2X network and, thus, affects the AIR of *all* N vehicles.

Algorithm 2 : Algorithm to calculate the optimal message frequency $\lambda_{O,n}$ of a vehicle n for relevance-aware resource allocation. NLMAX refers to a non-linear solving operation, obtaining the maximum argument for the given function within the respective limits. The algorithm is adapted from [31].

Result: $\lambda_{O,n}, \forall n \in \{1, ..., N\}$

1: $C \leftarrow$ `assessCbr();`
2: $\tilde{\Lambda}(\lambda_n) \leftarrow r_n \cdot \lambda_n \cdot \tilde{\rho}_{n,MA}$;
3: **for** $j \leftarrow 1$ **to** N **do**
4:     **if** $j \neq n$ **then**
5:         $\tilde{\Lambda}(\lambda_n) \leftarrow \tilde{\Lambda}(\lambda_n) + \tilde{r}_j \cdot \tilde{\lambda}_j \cdot \tilde{\rho}_{j,MA}(\lambda_n)$;
6:     **end if**
7: **end for**
8: $\lambda_{O,n} \leftarrow$ `nlmax(`$\tilde{\Lambda}(\lambda_n), \left[0, \frac{1-C}{T_{FD}}\right]$`);`

We define the approximated network's AIR of a vehicle n based on the assessed message frequency $\tilde{\lambda}_j$, information relevance $\tilde{r}_j$, and PDR $\tilde{\rho}_{j,MA}$ of other vehicles j as

$$\tilde{\Lambda}(\lambda_n) = \lambda_n \cdot r_n \cdot \tilde{\rho}_{n,MA}(\lambda_n) + \sum_{j \neq n} \tilde{\lambda}_j \cdot \tilde{r}_j \cdot \tilde{\rho}_{j,MA}(\lambda_n). \tag{37}$$

Optimization problem

Equation 37 denotes $\tilde{\Lambda}(\lambda_n)$ as a function of the vehicle's message frequency λ_n. Furthermore, the PDR $\tilde{\rho}_{n,MA}$ of our vehicle n and the PDRs $\tilde{\rho}_{j,MA}$ of other vehicles j are also denoted as a function of the vehicle's message frequency λ_n.

We use the non-linear function in Equation 37 to optimize the vehicle's approximated network's AIR by adapting its message frequency λ_n. The message frequency $\lambda_{O,n}$, optimizing the approximated network's AIR from the perspective of a vehicle n in the respective state, is given as

$$\lambda_{O,n} = \underset{\lambda_n \in \left[0, \frac{1-C}{T_{FD}}\right]}{\arg\max} \left(\tilde{\Lambda}(\lambda_n)\right), \tag{38}$$

where $\lambda_{O,n} \in [0, (1-C) \cdot T_{FD}^{-1}]$. C is the Channel Busy Ratio (CBR) and T_{FD} is the frame duration of the respective MCMs of vehicle n. For readability, we consider the same frame duration T_{FD} for all MCMs. The upper limit $(1-C) \cdot T_{FD}^{-1}$ of $\lambda_{O,n}$ ensures that a vehicle n cannot exceed the channel resources. Notably, Equation 38 is only optimal from the perspective of vehicle n w. r. t. its current *and* incomplete knowledge of the decentralized V2X network.

Optimizing the network's AIR

In the following, we present our procedure for optimizing the message frequency λ_n for a vehicle n in a decentralized V2X network and obtain its optimal message frequency $\lambda_{O,n}$. The pseudo-code of our procedure is given in Algorithm 2. We first assess the CBR C in line 1. In a numerical environment, C is obtained by Equation 17. In simulations or real-world scenarios, the CBR C is assessed with the procedure suggested by the European Telecommunications Standards Institute (ETSI) in [103]. In line 2, the portion of vehicle n's network's AIR is obtained. The message frequency λ_n is used to optimize the approximated network's AIR in the limits $\left[0, (1-C) \cdot T_{FD}^{-1}\right]$. In the for-loop from lines 3 to 7, we obtain the approximated network's AIR by all perceived vehicles N in line 5. Remember that each vehicle only approximates other vehicles' PDRs, information relevance, and message frequencies. We exclude the vehicle's own portion of the network's AIR in line 4, as it was already considered in line 2. Finally, we maximize the approximated network's AIR $\tilde{\Lambda}(\lambda_n)$ from the perspective of vehicle n. In this thesis, we use the NLOPT framework [116] to optimize the non-linear function $\tilde{\Lambda}(\lambda_n)$. The NLOPT framework provides various optimization algorithms for different use cases. We decided on the well-known SIMPLEX approach [168] because it fits our optimization problem as a lightweight and derivative-free optimization algorithm. In line 8, NLMAX, from the NLOPT framework, using the SIMPLEX algorithm, maximizes the given function $\tilde{\Lambda}(\lambda_n)$ and returns the optimal message frequency $\lambda_{O,n}$ in the limits $\left[0, (1-C) \cdot T_{FD}^{-1}\right]$ as a result.

The limits of the optimal message frequency exceed the maximum allowed message frequency of V2X applications. In the following, we explain how each vehicle adapts its message frequency λ_n to the calculated optimal message frequency $\lambda_{O,n}$ in a decentralized V2X network and converges to a stable state.

5.2.2 *Decentralized Adaptation of Resource Allocation*

The procedure in Algorithm 2 calculates the optimal message frequency $\lambda_{O,n}$ w. r. t. the vehicle's current information relevance, the relevance of other vehicles, and the channel load. However, $\lambda_{O,n}$ can be larger than the maximum message frequency λ_{MAX}. Furthermore, an instantaneous adaptation of all vehicles to their calculated optimal message frequency can lead to synchronization problems. As an example, we consider an intersection scenario with high vehicle density. In the beginning, we have a low channel load because all vehicles send with their minimum message frequency. Assume that vehicles approaching the intersection require decelerating because of an emergency, e. g., to prevent an accident. According to our design in Section 4.3, the information relevance of vehicles approaching the intersection increases immediately because the vehicles must adjust their maneuver to avoid an accident. Considering a high information relevance and a low channel load, Algorithm 2 obtains a message frequency close to the upper limit $(1-C) \cdot T_{FD}^{-1}$ for all vehicles involved in the emergency. Furthermore, even vehicles with a slight increase in the information relevance would significantly increase their message frequency because the information relevance of other vehicles and the channel load were perceived low before. In the considered scenario, Algorithm 2 exceeds the available channel resources and, therefore, severely impairs the communication quality. Moreover, in the next time step, Equation 35 decreases the message frequency to counteract channel congestion. Hence, an instantaneous adaptation to the optimal message frequency leads to synchronization problems. The resulting oscillation of the channel load severely impairs the communication quality of the V2X network: On the one side, messages cannot be received if the channel load is high, causing message collisions. On the other side, messages are not sent to counteract the channel congestion if the channel load is low.

Synchronization

Channel load oscillation

Content-agnostic adaptation

Linear Message Rate Integrated Control (Limeric) [15] has been proposed to counteract channel congestion and avoid synchronization problems in V2X networks. In each time step t, a vehicle adapts its channel capacity share $s_n(t)$ as

$$s_n(t) = (1 - \alpha_L) \cdot s_n(t-1) + \beta_L \cdot (s_T - s_C(t-1)), \tag{39}$$

where $s_n(t-1)$ is the channel capacity share of vehicle n in the previous time step $t-1$ and s_T denotes the target channel capacity share of the V2X network. $s_n(t)$ can be written as the message frequency $\lambda_n(t) = s_n(t) \cdot T_{FD}^{-1}$. The exponential forgetting factor $\alpha_L \in]0,1[$ and adaptive gain factor $\beta_L \in \mathbb{R}^+$ of Limeric in Equation 39 determine the convergence speed to the target channel capacity share s_T. In summary, Limeric works as follows: Each vehicle assesses the channel capacity share of the last iteration $s_C(t-1)$, similar to the CBR C, and adapts its message frequency according to the difference to the target channel capacity share s_T. Equation 39 lets all vehicles converge to the same channel capacity share. The authors have shown that Limeric achieves three goals by letting each vehicle adapt its channel capacity share: Limeric *i)* provides fairness because all vehicles in the same channel converge to the same target channel capacity share; *ii)* avoids oscillation; and *iii)* keeps the V2X channel capacity share below the target channel capacity share s_T. That way, Limeric counteracts channel congestion, improving the throughput in congested channels.

Individual message frequency

However, letting all vehicles converge to the same target channel capacity share independent of their information relevance impairs the communication quality from the application perspective. According to our information relevance assessment for cooperative driving in Section 4.3, information is not equally important. Algorithm 2 obtains the optimal message frequency $\lambda_{O,n}$, which varies for vehicles with different information relevance. Consequently, we let each vehicle adapt to its optimal message frequency as

$$\lambda_n(t) = (1 - \alpha_R) \cdot \lambda_n(t-1) + \beta_R \cdot (\lambda_{O,n} - \lambda_n(t-1)). \tag{40}$$

Equation 40 substitutes the channel capacity share by the vehicle's message frequency for consistency with Algorithm 2. The target capacity share is defined as $s_T \in [0,1]$ and cannot exceed the available channel resources. The optimal message frequency $\lambda_{O,n}$ is limited to the remaining channel resources as $\lambda_{O,n} \in \left[0, (1-C) \cdot T_{FD}^{-1}\right]$.

We refer to the exponential forgetting and adaptive gain factor of our relevance-aware approach as $\alpha_R \in]0,1[$ and $\beta_R \in \mathbb{R}^+$, respectively. The exponential forgetting factor lets vehicle n forget its previous message frequency $\lambda_n(t-1)$. α_R is a fairness factor, where vehicles behave altruistic for $\alpha_R \to 1$ and egoistic for $\alpha_R \to 0$, i. e., the first summand is zero for $\alpha_R \to 1$, giving more channel resources to other vehicles. The second summand in Equation 40 denotes the difference between the message frequency of the last time step $\lambda_n(t-1)$ and the optimal message frequency $\lambda_{O,n}$, obtained from Algorithm 2. The second summand is positive if vehicle n requires to increase its message frequency, zero if it reached its optimal message frequency, and negative otherwise. In this context, the adaptive gain factor β_R scales the second summand. A vehicle will not immediately converge to its optimal message frequency.

That way, we avoid oscillations and vehicles cannot exceed the available channel resources. The authors in [15] have shown that convergence is guaranteed if

Message frequency convergence

$$\alpha_R + N \cdot \beta_R < 2 \tag{41}$$

for Equation 39 holds.

In the following, we discuss the applicability of the added condition from Equation 41 to guarantee convergence for Equation 40. At the beginning of this section, we have introduced the problem of oscillation for decentralized resource allocation, which prevents vehicles from converging to their optimal message frequency. The oscillation occurs if a significant number of vehicles synchronously update their message frequencies based on the same assessed channel load. Similar to [15], the channel load λ_L in the steady-state for Equation 40 with N vehicles is

$$\lambda_L = \frac{\beta_R \cdot \sum_{n=1}^{N} \lambda_{O,n}}{\alpha_R + N \cdot \beta_R}. \tag{42}$$

Hence, with the fulfilled condition of Equation 41, vehicles cannot exceed the channel resources of the V2X network, where Equation 40 represents an asymptotically stable linear discrete-time system. Consequently, Equation 40 is a generalization of Equation 39. Each vehicle converges to its single-fixed point, where we require, similar to $s_T \leqslant 1$, that each vehicle does not exceed the maximum available channel resources, ensured by $\lambda_{O,n} \leqslant (1 - C) \cdot T_{FD}^{-1}$.

Limiting resource allocation

Equation 40 allows exceeding the minimum and maximum message frequency of vehicles. Therefore, we limit the message frequency between λ_{MIN} and λ_{MAX} as

$$\lambda_n(t) = \max(\lambda_{MIN}, \min(\lambda_{MAX}, \lambda_n(t))). \tag{43}$$

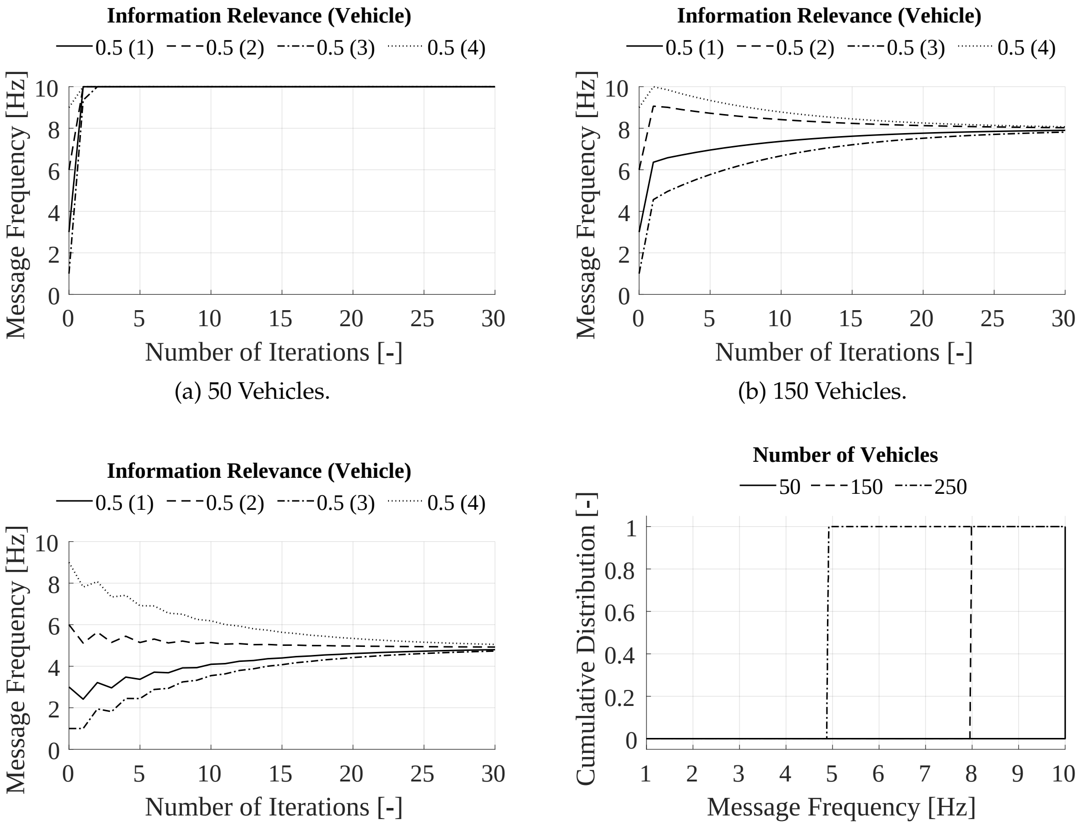
5.2.3 *Numerical Analysis*

In the following, we numerically analyze the behavior of our proposed relevance-aware resource allocation approach w. r. t. convergence of the vehicles' message frequency depending on their information relevance. For this purpose, we use the IEEE 802.11p V2V access technology, detailed in Chapter 7.

In this analysis, we let N vehicles adapt their message frequency according to our proposed approach synchronously in a series of discrete iterations. The vehicles consider the other vehicles' message frequency and information relevance in the previous iteration to adapt the message frequency in the current iteration. Synchronous message frequency updates are challenging for resource allocation in decentralized V2X networks. All vehicles update their message frequency in the same iteration, which may heavily increase or decrease the channel load and can lead to unstable behavior.

Vehicle density

An important aspect of resource allocation in decentralized V2X networks is the number of vehicles in the communication range. In the following, we analyze our approach for 50, 150, and 250 vehicles, where all vehicles are in the communication range of each other and use the same channel. The different channel models used in our evaluation are described in detail in Section 6.2. This numerical analysis considers



(a) 50 Vehicles.

(b) 150 Vehicles.

(c) 250 Vehicles.

(d) Cumulative distribution in the steady-state.

Figure 13: Message frequency convergence for vehicles with an equal information relevance in a numerical IEEE 802.11P network model.

the effects of limited channel resources and neglects radio propagation effects such as path loss and fading. We refer to this as the SIMPLE channel model.

In the following, we analyze the convergence of the vehicle's message frequency in scenarios with different numbers of vehicles. Firstly, we consider that all vehicles have an equal information relevance, meaning that the information of all vehicles is equally important. Therefore, we expect that all vehicles converge to the same message frequency. Secondly, we analyze the case that the information relevance is uniformly distributed among all vehicles. In both cases, the information relevance assigned to a vehicle does not change over the observed iterations. We analyze the impact of dynamic information relevance on the performance of our approach in Chapter 7. The parameters used in this analysis are explained in detail in Section 7.1.3. *Static vs. dynamic relevance*

Equal Information Relevance

Figure 13 depicts the vehicle's message frequency convergence over the number of iterations. We consider three scenarios with different numbers of vehicles, where all vehicles have the same information relevance. As an example, we select an information relevance of 0.5. However, our approach obtains the same results if all vehicles have the same information relevance greater than 0. For better illustration, we do not depict all vehicles but only 4 vehicles out of the set of N vehicles. In the first iteration, the message frequency is uniformly distributed among all vehicles. However, the depicted vehicles have a message frequency of 1 Hz, 3 Hz, 6 Hz, 9 Hz. That way, the convergence to the same message frequency from different initial message frequencies for vehicles with the same information relevance is better illustrated.

Relaxed channel conditions

In Figure 13a, we consider 50 vehicles. We see that all vehicles adapt to the maximum message frequency of 10 Hz after 2 iterations to maximize the network's AIR because the channel is not congested.

Counteract channel congestion

Results of the scenario with 150 vehicles are depicted in Figure 13b. We see that the message frequency converges to 8 Hz. For 150 vehicles, the channel is already congested if all vehicles send with the maximum message frequency of 10 Hz. In a congested channel, the number of message collisions is increased (cf. Figure 4). Therefore, our relevance-aware resource allocation approach adapts the message frequency to the perceived channel congestion. All vehicles converge to the same message frequency because the information of all vehicles is equally important.

In Figure 13c, we consider 250 vehicles. The vehicles' message frequencies converge to 5 Hz because the channel congestion is higher compared to the scenario with 150 vehicles. In this scenario, our relevance-aware resource allocation approach obtains an optimal message frequency of 5 Hz for all vehicles.

The previous figures only consider a set of 4 vehicles and do not depict the distribution of all vehicles' message frequencies. The cumulative distribution of the vehicles' message frequency in the steady-state is depicted in Figure 13d, highlighting the same convergence of the vehicles' message frequencies for all vehicles in the scenarios.

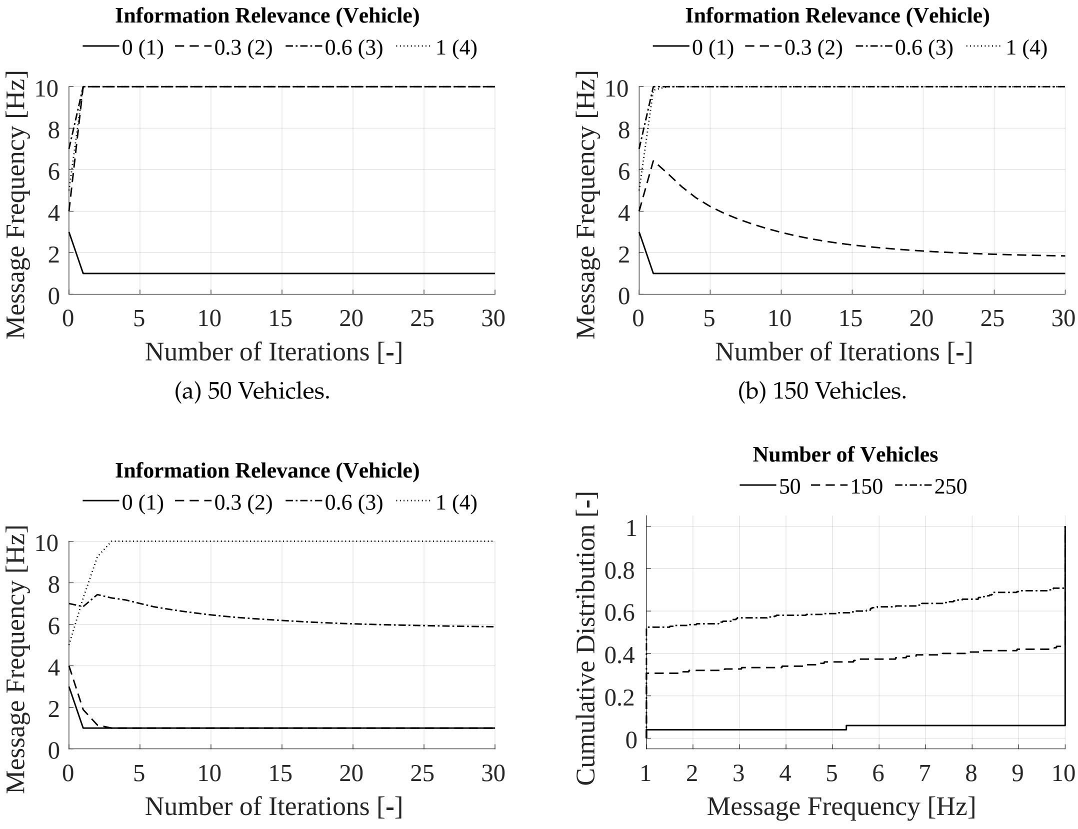
Adaptive congestion control

Notably, our approach adapts all vehicles to the same message frequency in a decentralized V2X network if the information relevance is the same for all messages. Hence, our approach also applies to V2X applications that cannot assess information relevance. In this case, the information relevance is assumed static and equal for all messages. That way, our approach works as an adaptive congestion control mechanism, similar to Limeric [15] and ETSI Adaptive Decentralized Congestion Control (A-DCC) [102], considering an equal information relevance of all messages. In this scenario, our approach maximizes the throughput of the channel.

Uniformly Distributed Information Relevance

In the following, we analyze the case of a uniformly distributed information relevance between 0 and 1 for all vehicles.

Figure 14 depicts the vehicle's message frequency convergence over the number of iterations. We again consider three scenarios with 50, 150, and 250 vehicles and depict 4 vehicles out of the set of N vehicles. Specifically, we select vehicles with an information relevance of 0, 0.3, 0.6, and 1.0. With this set of information relevance, the convergence to different message frequencies is vividly presented for all three scenarios. The message frequency is uniformly distributed for all vehicles.



(a) 50 Vehicles. (b) 150 Vehicles.

(c) 250 Vehicles. (d) Cumulative distribution in the steady-state.

Figure 14: Convergence of the message frequency for vehicles with a uniformly distributed information relevance in a numerical IEEE 802.11P network model.

In Figure 14a, we consider 50 vehicles, where all vehicles increase their message frequency to 10 Hz except the vehicle with an information relevance of 0. This vehicle decreases its message frequency to the minimum message frequency of 1 Hz. The vehicle with an information relevance of 0 cannot contribute to the network's AIR. However, Equation 43 guarantees that the message frequency of vehicles is not starved.

Prevent channel congestion

Figure 14b depicts the scenario with 150 vehicles, where the channel is getting congested. Hence, the vehicle's message frequency with an information relevance of 0.3 is reduced below 2 Hz. The vehicle with an information relevance of 0 remains at a message frequency of 1 Hz. In contrast, the vehicles' message frequencies with an information relevance of 0.6 and 1.0 again increase to 10 Hz. In this scenario, the vehicle with an information relevance of 0.3 cannot contribute sufficiently to the network's AIR for a higher message frequency. Hence, our approach decreases the message frequency to prioritize information from vehicles with higher relevance.

Prioritize relevant information

In Figure 14c, we consider 250 vehicles, where the vehicles' message frequencies with less relevant information are further decreased. Specifically, the vehicle's message frequency with an information relevance of 0.6 is reduced below 6 Hz. In this scenario, only the vehicle with an information relevance of 1.0 has a message frequency of

10 Hz. Similar to Figure 13c, the channel is highly congested for 250 vehicles and our approach prioritizes highly relevant information.

We again depict the cumulative distribution of the vehicles' message frequencies in Figure 14d after 30 iterations. In this figure, we see that for 50 vehicles, almost all vehicles have the maximum message frequency. In contrast, for 150 and 250 vehicles, only vehicles with relevant information send with the maximum message frequency.

In summary, our approach increases all vehicles' message frequencies to the maximum message frequency in relaxed channels. Under congested channel conditions, our approach decreases the message frequencies of vehicles with low relevant information to counteract channel congestion and prioritize relevant information.

5.3 ADAPTIVE DATA DISSEMINATION STRATEGY FOR COOPERATIVE DRIVING

V2V communication with relevance-aware resource allocation is particularly suited to increase awareness and provide reliable, low-latency communication for cooperative driving in close communication range. However, we have discussed that most cooperative driving use cases[1] require a high communication range to coordinate a maneuver early, decreasing the costs for the vehicle offering cooperation. As outlined in Section 2.1.2, the communication range of V2V networks is severely limited, independent of the concrete V2X access technology, and the limited communication range can be insufficient for cooperative driving (cf. Table 2). In this context, combining V2V with V2N communication offers great potential to improve the communication quality for vehicles coordinating cooperative maneuvers.

Adaptive data dissemination

In this section, we propose an adaptive data dissemination strategy for cooperative driving, using heterogeneous V2X access technologies. Consequently, we *i)* realize local awareness among vehicles in the vicinity, *ii)* increase the communication range for early maneuver coordination, and *iii)* provide high communication quality while coordinating a cooperative maneuver. In this context, a single V2X access technology is insufficient to fulfill the high communication requirements of cooperative driving.

Local awareness

Our adaptive data dissemination strategy for cooperative driving works as follows: A vehicle n always sends MCMs via V2V communication to realize local awareness and provide reliable, low-latency communication for other vehicles nearby.

Early coordination

A vehicle n preemptively obtains the need to request cooperation based on its current route to enable early maneuver coordination. Vehicle n might require cooperation if a lane on its route does not have the right-of-way. As an example, assume that a lane on vehicle n's route requires turning left in an intersection and the lane interferes with another lane. However, vehicle n has not perceived vehicles on the interfering lane because of the limited V2V communication range. Our approach extends the communication range using V2N GEOCAST communication to address and inform potential cooperation partners on the interfering lane early.

High V2X quality

Now suppose that vehicle n recognizes a cooperation conflict with another vehicle j via at least one of the available V2X access technologies, where vehicle j has the right-of-way. Hence, vehicles n and j coordinate a cooperative maneuver. Dur-

1 Except, e. g., platooning, which is not within the scope of this thesis.

ing the coordination of the cooperative maneuver, high V2X communication quality is required. Both vehicles assess the communication quality to each other using our measurement-based AoI assessment. To provide high communication quality while coordinating the cooperative maneuver, we use V2N UNICAST communication if the minimum AoI to the cooperation partner is insufficient. In this phase, we *additionally* send MCMs with V2V communication to maintain local awareness. V2N communication using UNICAST transmission cannot realize local awareness, especially in scenarios with high vehicle density [135, 146, 220, 225].

In the following, we explain the network-assisted GEOCAST service and elaborate on our proposed V2X access technology selection to realize the adaptive data dissemination strategy described above.

5.3.1 *Network-Assisted Geocast Service*

Cooperative driving is a location-based service, where vehicles are relevant depending on their current position – usually in close range and approaching the sender. GEOCAST service for V2N networks was introduced and analyzed in [94] to enable location-based dissemination for V2N communication. Vehicles using the GEOCAST service send their MCMs with the intended destination location to the respective V2X application server, which monitors the position of all connected vehicles.

Location-based dissemination

Implicit vs. explicit localization

A vehicle's position is either implicitly obtained by the V2X application server using a positioning service or explicitly by the vehicles reporting their position to the V2X application server. The implicit approach, e. g., suggested in [171], primarily uses the signal strength to obtain the position of vehicles in a cell.

Grid-based dissemination

An explicit approach is suggested in [94], using a GRID-based approach. A vehicle's position refers to a specific cell on the GRID, where the cell sizes can be adapted. For example, the GEOHASH approach [172] encodes a vehicle's position on the GRID into a short string (GEOHASH). All vehicles within a cell obtain the same GEOHASH. The GEOHASH approach allows adapting the cell size by increasing the GEOHASH length for smaller cell sizes and vice versa. Vehicles report the new GEOHASH via V2N communication to the V2X application server if their GEOHASH changes. The approach suggested in [94] works as a publish-subscribe mechanism, where vehicles subscribe at the V2X application server to events within their current GEOHASH [158]. The V2X application server publishes events to subscribed vehicles in the respective GEOHASH. For example, a vehicle informs other vehicles within a GEOHASH about an emergency using the V2X application server.

Geohash size

For large cell sizes, vehicles on multiple lanes are clustered in the same GEOHASH, increasing the number of subscribed vehicles. Hence, publishing multiple events to large cell sizes increases the channel load in the V2N network because of the high number of subscribed vehicles. In contrast, for small cell sizes, frequent cell updates are required to subscribe to the current GEOHASH, because of the vehicles' high mobility.

Lane-based dissemination

For cooperative driving, only vehicles from a specific lane are relevant for a cooperative maneuver, i. e., the lane interfering and having priority over another lane. For example, only vehicles from a lane approaching an intersection are relevant for the cooperative driving use case left-turning at an intersection. In this context, a GRID-based approach does not differentiate between the approaching and leaving lane. We extend the `GeocastEnabler` [94] and explain our `GeocastForwarder` service in the following to realize LANE-based data dissemination for cooperative driving in V2N networks.

Enabling Lane-Based Geocast Service

Road network notation

The `GeocastEnabler` provides a GEOCAST service for V2N networks, clustering vehicles in lane segments. In the following, we refer to the SUMO [134] notation for the road network. Roads and junctions can consist of multiple lanes, where unique IDs differentiate roads, junctions, and corresponding lanes. Lanes are described by their `laneLength` such that vehicles can localize themselves on a lane using the unique `laneId` and the `laneDistance` traveled on the lane. The `laneDistance` starts at 0 m at the beginning of the lane and is limited by the respective `laneLength`.

Lane segment

In addition to the road network notation of SUMO, we introduce lane segments. For example, for the cooperative driving use case merging on highways, we are only interested in vehicles close to the merging point. However, lanes on a highway can be several kilometers in length. Sending messages to all vehicles driving on a highway lane increases the channel load but only addresses a few relevant vehicles for the cooperative maneuver. Therefore, we divide lanes into multiple segments, where each segment has the same `segmentLength`. We use the `laneLength` and the `segmentPrecision` to divide a lane into segments of equal `segmentLength`. For example, with a `segmentPrecision` of 2, a lane with a `laneLength` of 1000 m is divided into two segments. Thus, each lane segment has a `segmentLength` of 500 m. The segments are identified with the `segmentId` 1 and 2, for the first and second lane segment, respectively.

Lane-based Geocast

The LANE-based GEOCAST service proposed in this thesis works as follows: A vehicle notifies the `GeocastEnabler` with a `GCNotifyMsg` (GEOCAST notification message) when it enters a new lane segment, including the `laneId` and corresponding `segmentId`. The `GeocastEnabler` confirms the reception with a `GCConfMsg` (GEOCAST confirmation message), which includes the requested `segmentPrecision` by the server. A vehicle sends the `GCNotifyMsg` until it receives a `GCConfMsg` from the `GeocastEnabler`.

The message frequency of `GCNotifyMsg` until receiving a `GCConfMsg` can be parameterized and is context-dependent. In this thesis, we use the minimum message frequency λ_{MIN} of 1 Hz. V2N networks send messages with high reliability (cf. Section 2.1) such that a higher message frequency only increases the channel load. The default `segmentPrecision` is 1, meaning that a lane only consists of one segment if a vehicle enters a new lane. The `GeocastEnabler` adapts the `segmentPrecision` of each lane depending on the respective context, e. g., vehicle density, velocity, and application. For example, for merging on a highway, we specifically address vehicles in the last lane segment close to the merging point if the lane is divided into multiple segments. However, a higher `segmentPrecision` also increases the number of `GCConfMsg` because vehicles enter new lane segments more frequently. Hence, depending on the current context, the `GeocastEnabler` requests a higher `segmentPrecision` in the `GCConfMsg`. Based on the `segmentPrecision` in the `GCConfMsg`, the vehicle obtains the `segmentLength` of its

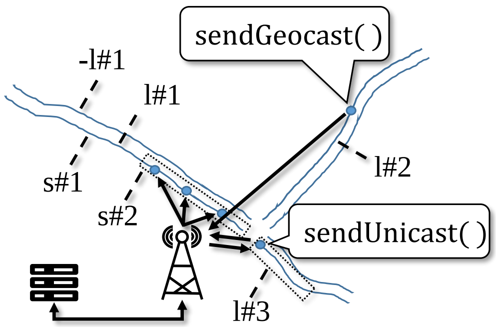


Figure 15: Illustrating the Lane-based Geocast service in an intersection with three arms. Vehicles are illustrated as blue dots.

current lane and notifies the `GeocastEnabler` when entering a new lane segment in the same lane with a `GCNotifyMsg`.

Other Geocast services, such as the `GeocastForwarder` explained in the following, use the `GeocastEnabler` to address vehicles on specific lane segments.

Geocast Message Forwarding

The `GeocastForwarder` offers services for vehicles to forward their MCMs to other vehicles in the V2N network. The methods explained in the following will be used for our adaptive data dissemination strategy.

Unicast

Vehicles send MCMs, denoted as `msg`, to a specific vehicle using the Unicast transmission mode. The intended receiver is identified by its `v2xId`.

```
void sendUnicast(V2xId, msg);
```

Lane-based Geocast

For Geocast dissemination, vehicles send messages using our Lane-based approach. Vehicles identify the relevant lane by the respective `laneId`. Furthermore, the lane is geographically limited with a start and stop distance, referred to as `startDistance` and `stopDistance`, respectively. That way, only vehicles on the given `laneId` between the `startDistance` and `stopDistance` are relevant for the sent `msg`. Suppose the respective `laneId` has been split into multiple lane segments by the `GeocastEnabler` with a `segmentPrecision` greater than 1. Then, the `GeocastForwarder` selects and forwards the `msg` to the lane segments covering the given `startDistance` and `stopDistance` of the lane. To address vehicles on multiple lanes, we use a `listOfLanes` container. We use the C++ container `std::list`, where each list entry is a tuple, including the `laneId`, `startDistance`, and `stopDistance` as

```
std::list<std::tuple<std::string, int, int>> listOfLanes;
listOfLanes = std::make_tuple(laneId, startDistance, stopDistance);
```

Finally, for Lane-based Geocast, we use the following method to send the `msg` to one or multiple lanes.

```
void sendGeocast(listofLanes, msg);
```

The concept of Lane-based Geocast communication is depicted in Figure 15. On lane `l#3` (bottom-right), a vehicle has entered a new lane segment and sends a `GCNotifyMsg` to the cellular network. The GEOCAST server in the cellular network confirms the new lane segment with a `GCConfMsg`. On lane `l#2`, a vehicle sends a `msg` via the `sendGeocast()` method to lane `l#1` and wants to address vehicles close to the intersection by adjusting the `startDistance` and `stopDistance`. The `GeocastForwarder` selects the lane segment `s#2` based on the requested `startDistance` and `stopDistance` of the sending vehicle for the respective lane and forwards the message to all vehicles on this lane segment.

Adapting the Lane Segment Length

Following our proposed LANE-based GEOCAST approach, the number of vehicles addressed on a lane depends on the selected `startDistance` and `stopDistance` by the message sender and the `segmentPrecision`, selected by the `GeocastEnabler`.

Segment precision

The selection of the `segmentPrecision` has a significant impact on the channel load for V2N communication: A high `segmentPrecision` allows to send messages only to relevant vehicles but requires updating the lane segment more frequently, increasing the number of messages in the up- and downlink for the notification and confirmation.

Lane segment length

The `startDistance` and `stopDistance` for a LANE-based GEOCAST message severely depend on the context and the considered cooperative function. For our considered cooperative driving use cases left-turning at an intersection and merging on a highway, we consider the following generic approach: Suppose we have obtained a lane of interest that interferes with our current route and the respective lane has the right-of-way. The considered lane with the lane length l_L allows for the maximum velocity v_{MAX} and the intersection or merging point is connected to the end of the respective lane. Consequently, we set the `stopDistance` to the lane length l_L. Then, we obtain the `startDistance` as $l_L - T_{TH} \cdot v_{MAX}$, where T_{TH} is the time horizon of our trajectory. That way, we address all vehicles that might be relevant for our considered cooperative function on the lane of interest using our LANE-based GEOCAST approach.

5.3.2 V2X *Access Technology Selection*

After introducing our GEOCAST service, we present our data dissemination strategy using heterogeneous V2X access technologies for cooperative driving. The cooperative driving application creates V2X messages with the maximum message frequency.

Algorithm 3 selects the dissemination approach for each created `msg`. The same `msg` can be sent via different V2X access technologies, i. e., we create duplicates of the same `msg` if required. The data required for Algorithm 3 is the number of vehicles N, the vehicle's trajectory χ_n, and its MCM `msg`.

Increasing local awareness

In line 1, the function `isRelevant()` represents our relevance-aware resource allocation described in Section 5.2. The method checks if the considered `msg` should be sent via SHB according to its information relevance, the information relevance of other messages, and the channel load in the V2V network to increase local awareness. If the `msg` is relevant, it is sent via the `sendSHB()` method.

Algorithm 3 : Data dissemination strategy for a vehicle n with heterogeneous V2X access technologies for cooperative driving.

Data: Perceived vehicles N, own trajectory χ_n, and message `msg`

1: **if** `isRelevant(`*msg*`)` **then**
2:     `sendSHB(`*msg*`); // via V2V`
3: **end if**
4: **for each** cooperation partner j **in** N **do**
5:     **if** `isAoIAboveThreshold(j)` **then**
6:         `sendUnicast(`j`.getV2xId(),`*msg*`); // via V2N`
7:     **end if**
8: **end for**
9: *nextPotCoop* $\leftarrow$ `getNextPotentialCooperation(`χ_n`)`
10: **if** *nextPotCoop*`.isValid()` **then**
11:     [*laneId, startDistance, stopDistance*] $\leftarrow$ *nextPotCoop*`.getLaneBoundaries()`
12:     `sendGeocast(`*laneId, startDistance, stopDistance,* *msg*`); // via V2N`
13: **end if**

Cooperation partners, i. e., vehicles having a cooperation conflict or executing a cooperative maneuver with the considered vehicle, are selected among all perceived vehicles in line 4. Otherwise, i. e., the vehicle has no cooperation partner, the for-loop is skipped. If a cooperation partner j among vehicles N is found, `isAoIAboveThreshold()` assesses the communication quality according to the measurement-based AoI model described in Section 4.2.2. If the assessed AoI is above the respective cooperative driving application's threshold, the `msg` is sent via V2N UNICAST to the respective vehicle with the `sendUnicast()` method. In this context, `getV2xId()` obtains the V2X ID of the respective vehicle j.

Improving V2X quality

Enabling early coordination

To enable early coordination of maneuvers, `getNextPotentialCooperation()` obtains the next potential cooperative maneuver from the vehicle's trajectory χ_n. Potential cooperative maneuvers are not obtained from trajectory conflicts between vehicles but from map data. For example, a vehicle approaching an intersection obtains the traffic rule for its corresponding action from map data, e. g., turning left or driving straight in an intersection. Assume that the vehicle wants to turn left in the intersection, but another lane crosses straight and has the right-of-way. In this case, the maneuver to turn left implies the need for a potential cooperative maneuver. In contrast, vehicles on the straight crossing lane have the right-of-way (also for other potentially crossing lanes) and do not need to request a cooperative maneuver in the intersection.

Extending to other use cases

Our approach can also be extended to other use cases such as cooperative merging on highways or lane-change to obtain potential cooperative maneuvers at the merging point. If a potential cooperative maneuver for the trajectory exists, we identify the lane segment of interest with the `laneId`, `startDistance`, and `stopDistance`. Finally, `sendGeocast()` sends the `msg` with the lane properties to the GEOCAST server, where the `msg` is forwarded via UNICAST to vehicles on the requested lane segments. The message frequency for `sendGeocast()` and `sendUnicast()` is not limited by our relevance-aware resource allocation approach. Hence, V2N communication sends with the maximum message frequency if the adaptive data dissemination strategy selects it.

In summary, our adaptive data dissemination strategy realizes cooperative awareness using V2V SHB transmission, where we use our relevance-aware resource allocation to prioritize relevant information. Our approach extends the communication range of V2V SHB with V2N communication and addresses relevant vehicles with our LANE-based GEOCAST approach to allow early maneuver coordination. Lastly, to provide high communication quality during the execution of a cooperative maneuver, V2N UNICAST communication is used if we assess insufficient communication quality for the V2V SHB communication.

5.4 COMMUNICATION-AWARE COOPERATIVE DRIVING

Cooperative driving in [137] is divided into the phases of *detection*, *negotiation*, and *execution*, where all three phases require high communication quality for maneuver coordination. However, physical constraints of V2X networks impair the communication quality and, therefore, degrade the performance of cooperative driving.

Safety for maneuver coordination

In [138], the authors analyzed the impact of impaired communication quality for their cooperative driving approach [137], focusing on the three phases mentioned above. The authors qualitatively analyzed that unreliable, low-range V2X communication decreases the traffic efficiency of cooperative driving but does not introduce additional safety risks. However, the authors excluded the case that a vehicle has to abort the cooperative maneuver in the *execution* phase.

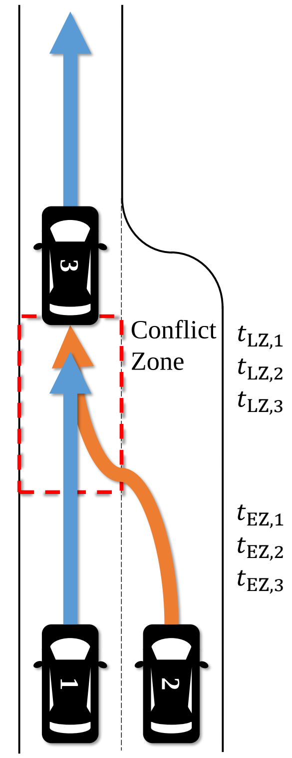
Safety for maneuver execution

In the following, we specifically focus on impaired communication quality during the maneuver *execution* phase. Suppose that an emergency event occurs, e. g., a pedestrian crosses the road in an intersection during the cooperative maneuver *execution*. Hence, a vehicle involved in the cooperation requires deviating from its current maneuver, introducing a safety risk for the other involved vehicles. Moreover, we consider a scenario with impaired communication quality such that the vehicles involved in the cooperation might not be informed about the emergency in time.

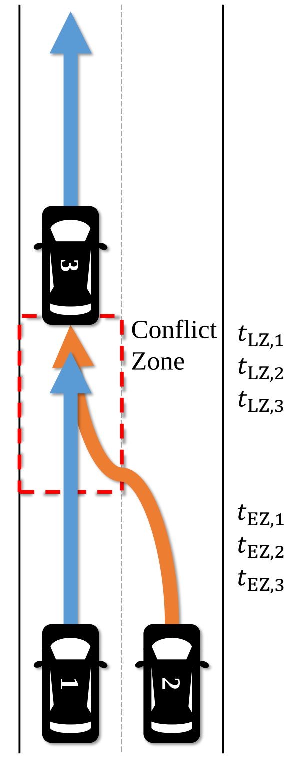
In this section, we formalize trajectory-based coordination of cooperative driving maneuvers. After that, we formulate the necessary condition for safe maneuver *execution* and perform a sensitivity analysis for impaired communication quality based on our derived safety conditions. Finally, we propose a communication-aware approach for trajectory-based cooperative driving, decreasing traffic efficiency to maintain safety in scenarios with impaired communication quality.

5.4.1 *Trajectory-Based Coordination of Cooperative Driving Maneuvers*

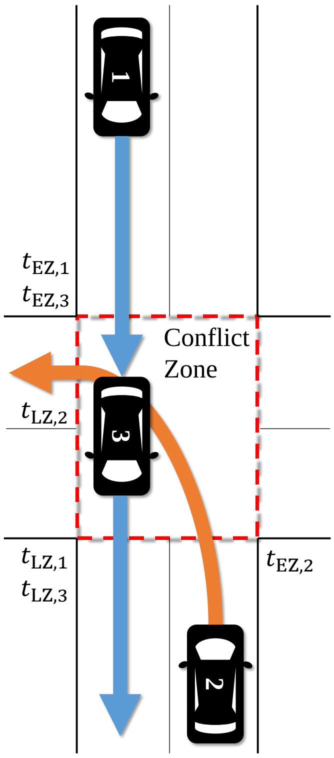
Cooperative driving enables the coordination of conflict-free future paths, allowing vehicles to improve traffic efficiency in congested vehicular traffic scenarios. Trajectories were used [137, 142] to represent a vehicle's future position as a function of time within a limited time horizon, denoted as T_{TH}. A trajectory starts at the current vehicle's position and is conflict-free if the trajectory does not collide with other re-



(a) Merging on a highway.



(b) Cooperative lane change.



(c) Left-turning at an intersection.

Figure 16: Conflict zones for different cooperative driving use cases, denoting the time when vehicles enter and leave the conflict zone.

ceived trajectories in its time horizon $0 \leqslant t \leqslant T_{TH}$. Following the approach in [137], a vehicle obtains a set of trajectories, representing possible future maneuvers based on its current position and velocity. From the set of trajectories, the vehicle obtains and executes its best conflict-free trajectory, denoted as planned trajectory.

Conflict-free coordination

Conflict resolution

Assume a vehicle recognizes a conflict of its planned trajectory with a planned trajectory of another vehicle and does not have the right-of-way for the mentioned maneuver. For the time the conflict exists, the vehicle without the right-of-way has to select another conflict-free trajectory, e. g., decelerating while approaching an intersection. With cooperative driving, the vehicle without the right-of-way can avoid decelerating and requests cooperation by sending the conflicting trajectory as the desired trajectory. Notably, cooperation is also connected to costs for the vehicle offering cooperation, e. g., decelerating or changing the current lane to open a gap for the requesting vehicle.

Conflict zone

In this scenario, the trajectories of two vehicles are colliding in the temporal *and* spatial domains. Figure 16 illustrates such a conflict for merging on a highway in Figure 16a, cooperative lane change in Figure 16b, and left-turning at an intersection in Figure 16c. For each use case in Figure 16, we denote the area where the vehicles' trajectories collide as a conflict zone. We define that only one vehicle can be in the conflict zone simultaneously. The conflict zone can have different shapes, depending on the model description, road topology, and cooperative driving use case. The conflict zone shape can be reduced to the vehicles' dimensions. However, for the numerical model, we consider the left-turning at intersection use case with a rectangular conflict zone shape, as depicted in Figure 16c.

For a vehicle n, we denote the time when the vehicle enters and leaves the conflict zone as $t_{EZ,n}$ and $t_{LZ,n}$, respectively. Using the own and received trajectories, a vehicle n obtains $t_{EZ,j}$ and $t_{LZ,j}$ for other vehicles j involved in the conflict zone, such as depicted for the use cases in Figure 16.

Maneuver coordination

Assume that in Figure 16c, vehicles 1 and 2 recognize a conflict of their trajectories because both arrive in the conflict zone simultaneously, i. e., $t_{EZ,1} = t_{EZ,2}$. Vehicle 1 must ensure to enter the conflict zone after vehicle 2 has left it to offer cooperation, requiring $t_{EZ,1} > t_{LZ,2}$. In the following, we provide a trajectory-based representation of the vehicles' paths to determine when vehicles enter and leave the conflict zone.

Trajectory-based representation

Let $\chi_n(t)$ denote the planned trajectory of a vehicle n, which denotes the position of vehicle n on the road as a function of time t. Following the description of trajectory sections in Section 4.1.2, a trajectory consists of multiple sections and each trajectory section is represented with one or multiple longitudinal polynomials. For simplicity, we assume that each trajectory section consists of one longitudinal polynomial in the following. We can write the trajectory $\chi_n(t)$ as a sum of longitudinal polynomials $\Omega_e(t)$, where $e \in \mathbb{N}$, as

$$\chi_n(t) = \sum_{e>0} \Omega_{n,e}(t). \tag{44}$$

In Equation 44, each longitudinal polynomial represents a trajectory section and describes the vehicle path for a specific lane. In general, trajectories are also described with lateral polynomials to represent the vehicle's offset on a lane. For left-turning at an intersection, both vehicles remain in the middle of the lane. Hence, it is sufficient to use the representation in Equation 44. However, for merging on highways or cooperative lane change, we must also describe the lateral offset for the lane change. In Equation 44, the first polynomial $\Omega_{n,1}$ with $e = 1$ starts at time $t = 0$ and the second longitudinal polynomial $\Omega_{n,2}$ starts at the end of the first polynomial. The last longitudinal polynomial ends with the time horizon T_{TH}.

Longitudinal polynomial

We represent each longitudinal polynomial $\Omega_{n,e}(t)$ of a vehicle n with a constant deceleration model, giving

$$\Omega_{n,e}(t) = d_{n,e} + v_{n,e} \cdot t + 0.5a_{n,e} \cdot t^2, \tag{45}$$

where $d_{n,e}$, $v_{n,e}$, and $a_{n,e}$ are the vehicle's progress on the lane, its velocity, and acceleration at the start of the polynomial $\Omega_{n,e}(t)$.

In the following, we analyze the safety aspect of cooperative driving while executing a cooperative maneuver. We use the trajectory representation in Equation 44 and Equation 45 of a vehicle's path and its corresponding longitudinal polynomials for our communication-aware cooperative driving approach.

5.4.2 *Sensitivity Analysis for Cooperative Driving*

In this thesis, we assume that vehicles cooperate if the costs required to offer cooperation are sufficiently low. During the execution of a coordinated maneuver, vehicles will not abort the maneuver to increase their traffic efficiency, e. g., accelerating to close the gap required for cooperation. However, during cooperation, any vehicle involved in the cooperative maneuver can be in an emergency and, in contrast to its last sent planned trajectory, must decelerate. For this scenario, we analyze the impact on traffic safety for vehicles executing a cooperative maneuver.

Unexpected events

Safety conditions

We refer to the illustration in Figure 16c, where vehicle 1 offers cooperation for vehicle 2 to turn left in the intersection. For this cooperative maneuver, vehicle 3 first leaves the intersection. After that, vehicle 2 followed by vehicle 1 pass the conflict zone in the intersection. Consequently, the following conditions for the coordinated maneuver must hold to ensure traffic safety in the conflict zone:

$$t_{EZ,2} \geqslant t_{LZ,3} \tag{46a}$$

$$t_{EZ,1} \geqslant t_{LZ,2} \tag{46b}$$

In the following, we neglect the case that a vehicle decelerates and stops before the conflict zone. The mentioned case does not introduce any additional safety risks for the cooperative maneuver *in* the conflict zone of the intersection. Furthermore, we assume that vehicles will not introduce additional safety risks by declining an offered cooperation, i. e., vehicles behave cooperatively.

Case 1: Vehicle 1 must decelerate.

In this case, the time when vehicle 1 enters the conflict zone $t_{EZ,1}$ increases, which results in an even larger gap to vehicle 3. In this scenario, Equation 46b is still fulfilled and the case does not introduce any additional safety risks for the considered vehicles in the conflict zone.

Case 2: Vehicle 2 must decelerate.

Vehicle 2 requested a cooperative maneuver to improve its traffic efficiency. However, vehicle 2 must decelerate unexpectedly, increasing its time when leaving the intersection $t_{LZ,2}$. Equation 46a is still fulfilled. Thus, no adaptation is required from vehicle 3. However, vehicle 2 must abort the cooperation or vehicle 1 must increase the time when entering the collision zone $t_{EZ,2}$, such that Equation 46b is still fulfilled.

Case 3: Vehicle 3 must decelerate.

Vehicle 3 is not directly involved in the cooperative maneuver of vehicle 1 and 2. However, if vehicle 3 must decelerate, its time leaving the collision zone $t_{LZ,3}$ increases, decreasing the cooperation gap between vehicles 2 and 3. Consequently, vehicle 2 must increase the time when entering the collision zone $t_{EZ,2}$, increasing the time leaving the collision zone $t_{LZ,2}$. Moreover, as vehicle 2 leaves the intersection later, vehicle 1 must increase its time entering the collision zone $t_{EZ,1}$.

In summary, for the two latter cases, we increase the time when arriving in the conflict zone to ensure that only one vehicle is in the conflict zone. However, this sensitivity analysis assumed that all vehicles are immediately aware of the emergency and have sufficient time to decelerate before entering the conflict zone. If the communication quality is impaired, the involved vehicles might not be informed in time and cannot ensure to arrive later in the conflict zone. In the following, we propose communication-aware cooperative driving to address the mentioned problem.

5.4.3 *Adapting Cooperative Driving to the Assessed Communication Quality*

In the previous section, we have described a trajectory-based cooperative driving model and analyzed traffic safety during the execution of a cooperative maneuver, focusing on left-turning at an intersection as an illustrative example. Our sensitivity analysis showed that unexpected events, forcing a vehicle involved in a cooperative maneuver to decelerate, introduce additional safety risks for cooperating vehicles. For example, if vehicle 3 in Figure 16c requires decelerating unexpectedly, the gap opened by vehicle 1 to offer cooperation for vehicle 2 reduces and might be insufficient for vehicle 2 to turn left safely. If vehicle 2 is aware of vehicle 3's unexpected behavior, it aborts the cooperation to avoid a collision and stops before the conflict zone.

Impaired communication quality

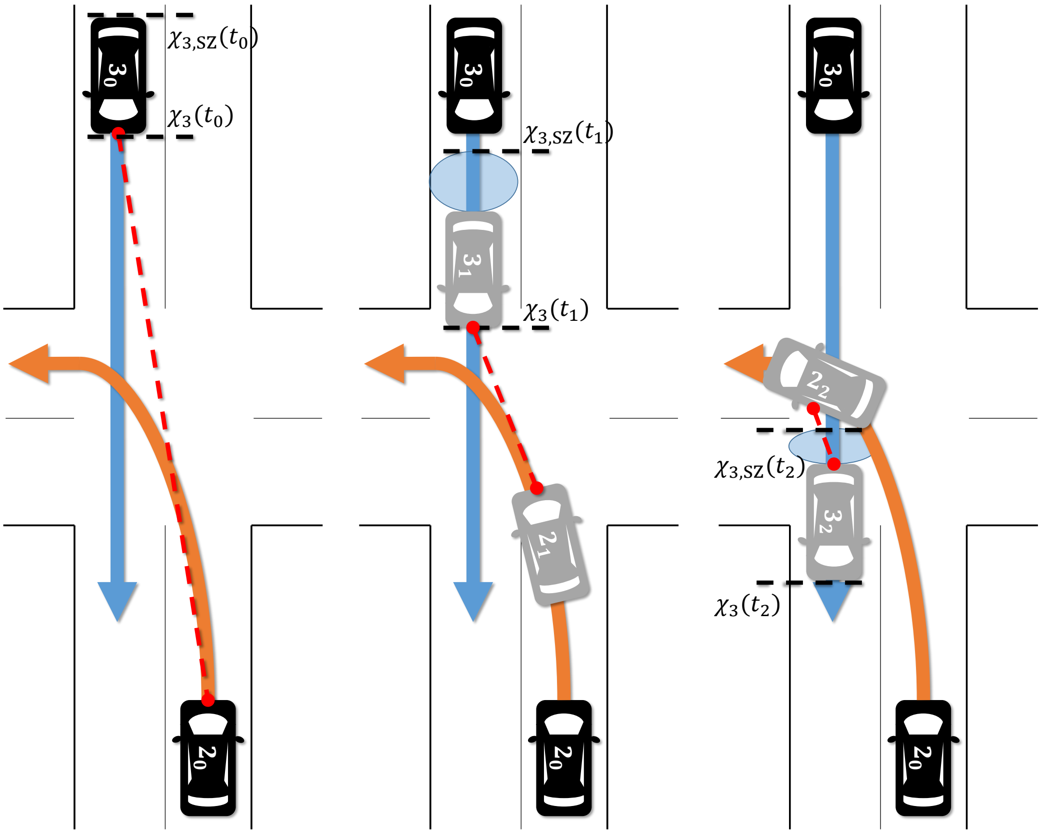
Consider the same scenario with impaired communication quality after vehicles 1 and 2 coordinated and started executing their cooperative maneuver. Consider that vehicle 3 again requires decelerating unexpectedly. However, vehicle 2 does not receive MCMs from vehicle 3 in time and, hence, is unaware of vehicle 3's unexpected behavior because of impaired communication quality. In the considered scenario, vehicle 2 does not adapt its maneuvers to stop before the conflict zone, leading to a collision of the cooperation partners. Note that vehicle 1 might also not receive MCMs from vehicle 3 in time. For readability, in the following, we focus on vehicle 2. However, our presented approach also applies for vehicle 1.

Traffic safety for platooning

In [197, 213, 214], the authors increase the gap between vehicles in a platoon for impaired communication quality and decrease the gap otherwise. However, their approach cannot be applied to the cooperative driving use cases considered in this thesis. The reasons are that *i)* vehicles in a platoon usually plan their cooperative maneuver within a short time period and *ii)* the distance between cooperation partners is small. The proposed approach in [197, 213, 214] instantaneously adapts to the current situation. However, cooperative driving use cases considered in this thesis coordinate the cooperative maneuvers over a longer time period. Hence, the communication distance between cooperation partners is large at the beginning and decreases during the maneuver execution.

Communication-aware cooperative driving

Consequently, we present our communication-aware cooperative driving approach to improve traffic efficiency and maintain safety. Our approach extends the trajecto-



(a) Current time t_0. (b) Prediction for time t_1. (c) Prediction for time t_2.

Figure 17: The concept of communication-aware safety zones for left-turning at an intersection, where vehicle 2 obtains the safety zones of vehicle 3 for different time steps on the trajectories.

ry-based, decentralized cooperative driving approach presented in [137]. From each received trajectory, we derive a safety zone trajectory, depending on the vehicle's maximum deceleration capability and assessed AoI, introduced in Chapter 4. The safety zone trajectory converges to the received trajectory for high communication quality and diverges otherwise. Ensuring collision-free trajectories between the received *and* safety zone trajectories enables communication-aware cooperative driving.

Concept of safety zone trajectories

Our concept is depicted in Figure 17, where vehicle 2 obtains a safety zone trajectory $\chi_{3,SZ}(t)$ for vehicle 3, based on its planned trajectory $\chi_3(t)$. We define that the safety zone trajectory $\chi_{3,SZ}(t)$ starts at the vehicle's back. The future positions of both vehicles on their trajectories for different time steps are depicted in grey. The vehicles depicted in black refer to their current positions at time t_0.

Consider that vehicle 3 sent an MCM with its planned trajectory $\chi_3(t)$, which is successfully received by vehicle 2. At the current time t_0, depicted in Figure 17a, the model-based assessed peak AoI is expected to be high because of the high communication range, illustrated as a red dashed line. Using $\chi_3(t)$, vehicle 2 obtains the future positions of vehicle 3 at different time steps t within the trajectory time horizon T_{TH}. $\chi_3(0)$ denotes the actual position of vehicle 3 when creating the respective trajectory. We assume that the actual position of vehicle 3 is highly accurate and is not impaired by inaccurate localization. Therefore, at time t_0, the safety zone trajectory is $\chi_{3,SZ}(0) = \chi_3(0) - l_3$, where l_3 is the length of vehicle 3. Remember that the safety zone trajectory is defined to start at the vehicle's back and, therefore, requires the vehicle's length as an offset.

Vehicle 2 predicts its and the other vehicle's position at time t_1 using the trajectory received at t_0, depicted in Figure 17b. At any time t between the current time t_0 and the time t_1, vehicle 3 might require decelerating unexpectedly. In a scenario with impaired communication quality, vehicle 2 is unaware of vehicle 3's unexpected deceleration. We approximate the time where vehicle 2 is unaware of vehicle 3 with the model-based assessed peak AoI. To obtain $\chi_{3,SZ}(t_1)$, we calculate the position of vehicle 3 at $\chi_3(t_1 - \hat{\Delta}(t_1))$ and assume that vehicle 3 decelerates with its maximum deceleration capability a_{MAX} for the time $\hat{\Delta}(t_1)$. The safety zone trajectory $\chi_{3,SZ}(t_1)$ diverges from the planned trajectory $\chi_3(t_1)$ because we assume a high AoI, depicted in Figure 17b. At time t_2 and in contrast to t_1, the safety zone trajectory $\chi_{3,SZ}(t_1)$ again converges to the planned trajectory $\chi_3(t_2)$ because the vehicles are closer, resulting in a lower AoI. Note that the trajectory of vehicle 2 is not allowed to collide with the safety zone trajectory of vehicle 3 at time t_2. We indicate the difference between the received and obtained safety zone trajectories as a blue circle in Figure 17. In the following, we explain how to obtain $\chi_{j,SZ}(t)$ for a vehicle j based on its sent trajectory $\chi_j(t)$.

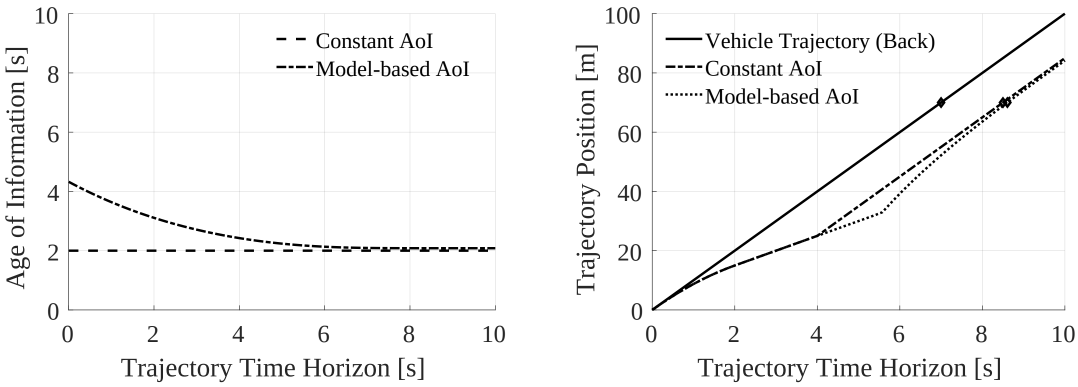
Numerical model

Vehicle n obtains the peak AoI $\hat{\Delta}_{n,j}(t)$ using vehicle j's and the own trajectories with our model-based assessment approach. $\hat{\Delta}_{n,j}(t)$ describes the peak AoI between vehicle n and j at different time steps t, depending on their trajectories. At any time t, we describe the peak AoI depending on the communication distance between both vehicles obtained from their trajectories, the channel congestion, and the message frequency of vehicle j.

At time t and with the assessed peak AoI of $\hat{\Delta}_{n,j}(t)$, we expect to receive the last information from vehicle j at $t - \hat{\Delta}_{n,j}(t)$. However, during the time $\hat{\Delta}_{n,j}(t)$, vehicle j can have an emergency, requiring the vehicle to decelerate with a_{MAX}. Hence, at time t, the position of vehicle j can be between $\chi_j(t)$ and $\chi_j(t - \hat{\Delta}_{n,j}(t)) - l_j - v(t - \hat{\Delta}_{n,j}(t)) \cdot \hat{\Delta}_{n,j}(t) - 0.5a_{MAX} \cdot \hat{\Delta}^2_{n,j}(t)$. We define the latter expression as the communication-aware safety zone trajectory.

However, for $t \leqslant \hat{\Delta}_{n,j}(t)$, the communication-aware safety zone trajectory of vehicle j is currently not defined because the trajectory $\chi_j(t)$ is not defined for $t < 0$. In that case, we consider the current position $\chi_j(0)$ of vehicle j and consider a deceleration for the time t. Furthermore, we need to differentiate the case that vehicle j decelerates to a standstill. For $t \leqslant \hat{\Delta}_{n,j}(t)$, vehicle j decelerates to a standstill if $t \leqslant v_j(t)/a_{MAX}$ holds and $\hat{\Delta}_{n,j}(t) \leqslant v_j(t)/a_{MAX}$ otherwise.

Finally, by differentiating the aforementioned cases, we get the safety zone trajectory $\chi_{j,SZ}(t)$ of vehicle j for $t \in [0, T_{TH}]$ as



(a) Age of Information.

(b) Safety Zone Trajectories.

Figure 18: Illustration of two considered peak AoI models (left) and the safety zone trajectory $\chi_{j,SZ}$ (right).

$$
\begin{aligned}
\chi_{j,SZ}(t) &= \chi_j(0) - l_j + \nu_j(0)\cdot t \qquad\qquad \textbf{if } t \leqslant \hat{\Delta}_{n,j}(t) \\
&+ \begin{cases} 0.5a_{MAX}\cdot t^2, & \textbf{if } t \leqslant \frac{\nu_j(0)}{a_{MAX}}, \\ 0.5\frac{\nu_j^2(0)}{a_{MAX}}, & \textbf{else}, \end{cases} \\
\chi_{j,SZ}(t) &= \chi_j(t-\hat{\Delta}_{n,j}(t)) - l_j + \nu_j(t-\hat{\Delta}_{n,j}(t))\cdot\hat{\Delta}_{n,j}(t) \quad \textbf{else}, \\
&+ \begin{cases} 0.5a_{MAX}\cdot\hat{\Delta}_{n,j}^2(t), & \textbf{if } \hat{\Delta}_{n,j}(t) \leqslant \frac{\nu_j(t-\hat{\Delta}_{n,j}(t))}{a_{MAX}}, \\ 0.5\frac{\nu_j^2(t-\hat{\Delta}_{n,j}(t))}{a_{MAX}}, & \textbf{else}. \end{cases}
\end{aligned} \tag{47}
$$

Illustration of safety zones

Figure 18 illustrates the concept of a safety zone trajectory for two different AoI models. In Figure 18a, the model-based assessed peak AoI is depicted as a function of time t. We refer to the evolution of the peak AoI for a pair of trajectories within their time horizons. The first AoI model is constant over time, giving $\hat{\Delta}_C(t) = 2\,\text{s}$. For the second AoI model, we use the model-based assessed peak AoI depicted in Figure 10, where we considered 200 vehicles in a congested channel. In Figure 18b, the solid line refers to the position of the vehicle j's back for the considered time period. The dashed line refers to the obtained safety zone trajectory of vehicle j for the constant AoI model. The dotted-dashed line depicts the safety zone trajectory of vehicle j for the model-based AoI. The trajectory of vehicle j is described with one polynomial, where $\Omega_{j,1}(t) = 10\frac{\text{m}}{\text{s}}\cdot t$ and is valid between $0 \leqslant t \leqslant 10\,\text{s}$. In Figure 18b we see that the safety zone trajectories are comparable to the actual trajectory for $t < 1\,\text{s}$, i. e., we have accurate information about vehicle j. At $t = 4\,\text{s}$ on the trajectory, the dashed line denoting the safety zone trajectory with $\Delta_1(t)$ stops diverging from the actual trajectory. Here, we consider the second case of Equation 47, where t is larger than the AoI. In contrast, the safety zone trajectory for the model-based AoI first increases until $t = 5.5\,\mathrm{s}$ and then converges to the safety zone trajectory of the constant AoI model because the AoI decreases in the considered time interval. Let us assume that a vehicle j leaves the conflict zone at $t = 7\,\mathrm{s}$, according to its trajectory $\chi_j(t)$. Considering $\Delta_1(7\,\mathrm{s}) = 2\,\mathrm{s}$, we know that vehicle j has safely left the conflict zone at 8.5 s and $\Delta_2(7\,\mathrm{s}) = 2.1$ s at 8.61 s. If vehicle n is expected to enter the conflict zone after vehicle j, vehicle n trades traffic efficiency for safety such that vehicle n enters the conflict zone 1.5 s or 1.61 s later compared to its planned trajectory, considering the constant and model-based AoI, respectively.

In summary, our communication-aware cooperative driving approach extends trajectory-based cooperative driving. For each received trajectory, our presented approach derives a safety zone trajectory depending on the model-based assessed peak AoI and maximum deceleration capability of the respective vehicle. The safety zone trajectory diverges from the received trajectory in scenarios with impaired communication quality. Hence, the safety margins between vehicles are adapted to account for unexpected events and high reaction times in scenarios with a high AoI.

Resource allocation

Our relevance-aware resource allocation approach significantly contributes to efficient channel usage in decentralized V2X networks. Our approach considers the assessed information relevance for its message and other vehicles' information relevance and message frequency to derive its optimal message frequency. That way, our approach aims to maximize the information relevance in a decentralized V2X network.

Adaptive dissemination

In addition, our proposed data dissemination strategy for cooperative driving with V2V and V2N access technologies addresses the strict communication requirements of cooperative driving. Our approach increases the communication quality for vehicles coordinating cooperative maneuvers.

Adaptive cooperative driving

Lastly, we increase traffic safety of cooperative driving in scenarios with impaired communication quality. Our communication-aware approach extends the decentralized cooperative driving approach to remain safe even in scenarios with impaired communication quality, decreasing traffic efficiency to maintain safety.

6 SIMULATION OF COOPERATIVE DRIVING IN VEHICULAR NETWORKS

To evaluate our proposed contributions, we use a Vehicle-to-Everything (V2X) network simulator with a cooperative driving application to coordinate maneuvers in scenarios with high vehicle density. In this thesis, we present CoDA.kom, a large-scale cooperative driving V2X network simulation framework. CoDA.kom builds upon the well-known V2X network simulation framework Veins [198], coupling the event-discrete network simulator OMNeT++ [219] and the vehicular traffic simulator SUMO [134]. In this chapter, we outline our simulation architecture CoDA.kom in Section 6.1, showing the required extensions to support cooperative driving. After that, we describe our channel models to represent radio propagation effects in Section 6.2. Finally, Section 6.3 describes our prototypical realization of the cooperative driving application left-turning at an intersection in detail.

6.1 OVERVIEW AND SIMULATION FRAMEWORK

In the following, we describe our simulation framework CoDA.kom, depicted in Figure 19. For this purpose, we discuss the implementation of the considered heterogeneous V2X access technologies, i. e., ETSI ITS-G5 and 3GPP LTE-V2N. After that, we explain the functionality of the middleware and facilities in the vehicle V2X stack.

6.1.1 *Heterogeneous Access Technologies*

In this thesis, we use heterogeneous V2X access technologies to exchange driving intentions and coordinate cooperative maneuvers. For this purpose, we explain the implementations of ETSI ITS-G5 and 3GPP LTE-V2N in the following.

ETSI ITS-G5

ETSI ITS-G5 uses IEEE 802.11p on the access layer, as described in Section 2.1. We use the implementation of Veins for the access layer of IEEE 802.11p [198].

Congestion control

The implementations of European Telecommunications Standards Institute (ETSI) Reactive Decentralized Congestion Control (R-DCC) and Adaptive Decentralized Congestion Control (A-DCC), as standardized in [102], are adapted from [181]. ETSI R-DCC and A-DCC obtain the Channel Busy Ratio (CBR) from the access layer and open or close the gate to the access layer for Decentralized Congestion Control (DCC). If the gate is closed and a new message from an application arrives, the respective message will be delayed or dropped.

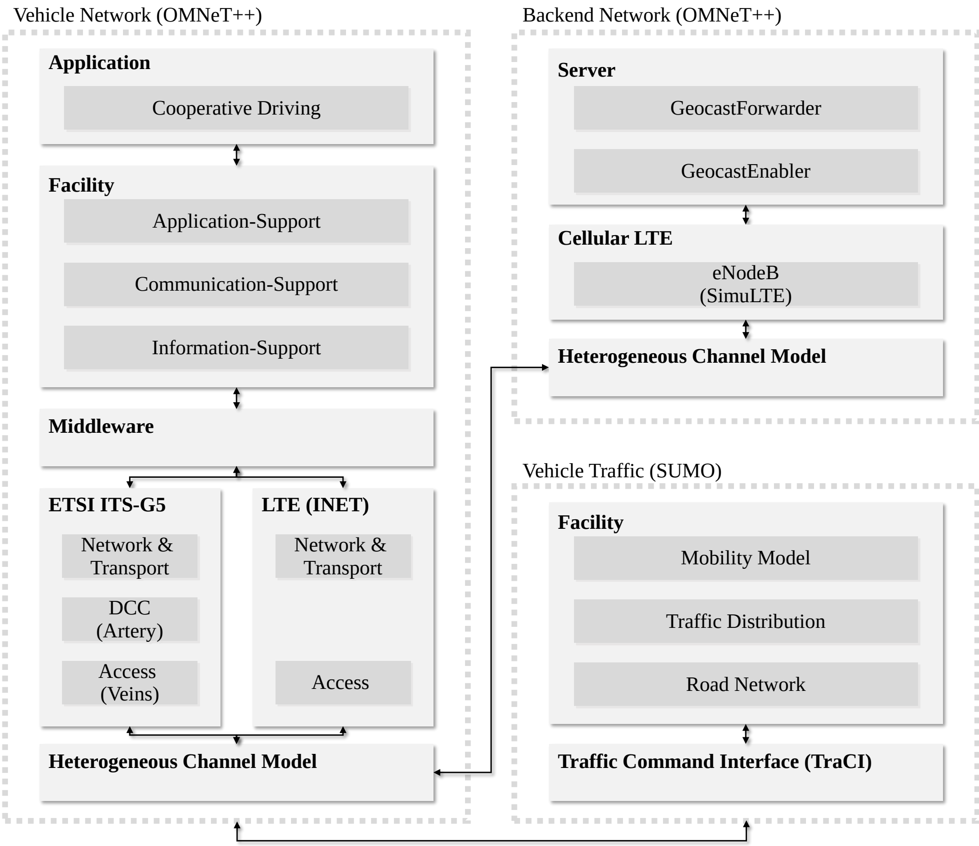


Figure 19: CoDA.KOM simulation framework for cooperative driving with heterogeneous V2X access technologies.

Network & Transport

On the network and transport layer, we implement the GeoNetworking protocol with ETSI ITS-G5 media-dependent functionalities [107], as standardized in [105]. Our implementation supports the geographical addressing modes described in Section 2.1 and continuously updates the location table based on received V2X messages. As security aspects are out of the scope for this thesis, the GeoNetworking layer does not add security headers to the messages. On the transport layer, we implement the Basic Transport Protocol (BTP) [101], which is a lightweight, connection-less transport protocol to address V2X services using source and destination ports.

Cellular-V2X

We use SIMULTE v1.1.0 [222] to implement 3GPP LTE-V2N communication. SIMULTE is compatible with VEINS, SUMO, and OMNET++ and claims to support the 3GPP LTE-V2X Releases 8 and beyond. On the access layer, we use the Long Term Evolution (LTE) Network Interface Card (NIC) card provided by SIMULTE. The simulation framework SIMULTE provides transmitter diversity and channel feedback computation on the physical layer. Furthermore, SIMULTE supports buffering, Channel Quality Index (CQI) reception, and resource allocation on the LTE access layer [222]. On the network and transport layers, we use IPv4 and User Datagram Protocol (UDP) from the INET v3.6.6 framework within OMNeT++ [219]. We select IPv4 as it induces less communication overhead and is, in contrast to IPv6, compatible with SimuLTE. UDP is suited for V2X communication because it is a connection-less and minimal transport protocol.

Geocast service

In 3GPP LTE-V2N networks, vehicles send messages to their connected base stations (eNodeB). The eNodeB forwards the messages to the respective 3GPP LTE-V2N server. We primarily implement two Geocast services in our 3GPP LTE-V2N network: The `GeocastEnabler` allows for a Lane-based Geocast communication (cf. Section 5.3). For this purpose, the `GeocastEnabler` continuously updates a location table containing the vehicles' unique lanes and segment IDs. A vehicle sends an update request to the `GeocastEnabler` if it enters a new lane segment. The `GeocastForwarder` acts as a relay for vehicles and forwards their V2X messages to the respective destinations. The `GeocastForwarder` supports two transmission modes. Using Unicast transmission, a vehicle sends a V2X message via the `GeocastForwarder` to a specific vehicle by providing its station ID. Using Geocast transmission, a vehicle uses the `GeocastForwarder` to send the same message to multiple vehicles at a specific location. In this transmission mode, the `GeocastForwarder` relays the respective V2X message to all vehicles within the requested lane segments as Unicast messages.

6.1.2 *V2X Application Interface*

CoDA.kom offers heterogeneous V2X access technologies to send messages. In the following, we introduce a middleware and facilities to support the V2X applications.

Middleware

The middleware abstracts the V2X access technologies from the respective V2X applications. All available V2X access technologies are connected to the middleware. V2X applications register their ports at the middleware to send and receive messages. Suppose the middleware receives a message from an application or facility. In that case, the middleware retrieves the data request primitive, defined in [101], as OMNeT++ control info to get the communication profile for the respective message. The middleware manages and updates a connection map container for all facilities. A facility that sends and receives messages registers itself at the middleware with its port number and respective gate information. If the middleware receives a message from the access layer, the data indication primitive, defined in [101], is used to retrieve the destination port of the message. The middleware forwards the message to the respective facility using the connection map container.

Facilities

The ETSI Intelligent Transport Systems (ITS) communication architecture differentiates between information-support, communication-support, and application-support facilities [100]. Information-support facilities aggregate and provide information for other facilities and applications. We implement the Local Dynamic Map (LDM) [95],

Information-support

which is the vehicle's data sink for received messages. The LDM updates its entries if new information is received and deletes entries when their respective lifetimes have been expired. The Vehicle Data Provider (VDP) [93] aggregates the vehicle's static and dynamic information, such as the vehicle's length, width, velocity, and heading. The Position and Timing (POTI) [93] provides the vehicle's current position and time.

Communication-support

In CoDA.KOM, communication-support facilities provide information for our proposed data dissemination strategies. We implement our measurement- and model-based communication quality assessment, as described in Section 4.2. Further, the communication-support facilities implement our relevance-aware resource allocation and adaptive data dissemination strategy for cooperative driving, explained in Section 5.2 and Section 5.3, respectively.

Application-support

Application-support facilities are responsible for the generation (request) and processing (indication) of V2X messages. We implement the cooperative awareness facility from [96] for Cooperative Awareness Messages (CAMs) and introduce the cooperative driving facility to create and process Maneuver Coordination Messages (MCMs). The message content is retrieved from the information-support facilities and the V2X applications. [96] proposes generation rules for creating CAMs, which are implemented on the application-support facility layer. In CoDA.KOM, application-support facilities provide an interface for adaptive message rate schemes such as our relevance-aware resource allocation approach proposed in Section 5.2. Consequently, our relevance-aware resource allocation approach replaces the generation rules mentioned above. By default, the cooperative awareness and cooperative driving facilities use ETSI ITS-G5 with Single-Hop Broadcast (SHB) mode as the V2X access technology. Additionally, the application-support facilities offer V2X access technology interfaces, enabling heterogeneous data dissemination strategies for cooperative driving.

6.2 REALISTIC CHANNEL MODELING

The V2X simulation framework VEINS provides an interface to model radio propagation effects on the physical layer. As depicted in Figure 19, the channel model is allocated below the V2X access technologies. CoDA.KOM uses two different channel models to analyze the performance of our proposed approaches: The SIMPLE channel model considers limited channel resources but neglects path loss and fading effects, i. e., the maximum communication range is only limited to the interference range of the respective V2X access technology. However, radio propagation effects severely impact the communication quality of V2X networks and need to be considered when analyzing the communication quality for cooperative driving. Therefore, we describe our REALISTIC channel model in the following.

Simple channel model

Radio propagation effects

6.2.1 *Properties*

The REALISTIC channel model combines Geometry-based Stochastic (GBS) and Geometry-based Deterministic (GBD) models and is applicable to different V2X access technologies. That way, a consistent representation of radio propagation effects of hetero-

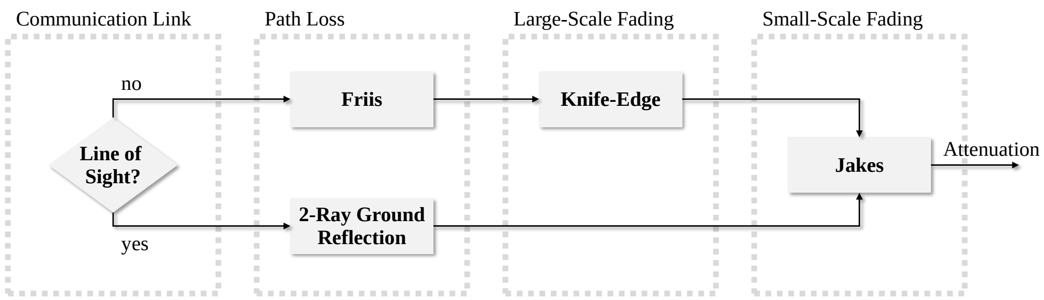


Figure 20: Concept of the REALISTIC channel model, where the attenuation assessment is divided into communication link, path loss, large-scale and small-scale fading. Adapted from [26].

geneous V2X access technologies is achieved. The REALISTIC channel model considers the transmitter and receiver's relative velocity, direction, height, and distance.

We specifically consider the carrier frequency of the respective V2X access technology to obtain path loss. Further, we consider multi-path propagation with the same angle of arrival if the receiver is a cellular base station. The antennas of cellular base stations are usually at a higher height such that reflections in the antenna's proximity are less dominant. In contrast, we consider multi-path propagation with different angles of arrivals for dynamic objects such as vehicles. The number of scatters, e. g., other vehicles and buildings, in a vehicle's environment is expected to be higher compared to a cellular base station [222].

The concept of the REALISTIC channel model is depicted in Figure 20. The attenuation of radio propagation effects is divided into the determination of the communication link, path loss, large-scale, and small-scale fading, which we detail in the following.

Communication Link

Obstacles, such as buildings and other vehicles, can interfere with the Line of Sight (LoS) of the transmitter and receiver, causing severe fading. To obtain the condition of the communication link, we obtain the first Fresnel ellipsoid, e. g., explained in [51], between the transmitter and receiver. According to [34], the LoS condition is assumed if there are no obstacles in 60 % of the first Fresnel ellipsoid. In this context, the antenna height significantly impacts the communication link condition and differs for Vehicle-to-Vehicle (V2V) communication and Vehicle-to-Network (V2N) communication.

Path Loss

High communication quality is expected under a LoS condition between the transmitter and receiver, i. e., no obstacles are shadowing the communication link. However, in [173], the authors identified that the destructive interference of the direct and reflected path of the wave from the ground significantly impacts the attenuation in V2X network environments. Consequently, for a communication distance d between the transmitter and receiver and a center frequency f_C, we consider a two-ray ground reflection model for a LoS condition, which is given as

$$P_R = P_T \cdot \frac{c}{2\pi \cdot d \cdot f_C} \cdot \left(2 \sin\left(\frac{2\pi \cdot f_C}{c} \cdot \frac{h_T \cdot h_R}{d}\right)\right)^2 G_R \cdot G_T. \tag{48}$$

P_R, P_T, G_R, G_T, h_R, and h_T are the signal powers, antenna gains, and antenna heights of the receiver and transmitter, respectively. The speed of light is denoted as c.

However, we do not have a direct path under Non-Line of Sight (NLoS) condition at the receiver. Hence, we consider the well-known Friis path loss model [211], which is given as

$$P_R = P_T \cdot \frac{c}{2\pi \cdot d \cdot f_C} G_R \cdot G_T. \tag{49}$$

Large-Scale Fading

In the case of a LoS condition, radio propagation is not impacted by shadowing. However, shadowing attenuates the radio propagation if one or more obstacles obstruct the communication link. We use a multiple knife-edge model to obtain the attenuation of obstacles shadowing the communication link between the transmitter and receiver. The multiple knife-edge model has been previously used in V2V networks [34]. We also apply the mentioned model for V2N links to consider shadowing from buildings in urban scenarios.

Small-Scale Fading

V2X networks are characterized by high mobility [183]. Especially in urban areas, radio propagation is reflected on the surface of other vehicles and buildings, causing multi-path propagation. Multiple waves are shifted at the receiver in the time and frequency domain, causing constructive and destructive superpositions of waves. In GBD channel models, multiple reflections of waves are computed with ray tracing methods to obtain a realistic representation for the superpositions of waves [183]. However, ray tracing induces high computational complexity. Therefore, we use the Jakes fading model [111], which is a GBS model. The Jakes model considers a fixed amount of waves and obtains the interference of the waves at the receiver considering the phase shifts because of delay spread and the Doppler effect. The Doppler effect is obtained from the relative velocity of the transmitter and receiver, calculated using the vehicles' velocities and headings. The delay spread is assumed to be normally distributed. Hence, the phase shift of each wave is calculated to obtain the channel impulse response for message transmission.

Jakes fading model

In this section, we described the channel models for heterogeneous V2X access technologies used in our evaluation. With the SIMPLE channel model, we focus on channel congestion effects and compare our numerical results with simulations. However, the SIMPLE channel model neglects radio propagation effects such as path loss and fading.

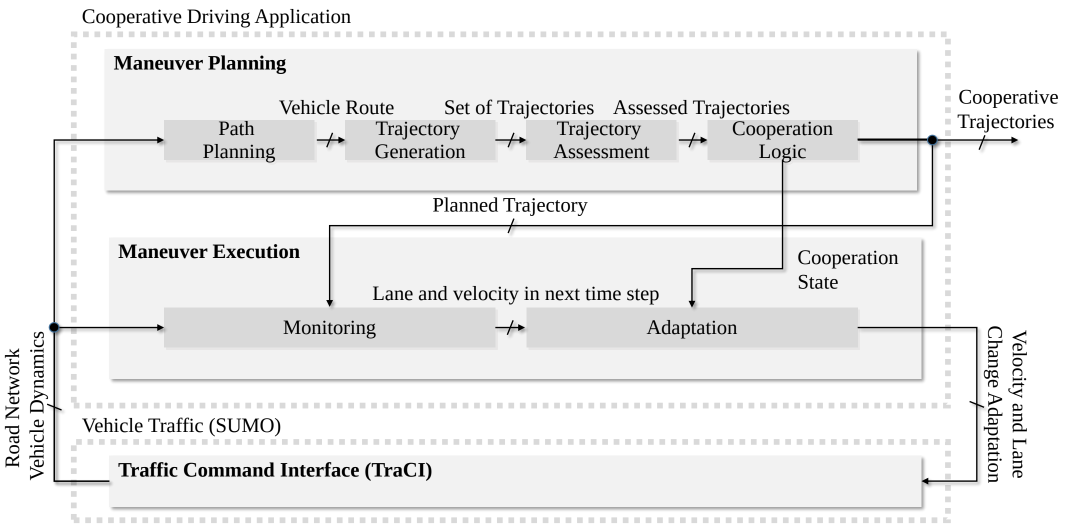


Figure 21: Prototypical realization of cooperative driving in large-scale V2X networks.

The REALISTIC channel model considers path loss, large-scale, and small-scale fading effects in V2X networks and is applicable to heterogeneous V2X access technologies.

6.3 PROTOTYPICAL REALIZATION OF COOPERATIVE DRIVING AT AN INTERSECTION

In this section, we describe the prototypical realization of a cooperative driving application and specifically focus on the use case left-turning at an intersection. Our framework can be extended to other cooperative driving use cases like merging on highways or cooperative lane change.

As depicted in Figure 21, we differentiate between maneuver planning and execution, which we describe in the following. The cooperative driving mechanism is based on [137], the framework used in the project IMAGinE (*Intelligent Maneuver Automation - cooperative hazard avoidance in realtime*) [91], and our suggested optimizations for large-scale network simulations in [28].

6.3.1 *Maneuver Planning*

The maneuver planning application obtains the possible paths of a vehicle, generates trajectories from the paths, checks the trajectories for conflicts with received trajectories from other vehicles, and coordinates cooperative maneuvers. Based on the IMAGinE project's approach [91], we divide the maneuver coordination into path planning, trajectory generation, assessment, and cooperation logic modules. In the following, we describe the mentioned modules in detail.

Path Planning

In SUMO, routes and traffic flows are described for each simulation scenario [134]. The traffic flows define how many vehicles are supposed to drive on a given route. A SUMO route consists of a list of roads[1]. A vehicle on a specific route in a simulation scenario starts on the first road and is removed after leaving the last road.

Route preparation

Using the Traffic Control Interface (TraCI) of SUMO [228], the path planning has access to the vehicle's route and fetches the list of roads for a vehicle's route. However, the road list does not contain the junctions of the route. Additionally, SUMO roads consist of one or multiple lanes, where not all lanes can be used to follow the vehicle's route, e. g., a lane is not connected to the subsequent road of the vehicle's route. Using the TraCI, only the vehicle's current and next lane can be obtained, which is insufficient for trajectory generation.

Global Map Provider

Therefore, we implement a `GlobalMapProvider` to fetch all SUMO routes defined for a scenario at the simulation start and create vehicle paths for each SUMO route. A vehicle path is derived from a SUMO route and contains a list of subsequent lanes for the respective route. Hence, a SUMO route can result in multiple vehicle paths. The vehicle path also contains specific information for the trajectory generation, e. g., the maximum allowed velocity per lane, right-of-way, and the lane's maneuver type.

Path update

If a vehicle is created in the simulation, the path planning module obtains the list of vehicle paths from the `GlobalMapProvider`. After that, the path planning module updates its vehicle path according to its current position, i. e., deletes passed lanes. Additionally, the path planning module tracks dynamic road information such as traffic light changes. After that, the updated vehicle paths are passed to the trajectory generation module.

Trajectory Generation

For each vehicle path, the trajectory generation module creates a set of trajectories. All trajectories are created considering the same envisaged time horizon. However, the trajectories differ in the spatial domain, i. e., each trajectory is created with a unique velocity profile. Hence, a trajectory set describes different possible driving maneuvers for the vehicle according to its current situation.

Trajectories

We divide a trajectory in a list of trajectory sections, where each section covers a specific lane. A trajectory section consists of longitudinal and lateral polynomials to describe the vehicle's movement on a lane.

Longitudinal polynomial

In a trajectory set, each trajectory has a unique acceleration profile to describe different driving maneuvers of the vehicle. The trajectory generation module ensures that a trajectory cannot exceed the maximum velocity of a vehicle or lane. Additionally, the trajectory generation also ensures that a trajectory does not exceed the maximum allowed velocity of the next lane. Therefore, the velocity is reduced to the maximum allowed velocity of the next lane before entering it. Unless the respective vehicle path does not indicate a lane change (two subsequent lanes of the same edge), the trajectory remains in the middle of a lane without any lateral offset. The lane change can happen

Lateral polynomial

1 In SUMO, roads are defined as edges.

at different positions on the lane. For each lane change position, we create a set of trajectories with different acceleration profiles. To represent lateral movement, we generate a lateral polynomial, which is a function of the longitudinal polynomial.

The generation of each trajectory is an iterative process, where polynomials (and the respective trajectory sections) are created until the trajectory's time horizon is reached. The trajectory generation module generates only one trajectory with the highest acceleration profile in each iteration to reduce the computation time. If the trajectory assessment detects a trajectory collision, further trajectories with lower acceleration profiles are created until a collision-free trajectory is found.

Iterative trajectory generation

Trajectory Assessment

The trajectory assessment module obtains the cooperation costs for the generated trajectories and performs a collision check with other received trajectories.

Cost assessment

Our cooperation cost assessment assigns a cost of 0 to the trajectory covering the most significant distance within the envisaged time horizon. That way, vehicles aim to drive with the maximum allowed velocity, increasing the vehicle throughput in the scenario. The trajectory with the highest deceleration profile covers the shortest distance within the envisaged time horizon and has the highest cooperation cost of 1. The costs of all other trajectories are linearly interpolated between 0 and 1 according to their covered distance.

Collision check

For each created trajectory, a collision check with trajectories received via V2X communication is performed. For each pair of trajectories (one of the own and one of another vehicle), we iterate in discrete time steps over both trajectories and check if both trajectories overlap in the time *and* spatial domain. The positions of two vehicles at different time steps are obtained from their trajectories. At each step, we perform a collision check with circles covering the vehicle's dimensions at the respective position. In addition to the vehicle dimensions, we also check for collisions with the vehicle's safety zones.

Trajectory safety zone

Safety zones extend the vehicle's dimension to the front and back to account for additional reaction time. The safety zone of the vehicle's front allows vehicles to stop behind each other in a traffic jam or at a red light and depends on the parameterized spacing of vehicles, which is set to 1 m in CoDA.KOM. The safety zone of the vehicle's back is derived from the vehicle's safety time and its velocity. For a safety time of 1 s and a velocity of 10 m/s, the safety zone of the vehicle's back has a length of 10 m. Hence, a vehicle with a velocity of 10 m/s maintains a margin to a preceding vehicle depending on the safety zones. The mentioned safety zone is replaced if we use our approach presented in Section 5.4.

Obtaining the right-of-way

The trajectory assessment module obtains the right-of-way for each trajectory collision based on the vehicles' maneuvers and positions. If a trajectory collision is detected, the trajectory assessment requests further trajectories from the generation module within the defined acceleration profile until a collision-free trajectory is found. The acceleration profile is iterated from the highest acceleration to the highest deceleration.

Cooperation Logic

The cooperation logic module selects the planned, desired, and cooperative trajectories from the set of created and assessed trajectories.

Trajectory assignment

We filter all trajectories that are either collision-free or have the right-of-way for all detected collisions from the set of trajectories. From the filtered trajectories, the trajectory with the lowest cost is assigned as the planned trajectory. All trajectories with lower costs than the planned trajectory are assigned as desired trajectories. Notably, these trajectories must have collisions without right-of-way. If no desired trajectories are found, the vehicle cannot request cooperation to increase its traffic efficiency. Otherwise, we select the desired trajectory with the lowest costs from all obtained desired trajectories. All collision-free trajectories are denoted as potential cooperative trajectories, i. e., the vehicle may offer cooperation with the alternative trajectories.

Discovery

Emergency

Requesting

Offering

We introduce a cooperation state machine with the states discovery, request, cooperation offer, cooperation request, and emergency. We always start in the discovery state (default state) and transitions to other states depending on the assigned trajectory. In case of an emergency, we immediately switch to the emergency state. After the emergency has been solved, we first switch to the discovery state before requesting or offering cooperation. If we have obtained a desired trajectory, we transition to the request state. We remain in this state until another vehicle offers cooperation or we can no longer request cooperation with a desired trajectory. If we requested and another vehicle offers cooperation, we switch to the cooperation request state and remain in this state until the cooperation is finished or one of both vehicles aborts the cooperation. We offer cooperation and transition to the cooperation offer state if the sum of our invested costs (difference of costs between our cooperative and planned trajectory) and the gained costs (difference of costs between the other vehicle's planned and desired trajectory) exceed a predefined cost threshold. The cost threshold is defined between -1 and 1, where vehicles with a cost threshold of -1 always offer cooperation. In contrast, vehicles with a cost threshold of 1 always deny cooperation. As an example, assume that our planned and cooperative trajectories have costs of 0 and 0.5, respectively. The requesting vehicle's planned and desired trajectories have costs of 0.8 and 0.2, respectively. Hence, our invested costs are 0.5 and the gained costs are -0.6, giving a cooperation cost of -0.1 for the cooperative maneuver. In this work, the cost threshold is set to 0. In the mentioned example, the vehicle offers cooperation because the cooperation cost for the cooperative maneuver is below the cost threshold. We remain in the cooperation offer state until the cooperation is finished or one of the vehicles aborts the cooperation. The cooperative trajectory replaces the planned trajectory if a vehicle offers cooperation. In this situation, the planned trajectory would have denied the cooperation request.

6.3.2 *Maneuver Execution*

The maneuver planning module obtained the cooperative trajectories, including the planned and optional desired trajectories. The cooperative trajectories are sent to other vehicles via V2X communication and the planned trajectory is sent to the maneuver execution module.

Monitoring

The maneuver monitoring obtains the vehicle's dynamics (position, velocity, and acceleration) for the current time and compares it with the planned trajectory.

SUMO and OMNeT++ are event-discrete simulators, meaning that the vehicle dynamics are not continuously updated but in discrete time steps, denoted as `timeStep`. Consequently, we obtain the vehicle's position and velocity in the next time step from the planned trajectory and compare it with the current vehicle dynamics.

Adaptation

The adaptation module is responsible for executing the cooperative maneuver described by the planned trajectory. For this purpose, the adaptation module controls the respective SUMO vehicle. TraCI offers an interface to control the vehicle's longitudinal and lateral movement, accessible via Veins in OMNeT++.

Controlling the driver

```
void setSpeedMode(speedMode);
```

We use `0` for the `speedMode`, which deactivates all checks of the SUMO driver, such as regarding the right-of-way rule or avoid passing a red traffic light. Similarly, we can control the lane change of SUMO.

```
void setLaneChangeMode(laneChangeMode);
```

For left-turning at an intersection, lane change is not required. To avoid conflicting lane changes with our maneuver planning module, we set the `laneChangeMode` to 257, only allowing for strategic lane changes and avoiding immediate collisions.

Operation modes

We offer two operation modes for the maneuver execution, i. e., continuous or on request. In the continuous mode, the maneuver execution controls the vehicle for the complete simulation such that the planned trajectory obtained in the maneuver planning module is always executed. If the operation mode is set on request, we set the velocity and lane change mode according to the cooperation state. If the vehicle is involved in a cooperative maneuver (offering or requesting cooperation), the maneuver execution module controls the vehicle for the time of the cooperative maneuver. When the maneuver is finished, the control is given back to the SUMO driver.

Decreasing simulation time

The TraCI is realized with a Transmission Control Protocol (TCP) connection on a computer. Continuously adapting the cooperative maneuver of all vehicles in every time step increases the computation time of the simulation. We use the operation modes for vehicles based on their route: If a cooperative maneuver is expected for a vehicle route, the operation mode of the vehicle is set to the continuous mode, allowing for a higher traffic efficiency. Otherwise, the operation mode is set on request, e. g., for vehicles waiting at a red traffic light.

Executing the maneuver

For controlled vehicles, we obtain the velocity in the next time step from the vehicle's planned trajectory, denoted as `nextVelocity`. After that, we send the command to change the vehicle's velocity to SUMO via TraCI.

```
void setSpeed(nextVelocity);
```

The TraCI function sets the vehicle velocity to `nextVelocity` in the next time step.

In this section, we outlined our simulation framework CoDA.kom, which is prototypical implementation of cooperative driving in OMNeT++ and SUMO. We divided the cooperative driving application in maneuver planning and execution. The former obtains the cooperative trajectories and decides for the cooperative maneuver. The latter executes the planned trajectory for the respective vehicle.

In this chapter, we discussed our prototypical realization of cooperative driving for the use case left-turning at an intersection in large-scale V2X networks. For this purpose, we outlined our simulation framework CoDA.kom, which builds upon the network simulator OMNeT++, the vehicular traffic simulator SUMO, and the V2X simulator Veins. We proposed our realistic channel model to capture the radio propagation effects of heterogeneous V2X access technologies. Finally, we presented our cooperative driving application, incorporating maneuver planning and execution, implemented in OMNeT++.

We use our prototypical implementation to evaluate the performance of V2X network adaptations and communication-aware cooperative driving in the following.

7 EVALUATION

The extensive evaluation performed in this chapter gathers evidence of the performance of the presented contributions in this thesis. Moreover, we emphasize our key design decisions and the behavior of our contributions in challenging scenarios.

Data assessment

Our first research goal focused on the communication quality and information relevance assessment in decentralized Vehicle-to-Everything (V2X) networks for cooperative driving. We presented a numerical communication model to assess the communication quality in a decentralized V2X network. Section 7.2 compares and confirms our proposed numerical communication model with simulation results.

Relevance-aware network adaptations

Relevance-aware V2X network adaptations focused on in our second research goal addresses the efficient use of channel resources to improve the communication quality for cooperative driving. We presented relevance-aware resource allocation to prioritize information for vehicles coordinating cooperative maneuvers. We conduct a numerical analysis in Section 7.3 to compare the convergence speed of the resource allocation approaches and analyze the timely delivery of relevant information. Moreover, we perform simulations to confirm our numerical results and analyze resource allocation considering realistic channel conditions in a highly mobile and congested urban intersection scenario. Furthermore, we presented an adaptive data dissemination strategy to increase the communication range and communication quality of vehicles coordinating cooperative maneuvers. Section 7.4 analyzes to which extent our approach increases the communication quality of vehicles coordinating cooperative maneuvers and, therewith, increases the traffic efficiency of cooperative driving.

V2X-aware cooperative driving

Finally, we focused on communication-aware cooperative driving in our third research goal to adapt cooperative driving to the assessed communication quality for increasing traffic efficiency and maintaining safety. Our presented approach adapts the safety margins between cooperating vehicles based on the assessed communication quality. Section 7.5 evaluates the behavior of our approach for different communication qualities in a controlled numerical analysis. Furthermore, we perform a simulation evaluation to compare our approach with the traffic efficiency and safety performance of reference approaches in an urban intersection scenario.

A comparison of our contributions to reference approaches in a reproducible setup is required to analyze the behavior and impact of V2X network adaptations and communication-aware cooperative driving. The setup must reflect the properties of cooperative driving from the communication and application perspective under congested traffic and channel conditions. Therefore, we perform numerical analysis to demonstrate the behavior of the V2X network and extend it with our event-based simulation framework CoDA.KOM to evaluate the performance of cooperative driving in a challenging urban intersection scenario. Our methodologies and the evaluation setup are discussed in the following.

7.1 EVALUATION SETUP

In this section, we briefly outline the numerical and simulation framework used in this evaluation. After that, we describe the urban intersection scenario considered in our simulation framework. Furthermore, we summarize our evaluation parameters, describing the V2X access technologies settings and the traffic scenario. Finally, we describe our considered metrics and the plot types used in this evaluation.

7.1.1 *Methodology*

We perform a numerical and simulation evaluation to analyze the performance of our contributions, where we briefly outline both methodologies in the following.

Numerical Framework

V2X model

For our numerical analysis, we use MatlabR2020b[1]. Our numerical communication model described in Section 4.2 is used to obtain the communication quality metrics in a decentralized V2X network. The communication model explicitly considers different vehicle message frequencies and is evaluated in discrete iterations. All vehicles synchronously update their message frequency in each iteration. The reliability and channel load are evaluated in each iteration after all vehicles have synchronously updated their message frequency.

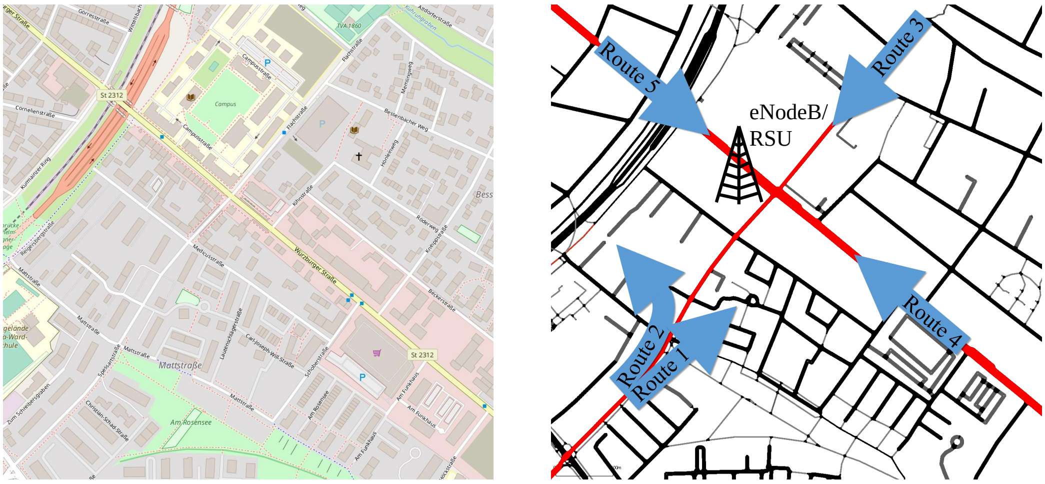
Synchronous updates

The synchronous update of the vehicles' message frequencies represents an edge case behavior of real-world decentralized V2X networks. However, previous work analyzed the mentioned edge case scenario [15] because synchronous message frequency updates cannot be excluded for a subset of vehicles in reality. Moreover, the scenario represents a particularly challenging case for convergence of the resource allocation approach in a decentralized V2X network. For example, all vehicles may first see a low channel load and synchronously increase their message frequencies. In the next iteration, the channel is congested, for which all vehicles again decrease their message frequencies. The described scenario leads to oscillation of the vehicles' message frequencies and the channel load, severely decreasing the communication quality of the respective resource allocation approach.

Simulation Framework

For simulations, we use CoDA.kom, introduced in Chapter 6. CoDA.kom is implemented in the event-discrete network simulator OMNeT++ [219]. For the simulation of vehicular traffic, the simulation framework Veins [198] couples OMNeT++ with the vehicular traffic simulator SUMO [134]. As described in Chapter 6, SUMO explicitly simulates the mobility of each vehicle and offers the TraCI [228] to obtain and control the dynamics of each vehicle separately. CoDA.kom uses the TraCI to control individ-

1 `https://de.mathworks.com/products/matlab.html` [Accessed November 7th, 2021]



(a) © OpenStreetMap contributors. (b) Adapted from SUMO [134].

Figure 22: Urban intersection scenario in Aschaffenburg.

ual vehicles and perform cooperative driving maneuvers with our cooperative driving application left-turning at an intersection.

V2X access technologies

CoDA.KOM offers decentralized and centralized V2X access technologies. We use the ETSI ITS-G5 as the decentralized V2X access technology. For the ETSI ITS-G5, we consider the access layer provided by VEINS. For radio propagation effects, we use our presented SIMPLE and REALISTIC channel models, described in Section 6.2. The European Telecommunications Standards Institute (ETSI) Decentralized Congestion Control (DCC), used as reference approaches in this evaluation, is adapted from the ARTERY framework [181]. We use the 3GPP LTE-V2N as the centralized V2X access technology and consider the SIMULTE framework [222], which claims to provide Long Term Evolution (LTE) features for Release 8 and beyond.

7.1.2 *Traffic Scenario*

In the simulation framework, we consider the urban intersection in Aschaffenburg, Germany, depicted in Figure 22. The roads *Flachstrasse* and *Wuerzburgerstrasse*, highlighted in Figure 22b, are crossing each other in the intersection.

KoPER intersection

The mentioned intersection was previously considered in the KoPER (*Cooperative Perception*)[2] project. The traffic flows were recorded with video and laser scanners and the results are published in [201]. Based on these traffic flow measurements, the authors in [112] extracted different scenarios and scenes.

OSM export

For our evaluation, we exported this intersection with OpenStreetMap (OSM)[3], depicted in Figure 22a. SUMO offers a tool to import OSM exports and create a SUMO road network, as depicted in Figure 22b. Relevant roads are highlighted in red. The exported area has a size of 1 km × 1 km with the intersection in the center. For further

2 `http://ko-fas.de/41-0-Ko-PER---Kooperative-Perzeption.html` [Accessed November 7th, 2021]
3 `https://www.openstreetmap.org/copyright` [Accessed November 7th, 2021]

reference, we depict the routes of interest within this evaluation as blue arrows in Figure 22b. Additionally, for the simulation of 3GPP LTE-V2N networks, we locate an eNodeB close to the intersection. Furthermore, we locate a Roadside Unit (RSU) next to the eNodeB for channel measurements of the decentralized V2X network.

Intersection scenario

The intersection has four arms, where traffic lights control each arm. From the scenarios extracted in [112], we consider the following scenario for our cooperative driving use case left-turning at an intersection in this evaluation: Vehicles on Route 4 and Route 5 are waiting at a red traffic light in the intersection. Vehicles on Route 1 drive straight at a green traffic light and vehicles on Route 2 turn left in the intersection. From the opposite direction, vehicles on Route 3 drive straight in the intersection at a green traffic light and cross the vehicles on Route 2. The traffic flows on Route 1, Route 2, and Route 3 are set to 650 veh/h, 300 veh/h, and 950 veh/h. The traffic flow scenario is from the traffic flow recordings in [201]. Together with the vehicles waiting at a red traffic light on Route 4 and Route 5, we have on average 150 vehicles in the simulation scenario simultaneously.

Note that we do not consider other vehicle routes, e. g., vehicles turning right in the intersection. Furthermore, the previously mentioned traffic light states will not change over time such that we remain with the scenario mentioned above. On all roads, vehicles drive with a maximum velocity of 8.33 m/s (30 km/h).

Left-turning at an intersection

In the considered scenario, vehicles following Route 2 and turning left in the intersection require cooperation from vehicles following Route 3. If cooperation is denied in a congested traffic scenario, vehicles on Route 2 wait in the intersection until there is a sufficient gap between vehicles on Route 3 to turn left safely. Additionally, vehicles on Route 1 have to wait if vehicles on Route 2 cannot turn left in the intersection because both routes share the same lane until the intersection, i. e., there is no dedicated left-turning lane for Route 2.

7.1.3 *Parameters*

In this section, we describe the parameters used in all following numerical and simulation evaluations. First, we introduce general parameters and, after that, the parameters for the V2X access technologies ETSI ITS-G5 and 3GPP LTE-V2N.

General

In Table 3, we depict general parameters for our evaluation setup. In the urban scenario, the vehicle's maximum velocity is limited to 8.33 m/s. Cooperative driving maintains a safety time of 2 s between vehicles. The resulting margin between vehicles increases with the vehicle's velocity and the respective safety time (cf. Chapter 6).

Message payload

In the project IMAGinE [91], we measured the message size of Maneuver Coordination Messages (MCMs) in a real-world scenario. For left-turning at an intersection and merging on highways, the trajectory's time horizon was set between 10 s and 20 s, depending on the respective use case. In this setup, the message size was measured between 300 B and 700 B without security overhead but header payload. For clarity of

Parameter	Value
Trajectory Time Horizon	10 s
Safety Time	2 s
Maximum Vehicle Velocity	8.33 m/s
Application Update Interval	100 ms
Message Payload Size	500 B
Minimum Message Frequency	1 Hz
Maximum Message Frequency	10 Hz
Antenna Height Vehicle	1.895 m
Antenna Height eNodeB	25 m
Thermal Noise	−104.5 dBm
Jakes Fading Paths	6
Mobility Update Interval	100 ms
Traffic Flow Route 1	950 veh/h
Traffic Flow Route 2	300 veh/h
Traffic Flow Route 3	650 veh/h

Table 3: General parameters for our evaluation setup.

the results, we use a fixed message payload size of 500 B and a trajectory time horizon of 10 s in this evaluation. The vehicle's and eNodeB's antenna heights are 1.895 m and 25 m [198, 222], respectively. The thermal noise of the channel is set to −104.5 dBm [198] for both V2X access technologies and we consider 6 fading paths for our REALISTIC channel model. Our mobility simulator SUMO is updated every 100 ms, allowing to coordinate and execute cooperative maneuvers.

ETSI ITS-G5

Table 4 depicts the V2X access-specific parameters. In the following, we focus on the parameters for ETSI ITS-G5.

The carrier frequency is set to 5.89 GHz and the channel bandwidth is 10 MHz, according to [103]. We refer to [90, 103] for further access layer-specific parameters. The delay spread for our REALISTIC channel model is 0.644 µs [23]. The bitrate is set to 6 Mb/s [103]. Vehicles send MCMs with a transmission power of 20 dBm. Further, the omnidirectional antenna radiation has a gain of 0 dB in all directions. The interference range is limited to 1500 m. Above this range, the message is immediately discarded, i. e., the attenuation is not obtained by the REALISTIC channel model. The sensitivity of the network card is −89, 5 dBm [198]. We use ETSI ITS-G5 in the Single-Hop Broadcast (SHB) transmission mode.

Parameter	ETSI ITS-G5	LTE
Carrier Frequency	5.89 GHz	2.1 GHz
Channel Bandwidth	10 MHz	-
Resource Blocks (up/down)	-	18
Delay Spread RMS	0.644 µs	0.363 µs
Number Bands (up/down)	-	25
Bit Rate	6 Mb/s	-
Interference Range	1500 m	-
Transmit Power (Vehicle)	20 dBm	20 dBm
Transmit Power (eNodeB)	-	46 dBm
Antenna Gain (Vehicle)	0 dB	0 dB
Antenna Gain (eNodeB)	-	16 dB
Antenna Radiation	Omnidirectional	Omnidirectional
Sensitivity	$-89,5$ dBm	-
Transmission Mode	Single-Hop Broadcast	Unicast

Table 4: Specific parameters for the V2X access technologies.

3GPP C-V2X

For 3GPP LTE-V2N networks, we set the carrier frequency to 2.1 GHz, which is a typical carrier frequency for cellular LTE networks in Germany[4]. Furthermore, we consider 18 resource blocks in the up- and downlink [146]. The delay spread for our REALISTIC channel model is 0.363 µs [222]. In this evaluation, we consider 25 bands for the up- and downlink [222]. For the transmit power of vehicles and the eNodeB, we consider 20 dBm and 46 dBm, respectively, and for the antenna gain 0 dB and 16 dB [222], respectively. The vehicles and eNodeB antennas have an omnidirectional radiation characteristic and the transmission mode is UNICAST.

7.1.4 *Evaluation Metrics*

In our evaluation, we use different metrics to show the properties of our approaches and compare their performance to reference approaches. In the following, we introduce our performance metrics and, after that, briefly describe our plot types.

4 `https://www.bundesnetzagentur.de/` [Accessed November 7th, 2021]

Performance Metrics

To evaluate the communication quality of our approaches, we use the channel metrics Channel Busy Ratio (CBR), normalized throughput, and Accessible Information Relevance (AIR), described in the following.

CHANNEL BUSY RATIO To evaluate the load on the V2X channel, we use the CBR, defined in [103]. The CBR denotes the fraction of time slots where the V2X channel is sensed busy (a message is currently sent) divided by the number of observed time slots. According to [103], the observation time of the CBR is set to 100 ms. In the numerical analysis, we obtain the CBR using Equation 17 in Section 4.2. A high CBR indicates channel congestion, impairing the communication quality. In contrast, a low channel load indicates an under-utilization of the available channel resources.

NORMALIZED THROUGHPUT The CBR does not differentiate between successfully and collided messages. The normalized throughput is the fraction of the successfully used data rate (messages that have been successfully received) divided by the theoretical data rate of the respective channel. In simulations, the observation time is set to 100 ms. In the numerical analysis, we obtain the normalized throughput using Equation 16 in Section 4.2. The normalized throughput decreases in highly congested channels. The channel utilization increases with high normalized throughput, improving the communication quality in the V2X network.

ACCESSIBLE INFORMATION RELEVANCE The normalized throughput weights the successfully delivered data equally. In V2X networks and specifically for cooperative driving, information is differently relevant, depending on the vehicle's current context. In Equation 35, we introduced the network's AIR, which weights successfully received messages in the V2X network with their information relevance. We obtain the network's AIR in simulations as the fraction of the successfully received information relevance divided by the maximum achievable information relevance in an observation time slot of 100 ms. A high network's AIR in congested V2X networks indicates that relevant information is prioritized with high communication quality.

We evaluate vehicle-specific communication metrics using the Packet Delivery Ratio (PDR) and Age of Information (AoI), outlined below.

PACKET DELIVERY RATIO We use the PDR to assess the communication quality in congested V2X networks. The PDR is the fraction of messages that have been successfully delivered (can be decoded by the receiver) divided by the total number of sent messages in the vehicle's interference range. In the simulation, the PDR is obtained from the VEINS Medium Access Control (MAC) layer. We divide the total number of successfully received messages by the total number of sent messages in the vehicle's interference range. Hence, the PDR is averaged over the simulation time per vehicle. For the numerical framework, we obtain the PDR according to Equation 15 in Section 4.2. The communication quality is impaired for a low PDR.

AGE OF INFORMATION The PDR is insufficient to evaluate the communication quality in V2X networks because the message frequency and latency are not considered. Therefore, we use the AoI, which denotes the freshness of received messages from a specific sender. We use the measurement-based AoI assessment from Equation 24 in simulations and the model-based AoI assessment Equation 29 in the numerical analysis (cf. Section 4.2). A high AoI indicates outdated information, negatively impacting the V2X application performance.

The overarching goal of this thesis is to improve traffic efficiency and maintain safety for cooperative driving maneuvers by adapting to the V2X communication quality. Hence, we evaluate traffic efficiency and safety with the metrics described in the following.

MINIMUM VELOCITY For the cooperative driving left-turning at an intersection and merging on a highway, offering cooperation is connected with costs to open a gap for the requesting vehicle. From the traffic efficiency perspective, the gap should be as small as possible to reduce the costs of the vehicle offering cooperation and decrease its energy consumption. We measure the cooperation costs of vehicles using their minimum velocity during a cooperative maneuver. A high traffic efficiency is achieved if the minimum velocity during a cooperative maneuver is close to the maximum allowed velocity, i. e., only light deceleration is required to offer cooperation, enabling foresight driving.

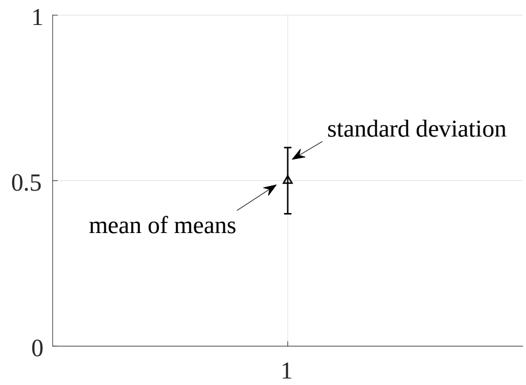
AVERAGE VELOCITY The minimum velocity only focuses on one specific vehicle in the scenario and cannot represent the traffic efficiency gained from cooperative driving. Hence, in scenarios with high vehicle density, we obtain the average velocity of vehicles for different routes. The traffic efficiency is high if the average velocity of all vehicles is close to the maximum allowed velocity in the scenario.

COLLISION VELOCITY We use the collision velocity to evaluate traffic safety of cooperative driving for impaired communication quality. If a vehicle collision is detected in the simulation, the vehicle's current velocity is denoted as its collision velocity. Traffic safety is maintained for a collision velocity of 0 m/s. In contrast, a high collision velocity indicates a severe vehicle collision.

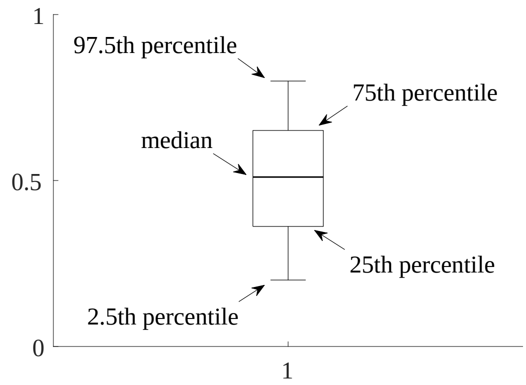
Plots Types

In the following, we introduce the plot types used in our evaluation to illustrate the performance metrics mentioned above.

ERROR BAR PLOT To visualize the range of different simulation runs, we use error bar plots, depicted in Figure 23a. The marker indicates the mean of means for all performed simulation runs in an experiment. Additionally, the lower and upper whiskers denote the standard deviation of the means of all runs. We use the error bar plot in conjunction with the box plot.



(a) Error bar plot.



(b) Box plot.

Figure 23: Illustrations of the different plot types used in this evaluation.

BOX PLOT To illustrate our simulation results, we use box plots, depicted in Figure 23b. The box plots visualize the aggregated performance metric results of a single simulation run. The lower and upper whiskers denote the 2.5th and 97.5th percentiles, respectively. Further, the lower and upper edge of the box denote the 25th and 75th percentiles, respectively. The solid line in the center of the box denotes the median.

7.2 COMPARING THE NUMERICAL MODEL WITH SIMULATIONS

In this section, we evaluate our numerical communication model presented in Section 4.2 by comparing it with simulation results. For this purpose, we analyze the communication quality for different vehicle densities and message frequencies.

V2X channel

We first evaluate the communication quality of the V2X channel, focusing on the CBR and normalized throughput in a decentralized V2X network. In Section 7.3, we compare the performance of our relevance-aware resource allocation approach with the ETSI DCC approaches in a numerical and simulation evaluation. Hence, an accurate assessment of the CBR is required, where the results of the numerical model must be comparable to the simulation results. Furthermore, we compare vehicle-specific communication quality metrics, focusing on the PDR, average latency, and AoI. Our relevance-aware resource allocation approach uses the PDR assessed by our numerical model. Therefore, an accurate numerical model is required for our relevance-aware V2X network adaptations. In the literature, a deviation of 1 % and up to 15 % between the numerical model and simulation results were accepted [25, 145]. Hence, in this evaluation, we analyze if the results of our numerical model can satisfy the mentioned requirement.

V2X quality

In addition to the general parameters introduced in Section 7.1, we briefly outline specific parameters for this evaluation in the following.

Parameter	Value
Number of Vehicles	0, ..., 300
Message Frequency	5 Hz, 10 Hz
Channel Model	SIMPLE channel model

Table 5: Parameters for the comparison of the numerical model and simulations.

7.2.1 *Scenario*

To compare the communication quality of our proposed numerical model and simulations, we consider a scenario with a fixed number of V2X-enabled vehicles.

We additionally introduce the parameters depicted in Table 5 to analyze the numerical model. The number of vehicles is analyzed in the interval between 0 and 300 vehicles. We use a step size of 50 vehicles in simulations. Furthermore, we consider a message frequency of 5 Hz and 10 Hz. To focus on communication effects caused by the medium access of IEEE 802.11P, we consider the SIMPLE channel model.

Simulation setup

The number of considered vehicles are placed after each other in the simulation within a warm-up period of 50 s to avoid unrealistic synchronizations. After an additional warm-up period of 5 s, we record the results for a simulation period of 100 s, performing 30 simulation runs for each parameter set. As we consider the SIMPLE channel model, the distance between vehicles, velocity, and shadowing effects do not impact the reliability of messages.

7.2.2 *Communication Channel Quality*

First, we focus on the channel quality w. r. t. the CBR and normalized throughput.

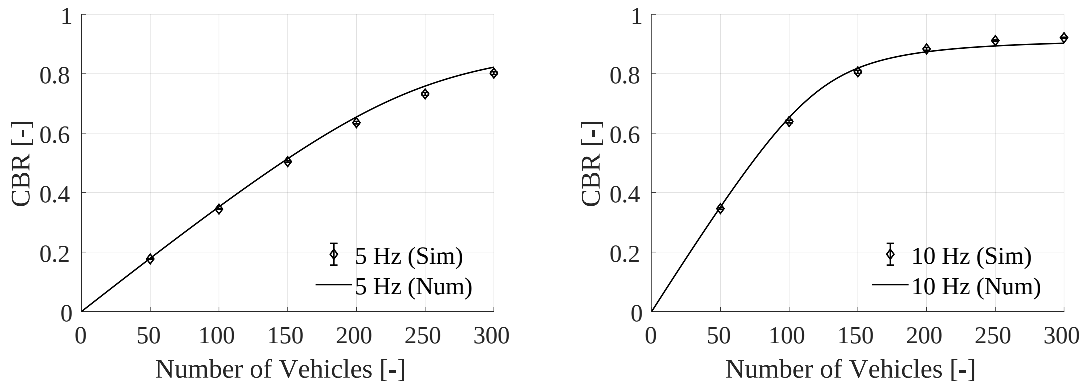
Channel Busy Ratio

V2X *channel congestion states*

The ETSI specifies the CBR assessment in [103], used to quantify the congestion level of communication channels. A V2X channel is considered congested above a CBR of 0.6 and relaxed below a CBR of 0.3 [103].

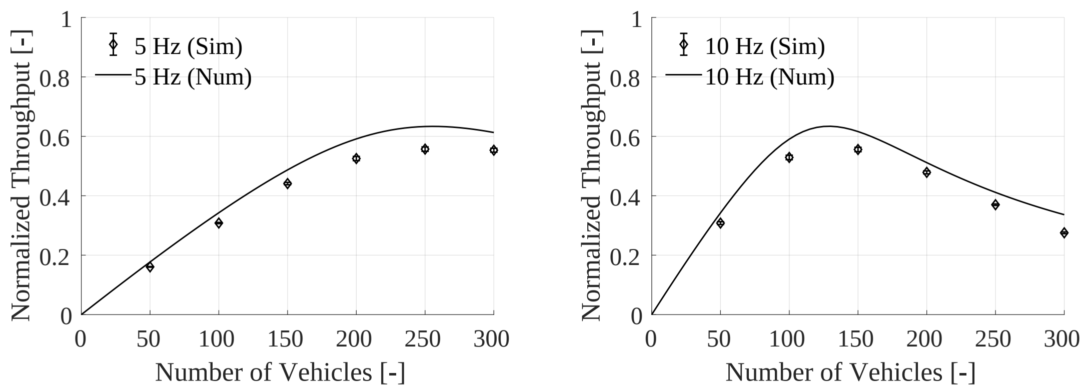
Figure 24 depicts the CBR obtained in the numerical and simulation evaluation between 0 and 300 vehicles, for a message frequency of 5 Hz and 10 Hz. Figure 24a shows that the numerical model coincides with the simulation results. The highest observed deviation of our numerical results compared to the simulation results is 3.5 % for 250 vehicles. Similar conformity between the numerical and simulation results is shown for 10 Hz, depicted in Figure 24b. Here, the numerical results deviate at most by 2.1 % for 300 vehicles compared to the simulations results. Our numerical model also shows the saturation effects of the CBR at approximately 0.90 for 250 vehicles with a message frequency of 10 Hz.

Channel saturation



(a) Message frequency of 5 Hz. (b) Message frequency of 10 Hz.

Figure 24: Comparison of the CBR for 5 Hz and 10 Hz.



(a) Message frequency of 5 Hz. (b) Message frequency of 10 Hz.

Figure 25: Comparison of the normalized throughput for 5 Hz and 10 Hz.

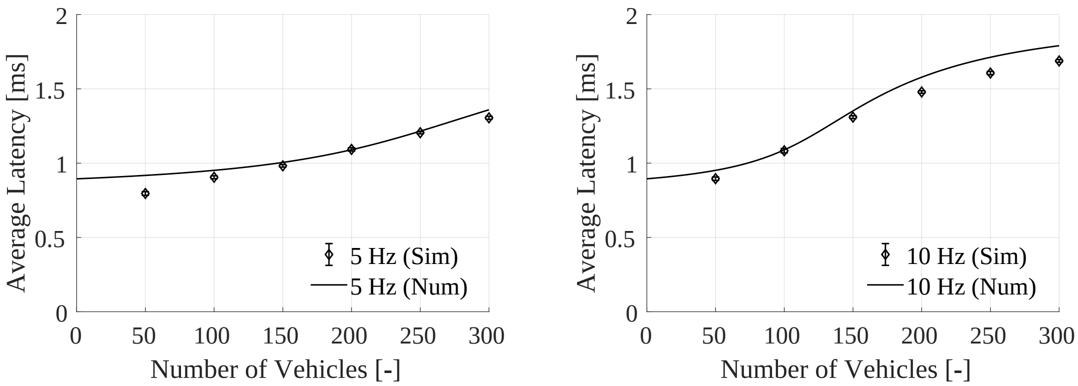
Normalized Throughput

Successful transmission rate

The CBR denotes the time the channel was sensed busy compared to the available channel slots. However, the CBR cannot differentiate between successful and collision transmissions. To illustrate the communication quality of the channel, we depict the normalized throughput in Figure 25 between 0 and 300 vehicles with a message frequency of 5 Hz and 10 Hz. We refer to Equation 16 for the normalized throughput assessed by the numerical model. Figure 25a depicts the normalized throughput for a message frequency of 5 Hz. We again observe that the numerical model coincides with simulation results. The numerical model deviates at most by 10.0 % compared to the simulations results for 250 vehicles. Similarly, Figure 25b depicts the normalized throughput for a message frequency of 10 Hz. The numerical model results deviate at most by 12.0 % for 100 vehicles.

Physical layer overhead

In simulations, the normalized throughput is obtained from the message size after the physical layer has successfully decoded the message. Hence, the additional over-



(a) Message frequency of 5 Hz.

(b) Message frequency of 10 Hz.

Figure 26: Comparison of the latency for 5 Hz and 10 Hz.

head caused by the physical layer is not reflected for each message in simulations, increasing the deviation between the numerical and simulation results. In contrast, the CBR is obtained by probing the channel directly, leading to a closer result between the numerical and simulation results. For a message frequency of 10 Hz, we observe a maximum normalized throughput of 0.63 and 0.56 between 120 and 150 vehicles in the numerical and simulation evaluation, respectively. The maximum normalized throughput for 5 Hz is observed between 225 and 275 vehicles with 0.63 and 0.56 in the numerical and simulation evaluation, respectively.

Maximum normalized throughput

In summary, our numerical model highly coincides with the simulation results, where the numerical results deviate by less than 12.0 % compared to simulations. Hence, we obtain comparable results between our proposed numerical model and simulations for the channel quality metrics CBR and normalized throughput.

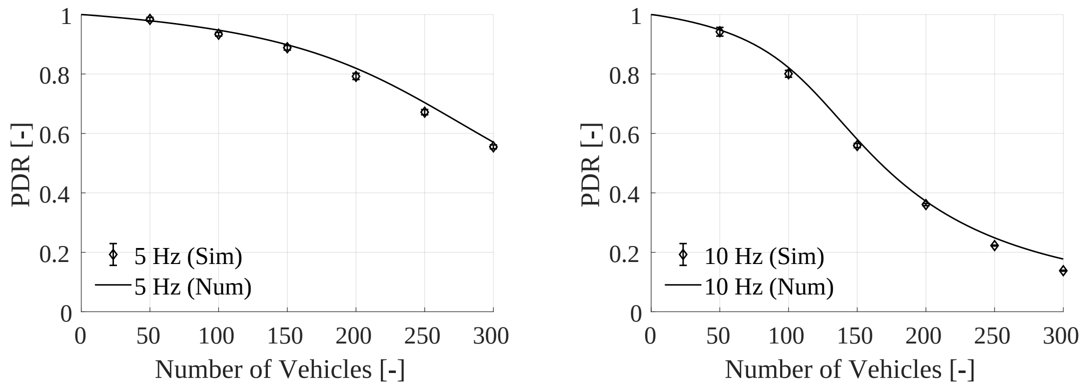
7.2.3 *Vehicle Communication Quality Metrics*

Despite the performance of the V2X channel, the communication quality of messages is a prerequisite for relevance-aware resource allocation and adaptive data dissemination strategies. In the following, we compare the PDR and average latency between the numerical model and simulations.

Average Latency

Figure 26 depicts the average latency in the interval between 0 and 300 vehicles for a message frequency of 5 Hz and 10 Hz.

We again observe that the numerical results coincide with the simulation results for a message frequency of 5 Hz and 10 Hz. The highest deviation between the numerical and simulation results of 13.3 % is observed for 50 vehicles and a message frequency of 5 Hz. For a message frequency of 10 Hz, the results of the numerical model deviate by 6.2 % from the simulation results for 250 vehicles.



(a) Message frequency of 5 Hz.

(b) Message frequency of 10 Hz.

Figure 27: Comparison of the PDR for 5 Hz and 10 Hz.

The numerical model approximates the average latency assuming that a message arriving at the MAC is expected to complete $0.5 \cdot (W - 1)$ backoff stages (cf. Section 4.2). However, the channel load for 50 vehicles and a message frequency of 5 Hz is low, increasing the probability that a message is directly sent without transitioning to any backoff stage. Hence, the numerical model approximates a higher average latency compared to the simulation results in scenarios with low channel congestion.

Impact of backoff stages

Packet Delivery Ratio

Figure 27 depicts the PDR in the interval between 0 and 300 vehicles for a message frequency of 5 Hz and 10 Hz.

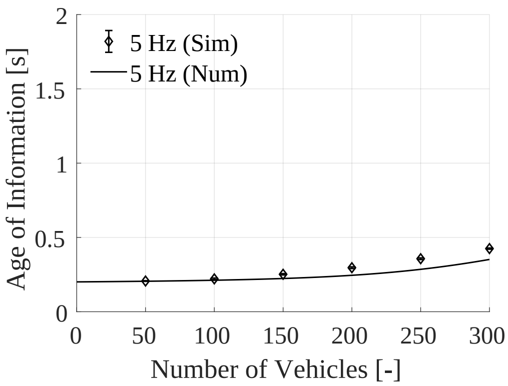
We observe that the PDR of the numerical model deviates by a maximum of 4.6 % compared to the simulation results for 250 vehicles with a message frequency of 5 Hz. The maximum deviation between the obtained PDR of the numerical model and the average PDR of the simulation results is 22.1 % for 300 vehicles and a message frequency of 10 Hz.

We observe that the simulation results deviate from the numerical model for more than 250 vehicles. In our numerical model, the PDR for a vehicle is obtained using the probability that no other vehicle sends in the same time slot. In a heavily congested channel, the probability that two or more vehicles send a message simultaneously increases. The numerical model currently does not capture collisions of more than two messages to reduce its complexity. Hence, the validity of our numerical model is limited to less than 300 vehicles sending with a message frequency of 10 Hz.

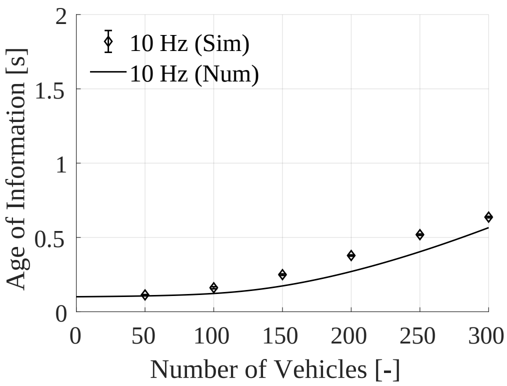
Age of Information

Finally, Figure 28 depicts the AoI between 0 and 300 vehicles for a message frequency of 5 Hz and 10 Hz.

Our model-based AoI assessment requires the probability of receiving at least one message (cf. Section 4.2.2) and is therefore not suited to be compared to the



(a) Message frequency of 5 Hz.



(b) Message frequency of 10 Hz.

Figure 28: Comparison of the measurement-based (simulation) and model-based (numerical) AoI assessment for 5 Hz and 10 Hz.

AoI assessment

measurement-based assessment in simulations. However, we have proposed a modified model-based AoI assessment in [29], which does not consider the probability of receiving at least one message, given as

$$\hat{\Delta}_m = \frac{1}{\lambda} + \frac{1-\rho}{\lambda \cdot \rho} + L. \tag{50}$$

For a message frequency of 5 Hz, we observe that the numerical model deviates by a maximum of 20.7 % compared to the simulation results for 300 vehicles. Similar results are observed for a message frequency of 10 Hz. The numerical model deviates by a maximum of 40.2 % for 250 vehicles.

Message lifetime

The high deviation between the numerical model and simulation results is because of the measurement-based AoI assessment. If a vehicle received a message from a vehicle and has not perceived the vehicle before or lost track of the vehicle because the message lifetime was exceeded, the AoI is set to the message lifetime. In the numerical model, the message lifetime is not considered. Therefore, the AoI is higher in the simulation results compared to the numerical model. The mentioned effect is dominant for a high vehicle density, where the channel reliability is low and vehicles often lose track of other vehicles.

In summary, we also confirm that the results from our numerical model and simulations for the PDR and an average latency of up to 250 vehicles are highly comparable, according to the requirements used in the related work. Therefore, we accurately obtain the vehicles' communication quality metrics in our proposed numerical model. However, we also showed that the PDR is not accurately modeled for more than 250 vehicles because the numerical model does not consider collisions of more than two messages. We also compared the measurement-based assessed AoI in simulations with a modified model-based AoI assessment in the numerical model. We found that both models are comparable. However, the measurement-based assessment increases the assessed AoI under unreliable channel conditions compared to the numerical model.

7.3 resource allocation in decentralized vehicular networks

In this section, we evaluate our relevance-aware resource allocation approach presented in Section 5.2, which prioritizes relevant information in a congested channel. The prioritization of relevant information is required to provide high communication quality for vehicles coordinating a cooperative maneuver. In the following, we compare the performance of our relevance-aware approach, denoted as Priority, with reference approaches for resource allocation and congestion control in decentralized V2X networks.

We analyze to which extent our relevance-aware resource allocation approach prioritizes relevant information under congested channel conditions and improves the network's AIR in challenging scenarios. We compare the channel load, normalized throughput, and PDR of the approaches for different vehicle densities. Moreover, we detail the resource allocation behavior, specifically focusing on the convergence speed and stability of the approaches. Furthermore, we aim to verify that optimizing the network's AIR, as focused by the Priority approach, improves the AoI of vehicles with relevant information.

7.3.1 *Scenario*

In the following, we describe the scenario considered for evaluating resource allocation in decentralized V2X networks. We specify relevant parameters for this evaluation and introduce the reference approaches to compare the performance of our approach.

Parameters

Parameter	Value
Number of Vehicles (Numerical)	50, 150, 250
Exponential Forgetting Factor (Priority)	0.1
Adaptive Gain Factor (Priority)	1/150
Channel Model	simple and realistic channel models

Table 6: Parameters for the evaluation of the relevance-aware resource allocation approach.

Specific parameters used in this evaluation are summarized in Table 6. In the numerical evaluation, we consider 50, 150, and 250 vehicles, whereas, in the simulation, we refer to the vehicle density detailed in Table 3. In the simulation area, we expect approximately 150 vehicles at the same time. Priority considers an exponential forgetting factor α_R of 0.1 and an adaptive gain factor β_R of 1/150 (cf. Section 5.2). Both parameters are taken from Linear Message Rate Integrated Control (Limeric) [15]. The mentioned parameters enable a faster message frequency convergence and differ from the A-DCC parameters. Fast convergence is required because Priority continuously adapts the vehicle's message frequency to its information relevance. In the numerical evaluation, we refer to the SIMPLE channel model and in the simulation evaluation, we consider the SIMPLE and REALISTIC channel models.

Reference Approaches

To evaluate the performance of PRIORITY, we consider the following reference approaches for resource allocation and congestion control. Notably, the message frequency of all approaches is limited to the lower and upper message frequency, as defined in Table 3.

NAIVE The NAIVE approach sends messages with the maximum message frequency λ_{MAX}. Hence, the NAIVE approach induces the highest channel load among all other approaches.

R-DCC R-DCC is a congestion control approach standardized by the ETSI in [102]. The state machine of R-DCC limits the message frequency of vehicles to the current channel congestion state of R-DCC. The ETSI proposes five different states, from idle to restricted. Each congestion state is valid for a specific CBR interval. R-DCC only transitions to the previous or next state, i. e., congestion states cannot be skipped. The mapping table in [102] denotes the allowed message frequency per vehicle for the respective congestion state. We consider the table for $0.5\,\text{ms} \leqslant T_{FD} < 1\,\text{ms}$, which matches our considered message size of 500 B.

A-DCC Instead of limiting the message frequency in discrete and finite states, A-DCC linearly adapts the message frequency to the assessed CBR. A-DCC is adopted from Limeric [15] and standardized in [102]. All vehicles aim to achieve a target CBR, which is set in [102] to 0.68. If the assessed CBR is below the target CBR, vehicles increase their message frequency and vice versa. For A-DCC, we consider the parameters denoted in [102].

RISK RISK has been proposed in [46] and is a resource allocation approach explicitly designed for cooperative driving. Similar to our parameters in Table 3, the message frequency of RISK in [46] is limited between 1 Hz and 10 Hz. Vehicles send messages with the upper message frequency if the approaching time obtained from the vehicle trajectories is below a predefined threshold. Otherwise, vehicles send with the lower message frequency. The authors in [46] studied thresholds between 0.5 s and 1.5 s. In our evaluation, we consider a threshold of 1.5 s to account for the lower velocity in our urban intersection scenario compared to the highway scenario in [46]. The RISK approach requires assessing the approaching time of vehicles from a trajectory-based cooperative driving application. Hence, we only evaluate RISK in simulations, where vehicles coordinate maneuvers with the cooperative driving application.

RISK DYNAMIC RISK DYNAMIC extends the RISK approach and additionally requires that a vehicle has moved a distance of 4 m before sending a subsequent message. The extension of this approach uses the message generation rule of the cooperative awareness message [96], aiming to reduce the message frequency of vehicles. Similar to RISK, we only evaluate RISK DYNAMIC in the simulation evaluation with cooperative driving.

7.3.2 *Numerical Analysis*

We use the numerical analysis to focus on the convergence speed, stability, and steady-state communication quality of the approaches. For this purpose, the information relevance of a vehicle does not change over time in the first numerical analysis. After that, we analyze the peak AoI of vehicles with a different information relevance. That way, we gather evidence if relevance-aware resource allocation improves the AoI of relevant messages. Finally, we observe a particularly challenging case, where *all* vehicles continuously obtain a new information relevance from a uniform distribution in the *same* iteration. We expect the reference approaches to be unaffected by a dynamic information relevance. Hence, we analyze to which extent a dynamic information relevance impacts the performance of PRIORITY compared to the reference approaches.

Channel congestion states

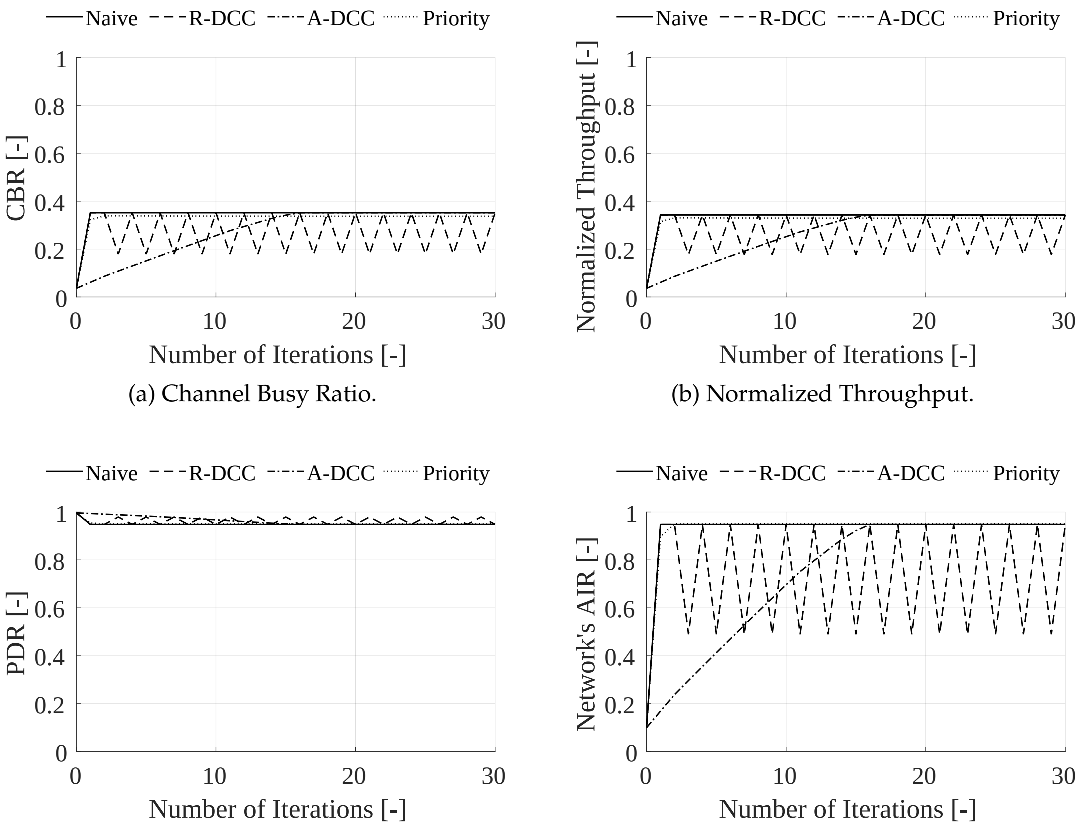
In this evaluation, we analyze the performance of different resource allocation approaches in a relaxed, highly congested, and restricted V2X channel. According to Section 4.2, we assume a relaxed channel state if $\leqslant 50$ vehicles send with a message frequency of 10 Hz because the CBR will not exceed 0.4 and the PDR is considerably high. For 150 vehicles, we consider that the channel is highly congested[5] with a CBR over 0.8. However, the V2X channel has its maximum normalized throughput if 150 vehicles send with a message frequency of 10 Hz (cf. Section 7.2). Therefore, we expect that the NAIVE approach has a high normalized throughput. For 250 vehicles, the channel is considered restricted because the CBR saturates and the normalized throughput decreases significantly. In each scenario, the vehicles' message frequency is uniformly distributed in the first iteration, independent of the information relevance. Vehicles update their message frequencies synchronously in each iteration.

Static Information Relevance

In the following, all vehicles have a static information relevance, i. e., the information relevance of a vehicle does not change over time. In the first iteration, vehicles obtain the information relevance from a uniform distribution. In real-world scenarios, only a few vehicles require to coordinate a cooperative maneuver and, therefore, have a high information relevance. If only a few vehicles have a high information relevance, our approach is expected to have a significant advantage compared to the reference approaches w. r. t. to the network's AIR. Hence, a uniform distribution of the information relevance denotes a specific challenge for the PRIORITY approach.

In the following, we analyze the communication quality of the V2X network, the convergence speed, and the stability of the approaches. The impact of convergence speed and stability on resource allocation mechanisms in decentralized V2X networks was discussed in Section 5.2.

5 The ETSI defines a channel restricted above a CBR of 0.6 [102].



(a) Channel Busy Ratio.

(b) Normalized Throughput.

(c) Packet Delivery Ratio.

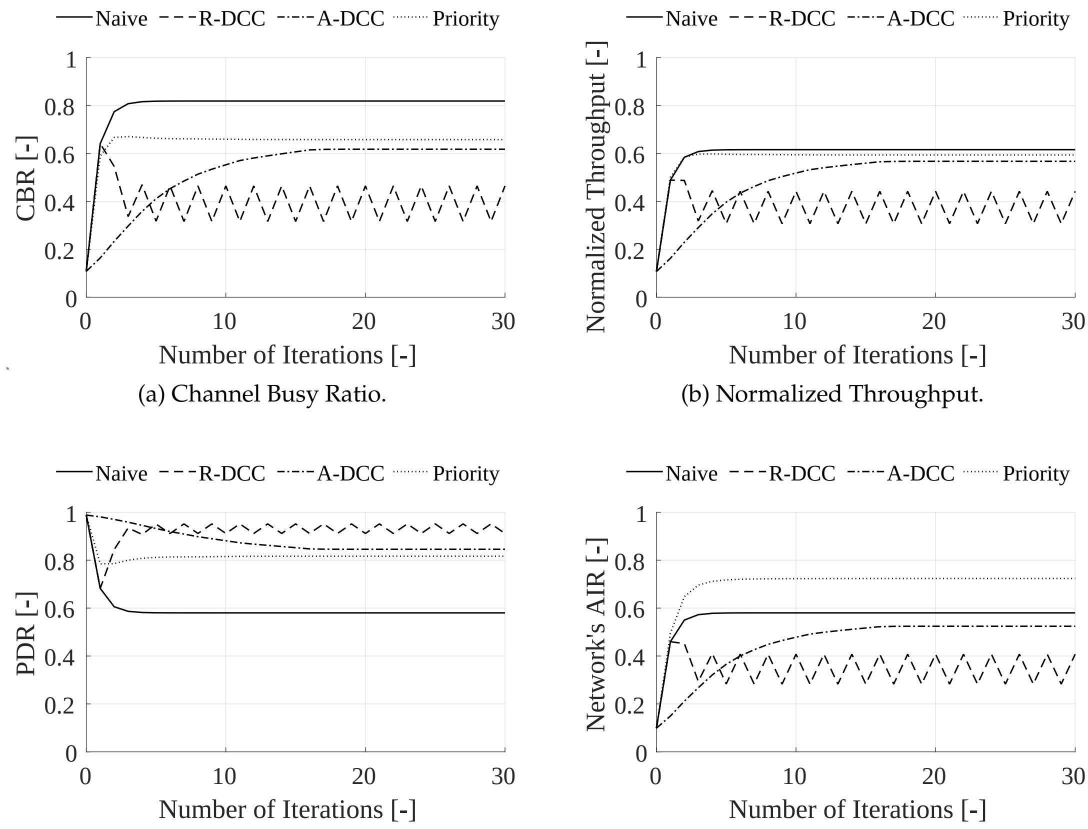
(d) Network's AIR.

Figure 29: Evaluation of the communication quality metrics over a series of iterations for 50 vehicles and static information relevance.

Relaxed channel state

Figure 29 depicts the communication quality for 50 vehicles. PRIORITY, A-DCC, and NAIVE achieve the highest normalized throughput of 0.33, 0.34, and 0.34 in the steady-state, respectively. For 50 vehicles, the CBR is comparable to the normalized throughput, which is seen in Figure 29a and Figure 29b. The channel is in the relaxed state, where the PDR is above 0.95 for all approaches, depicted in Figure 29c. That way, the probability that the channel is occupied with a successful transmission instead of a collision transmission is high, explaining the similarity of the CBR and normalized throughput. In Figure 29, we observe that R-DCC oscillates between consecutive iterations and cannot converge to a stable state. For example, the normalized throughput oscillates between 0.18 and 0.34. R-DCC transitions to the ACTIVE 1 state for a CBR above 0.3. In the ACTIVE 1 state, the message frequency of vehicles is limited to 5 Hz. In the next iteration, the CBR decreases to 0.18 because the message frequency of all vehicles is limited to 5 Hz. Below a CBR of 0.3, R-DCC again transitions to the RELAXED state and increases the message frequency to 10 Hz, causing oscillations because all vehicles synchronously update their message frequency. The oscillation of R-DCC decreases the communication quality after every second iteration compared to the other approaches, i. e., under-utilization of channel resources. Figure 29a shows that A-DCC

R-DCC shows unstable behavior



(a) Channel Busy Ratio.

(b) Normalized Throughput.

(c) Packet Delivery Ratio.

(d) Network's AIR.

Figure 30: Evaluation of the communication quality metrics over a series of iterations for 150 vehicles and static information relevance.

requires up to 15 iterations to reach the maximum CBR of 0.35 for 50 vehicles and converges considerably slower to its steady-state compared to the other approaches. For example, PRIORITY converges to its maximum CBR of 0.34 after 2 iterations. The reason is the conservative parametrization of the exponential forgetting and adaptive gain factors, causing a slow message frequency adaptation. With the parameterization of A-DCC, the system remains stable even in scenarios with significantly higher number of vehicles. Figure 29d compares the network's AIR. All approaches reach a network's AIR of 0.95, sending with the maximum message frequency because the V2X channel is in the relaxed state. Hence, the mentioned approaches can fully exploit the available channel resources. Interestingly, R-DCC cannot converge to a stable state, significantly decreasing its communication quality even for a relaxed channel because of oscillation.

Congested channel state

Figure 30 depicts the communication quality comparison of 150 vehicles competing for the channel resources. The NAIVE approach again induces the highest CBR of 0.82. In contrast, PRIORITY and A-DCC converge to a CBR of 0.66 and 0.62, respectively. From [15], we know that the steady-state of the CBR C for A-DCC is obtained as

$$C = \frac{N \cdot \beta \cdot C_T}{\alpha + N \cdot \beta}, \tag{51}$$

where N is the number of vehicles, α and β are the adaptive and exponential gain factors, and C_T is the target CBR. Equation 51 yields a steady-state CBR of 0.63 with the A-DCC parameters, confirming our obtained CBR for A-DCC in Figure 30 in the steady-state. The CBR of R-DCC again oscillates between 0.27 and 0.51, causing transitions between the ACTIVE 1 and 2 states. In contrast to 50 vehicles, the normalized throughput for 150 vehicles, depicted in Figure 30b, is significantly reduced for all approaches. The reason is that the PDR decreases with an increasing channel load. As the probability of collision transmissions increases, the channel throughput is decreased. We observe that the NAIVE and PRIORITY approaches achieve the highest normalized throughput of 0.62 and 0.59, respectively. A-DCC achieves a normalized throughput of 0.57 and R-DCC oscillates between 0.26 and 0.49. Notably, the NAIVE approach achieves the highest normalized throughput, although the PDR is significantly lower compared to the other approaches with a PDR of 0.58. In contrast, PRIORITY and A-DCC achieve a PDR of 0.82 and 0.85, respectively. R-DCC achieves the highest PDR but oscillates between a PDR of 0.90 and 0.96. In Figure 30d, we depict the network's AIR. PRIORITY achieves the highest network's AIR of 0.72 after less than 4 iterations. In contrast, NAIVE, and A-DCC achieve a network's AIR of 0.58 and 0.52, respectively. The network's AIR for R-DCC oscillates between 0.24 and 0.45. In a congested channel, PRIORITY achieves the highest network's AIR compared to the reference approaches after less than 4 iterations, i. e., PRIORITY prioritizes relevant information under congested channel conditions and converges fast to the steady-state. PRIORITY also outperforms R-DCC and A-DCC w. r. t. the normalized throughput. Interestingly, R-DCC and A-DCC achieve a lower normalized throughput and network's AIR than the NAIVE approach. Our evaluation also confirms the results in [195], where R-DCC and A-DCC were compared to the NAIVE approach in simulations.

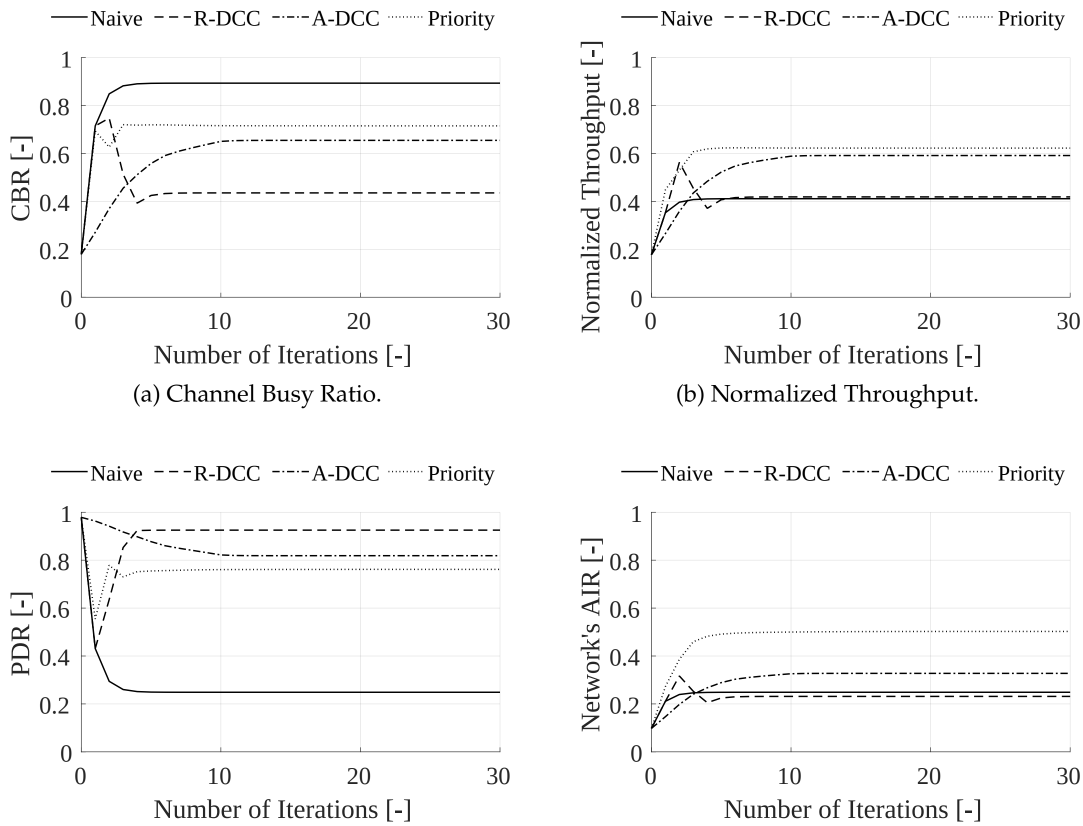
Channel congestion vs. congestion control

Prioritizing information in a congested channel

Restricted channel state

Finally, we consider a restricted channel, where 250 vehicles compete for channel access. Again, the NAIVE approach induces the highest CBR of 0.89, as depicted in Figure 31a. In contrast, PRIORITY and A-DCC have a CBR of 0.72 and 0.65, respectively. According to Equation 51 from [15], the steady-state CBR for A-DCC with 250 vehicles is 0.65 and, therefore, equal to our obtained CBR in Figure 31 in the steady-state. For 250 vehicles, R-DCC converges to the Active 2 state, inducing a CBR of 0.44 with a message frequency of 2.5 Hz. The evaluation of the CBR shows that R-DCC, A-DCC, and PRIORITY, in contrast to NAIVE, adapt to congested and restricted channels and counteract channel congestion by limiting the vehicles' message frequency to maintain a high PDR. In Figure 31b, we depict the normalized throughput for 250 vehicles. In contrast to 150 vehicles, the NAIVE approach achieves the lowest normalized throughput of 0.41. In contrast, PRIORITY achieves the highest normalized throughput of 0.62, whereas ETSI R-DCC and A-DCC achieve a normalized throughput of 0.42 and 0.59, respectively. The NAIVE approach only achieves a PDR of 0.25, depicted in Figure 31c, significantly decreasing its normalized throughput. In contrast, R-DCC, A-DCC, and PRIORITY achieve a PDR of 0.93, 0.82, and 0.76, respectively. In a restricted channel, message collisions significantly impair the communication quality of the NAIVE approach. Interestingly, the high PDR of R-DCC cannot compensate for the reduced message frequency. Hence, R-DCC achieves a comparable normalized throughput as

Counteracting channel congestion



(a) Channel Busy Ratio.

(b) Normalized Throughput.

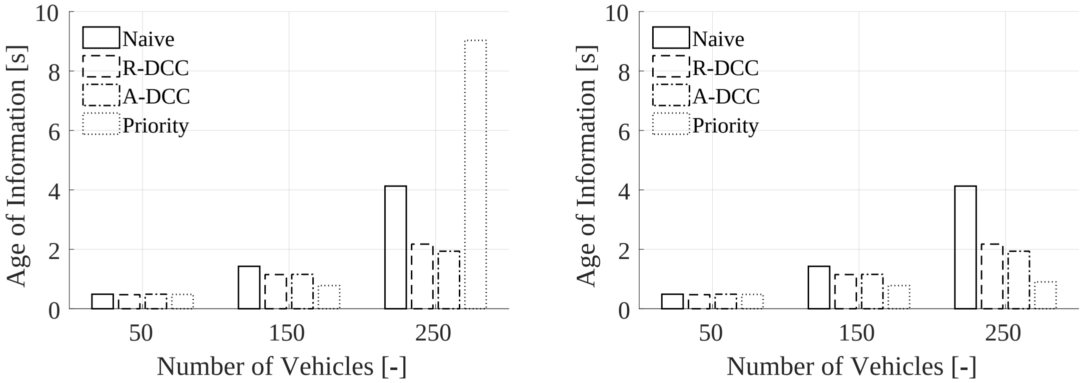
(c) Packet Delivery Ratio.

(d) Network's AIR.

Figure 31: Evaluation of the communication quality metrics over a series of iterations for 250 vehicles and static information relevance.

Naive, although its PDR is increased by 0.68. Priority prioritizes relevant information in a restricted channel state and, thus, achieves a network's AIR of 0.50. In contrast, the reference approaches R-DCC, A-DCC, and Naive only achieve a network's AIR of 0.23, 0.33, and 0.25. In a restricted channel, Priority achieves the highest channel throughput and network's AIR, outperforming the reference approaches. A-DCC and Priority achieve a comparable normalized throughput. However, A-DCC aims for a fair distribution of channel resources and does not prioritize relevant information. In contrast, Priority counteracts channel congestion *and* prioritizes relevant information in congested and restricted channels. In Section A.1 we perform an extended evaluation with 250 vehicles. In contrast to this evaluation, we consider a specific challenging case w. r. t. stability because all vehicles start with a message frequency of 1 Hz in the first iteration and adapt the message frequency synchronously. We observe oscillation for R-DCC and Priority in the first 4 iterations. However, Priority converges to a stable state and achieves the highest normalized throughput and network's AIR in each iteration compared to the reference approaches.

In summary, we conclude that all approaches except R-DCC achieve a high communication quality in a relaxed channel by fully exploiting the available channel resources.



(a) Information Relevance of 0.5. (b) Information Relevance of 1.0.

Figure 32: Evaluation of the model-based peak AoI for 50, 150, and 250 vehicles for vehicles with an information relevance of 0.5 and 1.0. The study considers a message reception probability of 0.99999.

In contrast, in a congested and restricted channel with 150 vehicles, R-DCC, A-DCC, and Priority reduce the vehicles' message frequency to maintain a high PDR. However, the Naive approach outperforms R-DCC and A-DCC in a congested channel by allocating more resources on the channel, compensating for the lower PDR. In a restricted channel, the higher resource allocation of the Naive approach cannot compensate for the significantly lower PDR and is outperformed by all other approaches. Priority increases the network's AIR by 24.1 % and 51.5 % compared to the reference approaches in a congested and restricted channel, respectively. Additionally, Priority also achieves the highest normalized throughput in a restricted channel compared to the reference approaches.

Impact of Information Relevance on the Age of Information

In the previous evaluation, we have shown that Priority achieves the highest network's AIR in a congested and restricted channel compared to the reference approaches. However, the previous evaluations also revealed that R-DCC achieves the highest PDR in all considered scenarios at the cost of a decreased message frequency compared to the other approaches.

Message frequency vs. reliability

In the following, we analyze to which extent a high message frequency can compensate for a lower PDR, focusing on the peak AoI of messages with different information relevance. In this context, a low AoI indicates a high communication quality, i. e., the information is current at the receiver. Overall, we evaluate if maximizing the network's AIR, as focused by Priority, improves the AoI of relevant messages.

Model-based peak AoI

Figure 32 compares the peak AoI of the considered approaches. The peak AoI is obtained from our model-based assessment presented in Section 4.2. We obtain the message frequency, PDR, and average latency from the previous evaluations in the steady-state after 30 iterations. According to Section 2.2, the related work requires a PDR between 0.99 and 0.9999 for cooperative driving use cases. Hence, we obtain the peak AoI under the assumption that we receive at least one message with a probability of 0.99999, following the requirement of [8].

In the following, we analyze the peak AoI from the perspective of a vehicle with an information relevance of 0.5 and 1.0. Notably, only PRIORITY considers the information relevance for resource allocation. Hence, we expect the reference approaches to be unaffected by the vehicle's information relevance and achieve comparable performance independent of the vehicle's information relevance.

Relaxed channel state

For 50 vehicles, all approaches achieve a peak AoI below 0.49, independent of the vehicle's information relevance. The channel is not congested and all approaches exploit the maximum allowed message frequency. We consider the last iteration from the previous evaluations, where R-DCC is in the RELAXED CBR state. In this iteration, R-DCC allows for a higher message frequency compared to the previous iteration, i. e., R-DCC oscillates between two states for 50 and 150 vehicles.

Prioritization of relevant information

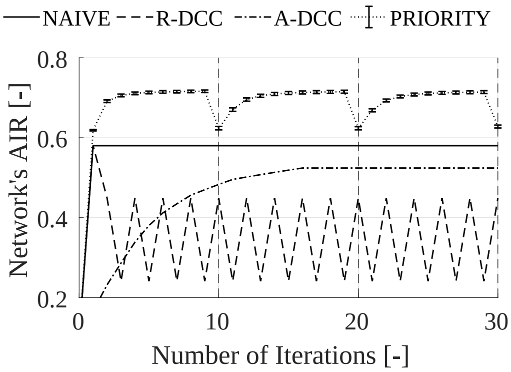
In the following, we focus on a vehicle with an information relevance of 0.5, as depicted in Figure 32a. In the scenario with 150 vehicles, PRIORITY achieves the lowest peak AoI of 0.78 s for the vehicles with an information relevance of 0.5. In contrast, R-DCC, and A-DCC achieve a peak AoI of 1.15 s. Hence, PRIORITY prioritizes messages of the vehicle with an information relevance of 0.5 over vehicles with a lower information relevance in a congested channel. In contrast, NAIVE achieves a peak AoI of 1.43 s because of the significantly lower PDR. For 250 vehicles, we observe that R-DCC and A-DCC achieve the lowest peak AoI below 2.17 s and 1.94 s, respectively. The NAIVE approach with a peak AoI of 4.13 s outperforms our PRIORITY approach with a peak AoI of 9.03 s. In the considered scenario, PRIORITY prioritizes vehicles with a higher information relevance than 0.5 because the available channel resources are insufficient for all vehicles. Hence, PRIORITY reduces the message frequency of the vehicle with an information relevance of 0.5, increasing its peak AoI.

Prioritization of highly relevant information

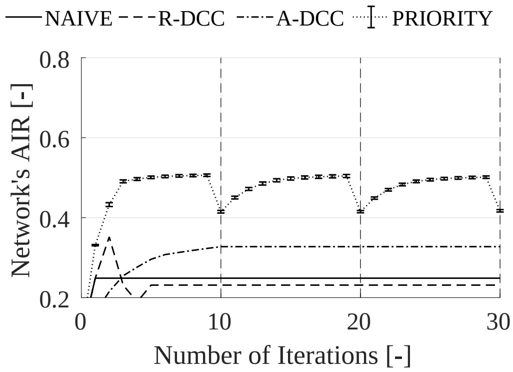
In the following, we consider a vehicle with an information relevance of 1.0 in the same scenario as analyzed before, depicted in Figure 32b. We observe that the reference approaches perform comparable irrespective of the vehicle's information relevance. However, PRIORITY prioritizes the vehicle with highly relevant information. For 150 vehicles, PRIORITY achieves comparable performance for a vehicle with an information relevance of 0.5 and 1.0, resulting in a peak AoI of 0.78 s. In a restricted channel with 250 vehicles, PRIORITY outperforms the reference approaches for a vehicle with an information relevance of 1.0. PRIORITY achieves a peak AoI of 0.90 s. In contrast, A-DCC, R-DCC, and NAIVE achieve a peak AoI of 1.94 s, 2.17 s, and 4.13 s, respectively. Hence, PRIORITY decreases the AoI of highly relevant information by more than 1 s in the considered scenario, significantly improving timely reception of relevant information compared to the reference approaches.

Dynamic Information Relevance

According to our proposed approach for information relevance assessment in Section 4.3, the relevance of vehicles is expected to change over time, depending on the vehicles' context. PRIORITY adapts the vehicles' message frequency to the assessed information relevance. In the following, we analyze the network's AIR for a series



(a) 150 vehicles.



(b) 250 vehicles.

Figure 33: Evaluation of the communication quality metrics over a series of iterations for 50, 150, 250 vehicles and dynamic information relevance. The dashed vertical line indicates a new distribution of the information relevance.

of iterations, where the vehicles' information relevance changes over time. All vehicles obtain a new information relevance from a uniform distribution after every 10 iterations, indicated as a vertical dashed line in Figure 33.

In this evaluation, we focus on the congested and restricted channel with 150 and 250 vehicles. From Figure 29 and Figure 32, we know that all considered approaches achieve a high communication quality in a relaxed channel state. We perform 30 runs for each approach to obtain the impact of different information relevance distributions. Hence, we depict the network's AIR as line plots. The line plot depicts the mean of means over all runs. For Priority, we also depict the standard deviation of the mean for each run. The standard deviation over multiple runs for the reference approaches is too small for illustration and is therefore not reported in the following.

Congested channel

Figure 33a depicts the network's AIR for 150 vehicles. As expected, a new information relevance distribution for all vehicles after every 10 iterations does not impact the network's AIR of R-DCC, A-DCC, and the Naive approach. In contrast, the network's AIR decreases for Priority when the information relevance of all vehicles is uniformly distributed after every 10 iterations. However, we see in Figure 33a that the network's AIR of Priority does not fall below 0.61. Hence, even if all vehicles obtain a new information relevance in a single iteration, Priority maintains a higher network's AIR compared to the reference approaches in the analyzed cases. Notably, the standard deviation over multiple runs is negligibly small and only marginally impacts the network's AIR of Priority.

Restricted channel

Figure 33b depicts the network's AIR for 250 vehicles. We again see that Priority has a higher network's AIR for all iterations compared to the reference approaches. After all vehicles synchronously get a new uniformly distributed information relevance, the network's AIR of Priority decreases to a minimum of 0.40. Even in this iteration, Priority outperforms A-DCC, achieving a network's AIR of 0.33.

Furthermore, we notice that after less than 5 iterations, the network's AIR of PRIORITY again reaches its maximum for the congested and restricted channel, allowing for fast adaptations to a new vehicles' information relevance.

In summary, PRIORITY counteracts channel congestion and achieves the highest network's AIR compared to the reference approaches. In addition, we demonstrated that our approach quickly adapts to a new information relevance distribution, outperforming the reference approaches even for a dynamic information relevance. Lastly, we showed that by optimizing the network's AIR, PRIORITY achieves the lowest peak AoI for highly relevant information under congested and restricted channel conditions.

7.3.3 *Simulation Analysis*

The numerical analysis has shown that PRIORITY outperforms the reference approaches w. r. t. the network's AIR and significantly decreases the AoI for vehicles with relevant information. However, the numerical analysis considered the SIMPLE channel model, neglecting path loss effects, vehicle mobility, and hidden node collisions. Furthermore, vehicles obtained the information relevance from a uniform distribution in the numerical analysis.

Realistic channel model and vehicle mobility

In the following, we analyze the effects of the REALISTIC channel model, i. e., path loss, hidden node collisions, and vehicle mobility on the performance of the considered approaches. To make the results comparable to our previous numerical analysis and specifically focus on the mentioned effects, we first consider that the vehicles again obtain the information relevance from a uniform distribution. Furthermore, the information relevance again does not change over time. We conclude this evaluation section with the resource allocation analysis for a cooperative driving scenario. Here, vehicles continuously assess the information relevance of MCMs according to our presented approach in Section 4.3.

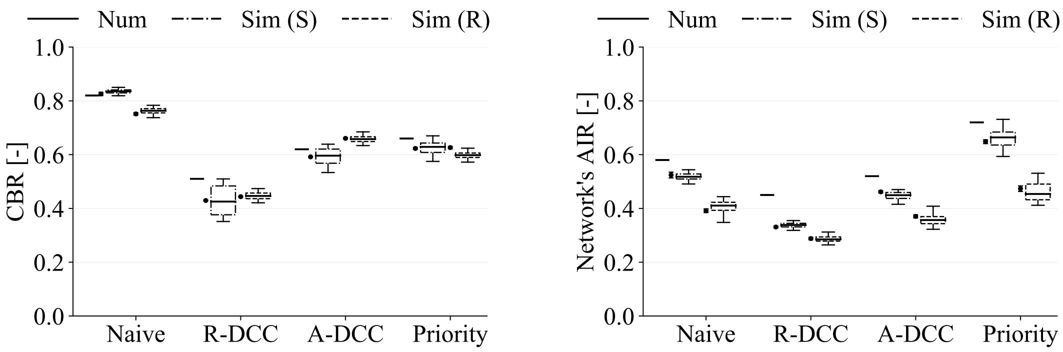
Information relevance assessment

Considering the REALISTIC channel model, we expect all approaches to be affected by path loss, hidden nodes, and vehicle mobility. In this context, the CBR allows to compare the induced channel load of the approaches, measured by a fixed RSU in the center of the intersection. Furthermore, we analyze to which extent the approaches increase the network's AIR in the center of the intersection.

Static Information Relevance

For evaluating resource allocation in a high mobility scenario with static and uniformly distributed information relevance, we consider the urban intersection in Figure 22. In the first evaluation, cooperative driving is deactivated, but vehicles send messages with the information relevance obtained from a uniform distribution. Vehicles from ROUTE 2 drive straight in the intersection instead of turning left to prevent a traffic jam in the intersection because vehicles cannot coordinate cooperative maneuvers in this first evaluation.

Figure 34 depicts the CBR and network's AIR for the considered approaches using the SIMPLE and REALISTIC channel models, denoted as Sim (S) and Sim (R), respectively.



(a) Channel Busy Ratio. (b) Network's AIR.

Figure 34: Evaluation of the CBR and network's AIR in a simulation environment with static information relevance using the SIMPLE and REALISTIC channel models. Numerical results are depicted for reference.

For comparison, we also report the numerical results in the steady-state as solid lines from the previous numerical analysis, denoted as Num.

Channel busy ratio

Figure 34a depicts the CBR for the SIMPLE and REALISTIC channel models. We observe that the NAIVE approach induces the highest CBR with a median of 0.84 and 0.76 for the SIMPLE and REALISTIC channel models, respectively. The CBR in simulations is comparable for both channel models with a CBR of 0.82 in the numerical analysis. Notably, the CBR is lower for the REALISTIC channel model in contrast to the SIMPLE channel model. Considering the REALISTIC channel model, the RSU receives less messages because of path loss and fading effects.

Adapting to the perceived CBR

In simulations, R-DCC induces a median CBR of 0.43 and 0.45 for the SIMPLE and REALISTIC channel models, respectively. For the numerical results of R-DCC, we consider the last iteration of the CBR with 0.51. Remember that R-DCC cannot converge to a steady-state in a congested channel with 150 vehicles, where the CBR oscillated between 0.27 and 0.51. Considering the mentioned effect, the simulation results of R-DCC for both channel models are in the range of the numerical results.

A-DCC induces a median CBR of 0.60 and 0.66 for the SIMPLE and REALISTIC channel models, respectively. A slightly higher CBR for the REALISTIC channel model is also observed for R-DCC. R-DCC and A-DCC adapt the vehicles' message frequency to the perceived CBR. However, considering the REALISTIC channel model, vehicles assess a lower CBR because of path loss and fading effects. Hence, the vehicles assess a lower CBR for the REALISTIC channel model compared to the SIMPLE channel model. Consequently, R-DCC and A-DCC allow for a higher vehicle's message frequency in the REALISTIC channel model compared to the SIMPLE channel model.

Compensation for hidden nodes

Interestingly, the mentioned effect is not observed for PRIORITY, where a median CBR of 0.66 and 0.63 is reported for the SIMPLE and REALISTIC channel models, respectively. Our relevance-aware resource allocation adapts to other vehicles' assessed information relevance and message frequency. In addition to the message payload, each perceived vehicle's information relevance and message frequency is maintained in the Local Dynamic Map (LDM). Outdated entries are deleted after the message lifetime expires (cf. Section 6.1). However, obtaining the channel congestion from the LDM increases the awareness of PRIORITY. In contrast to R-DCC and A-DCC, PRIORITY also adapts the resource allocation to vehicles outside its communication range until the entries in the LDM are deleted because the message lifetime expires.

In the following, we compare the network's AIR of the considered approaches. We observe that the network's AIR is significantly reduced for the REALISTIC channel model compared to the SIMPLE channel model for all approaches.

Impact of path loss

Considering the REALISTIC channel model, path loss effects and hidden node collisions severely decrease the network's AIR in addition to message collisions considered by the SIMPLE channel model. NAIVE outperforms R-DCC and A-DCC for 150 vehicles in simulations, similar to our numerical analysis. Compared to a network's AIR of 0.58 in the numerical evaluation, the NAIVE approach achieves a median network's AIR of 0.52 and 0.41 for the SIMPLE and REALISTIC channel models, respectively. R-DCC achieves the lowest network's AIR for all considered approaches with a median network's AIR of 0.34 and 0.29 for the SIMPLE and REALISTIC channel models, respectively. The difference in the network's AIR for R-DCC between the numerical and simulation results are again explained by the oscillation of R-DCC in the numerical analysis. The network's AIR oscillated between 0.24 and 0.45, where the simulation results are in the mentioned range of the numerical results.

Slow convergence speed of A-DCC

A-DCC achieves a higher network's AIR with a median of 0.45 and 0.36 for the SIMPLE and REALISTIC channel models, respectively. The lower network's AIR for A-DCC in simulations compared to the numerical results with a network's AIR of 0.52 for the SIMPLE channel model is because of the slow adaptation of the vehicle's message frequency. A-DCC requires multiple iterations to converge to a steady-state. The CBR is only updated every 200 ms according to the specification of [102] and the vehicle's message frequency after every 100 ms. We know from our numerical results that A-DCC required more than 15 iterations for 150 vehicles to converge to the steady-state (cf. Figure 30). However, in a scenario with high mobility, vehicles first perceive a low CBR before the intersection and, while entering the intersection, a higher CBR. Hence, a fast adaptation of the vehicle's message frequency to the perceived CBR when entering the intersection is required.

Similar to NAIVE, R-DCC, and A-DCC, the performance of PRIORITY is decreased when considering the REALISTIC channel model compared to the SIMPLE channel model because of path loss and hidden node collisions. However, PRIORITY outperforms the reference approach w. r. t. the network's AIR for the REALISTIC channel model. PRIORITY achieves a median network's AIR of 0.45 for the REALISTIC channel model. We also confirm the higher network's AIR of PRIORITY compared to the reference approaches from the error bars, reporting the mean of means and the standard deviation of the mean over 30 simulation runs. PRIORITY achieves a mean network's AIR of 0.47 over all simulation runs for the REALISTIC channel model. In contrast, NAIVE, R-DCC, and A-DCC only achieve a mean network's AIR of 0.39, 0.29, and 0.37 over all simulation runs, respectively.

In summary, we conclude that we achieve comparable results in simulations compared to the numerical results, considering the SIMPLE channel model. The REALISTIC channel model has a significant impact on the performance of the considered approaches. In contrast to R-DCC and A-DCC, PRIORITY better adapts to the lower communication range. In this context, PRIORITY obtains the message frequency of other vehicles from the LDM, where entries are maintained until the message lifetime expires. That way, the awareness of vehicles outside the communication range is increased for PRIORITY. Furthermore, we showed in this evaluation that path loss severely decreases the network's AIR for all approaches. However, PRIORITY achieves the highest network's AIR over all simulation runs, even when considering path loss and hidden node collisions, increasing the network's AIR by more than 20.5 % over all simulation runs compared to the reference approaches.

Dynamic Information Relevance

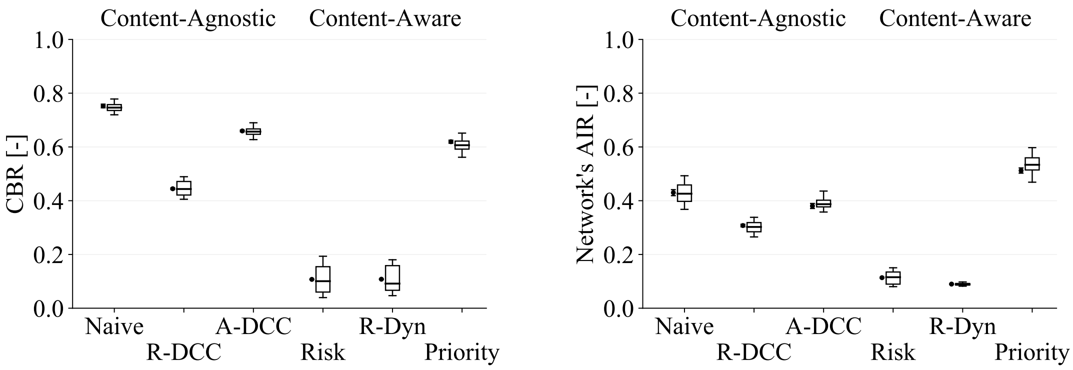
The previous evaluation assumed a uniformly distributed, static information relevance, i. e., the information relevance for a vehicle does not change over time. For cooperative driving, we have motivated that the information relevance depends on the vehicle's context and changes over time. For example, a vehicle coordinating a cooperative maneuver is expected to have a high information relevance until the trajectory conflict is solved.

Cooperative driving at an intersection

In the following, we study the effects of dynamic information relevance in our urban intersection in Figure 22 with the REALISTIC channel model. We consider our cooperative driving application left-turning at an intersection (cf. Section 6.3) and information relevance assessment (cf. Section 4.3). In contrast to the previous evaluation, vehicles on ROUTE 2 turn left in the intersection and require cooperation from vehicles on ROUTE 3. Until the trajectory conflict for vehicles on the mentioned routes exists, the information relevance of both vehicles will increase while approaching the intersection. In addition to the approaches considered in the previous evaluation, we additionally evaluate and compare the performance of RISK and RISK DYNAMIC. Using the cooperative driving application, we assess the continuous approaching time required for the threshold-based approaches RISK and RISK DYNAMIC.

Figure 35 depicts the communication performance for dynamic information relevance in our urban intersection. We have grouped the approaches in content-agnostic (NAIVE, R-DCC, and A-DCC) and content-aware (RISK, RISK DYNAMIC, and PRIORITY) approaches. First, we evaluate the CBR, depicted in Figure 35a. We again observe the highest CBR for the NAIVE approach with a median of 0.75, comparable to the CBR in Figure 34a. Similar results are obtained for R-DCC and A-DCC with a median CBR of 0.44 and 0.66, respectively. For the newly introduced reference approaches RISK and RISK DYNAMIC, we observe a significantly lower median CBR of 0.10 and 0.09, respectively. Both approaches send an MCM if the continuous approaching time is below a safety time threshold of 1.5 s [46]. In contrast to the highway scenario studied in [46], vehicles in our scenario have a maximum velocity of 8.33 m/s. Hence, vehicles must be very close to each other that the continuous approaching time is below the threshold of 1.5 s. Then, RISK and RISK DYNAMIC trigger MCMs with a message frequency of 10 Hz.

Threshold-based resource allocation



(a) Channel Busy Ratio.

(b) Network's AIR.

Figure 35: Evaluation of the CBR and network's AIR in a simulation environment with dynamic information relevance using the REALISTIC channel model.

Otherwise, the message frequency is limited to 1 Hz. Another effect is that RISK DYNAMIC even further reduces the message frequency of vehicles. RISK DYNAMIC requires a vehicle to have a continuous approaching time below the mentioned threshold *and* pass a distance of 4 m before triggering a subsequent message. The approach RISK DYNAMIC was introduced in [46] as the authors observed channel congestion by the RISK approach in their considered highway scenario. In our considered scenario with a maximum velocity of 8.33 ms, the maximum message frequency for RISK DYNAMIC is limited to approximately 2 Hz. In contrast to RISK and RISK DYNAMIC, PRIORITY requires more channel resources and reaches a median CBR of 0.61. However, we observe that the PRIORITY approach requires significantly less resources compared to the previous evaluation in Figure 34a. The reason is that we adapt the message frequency to the vehicle's information relevance. Specifically, vehicles waiting at a red light on ROUTE 4 and ROUTE 5 have no relevant information and prioritize more relevant messages of other vehicles.

Finally, we evaluate the network's AIR, depicted in Figure 35b. In this low-velocity scenario, we observe that the content-aware approaches RISK and RISK DYNAMIC achieve the lowest network's AIR with a median of 0.12 and 0.09, respectively. We also observe that the NAIVE approach outperforms R-DCC and A-DCC with a median network's AIR of 0.43. The reason is that R-DCC and A-DCC reduce the message frequencies of vehicles more than required and cannot prioritize relevant information. In this context, R-DCC and A-DCC achieve a median network's AIR of 0.30 and 0.39, respectively. We again confirm a higher network's AIR of PRIORITY compared to the reference approaches from the error bars, reporting the mean of means and the standard deviation of the mean over 30 simulation runs. PRIORITY achieves a mean network's AIR of 0.51 over all simulation runs. In contrast, NAIVE, A-DCC, and R-DCC achieve a mean network's AIR of 0.43, 0.31, and 0.38 over all simulation runs, respectively. PRIORITY adapts the vehicle's resource allocation to its information relevance. That way, MCMs from vehicles with relevant information are prioritized in the intersection. Content-agnostic approaches such as ETSI R-DCC and A-DCC aim for a fair distribution of channel

Prioritizing relevant information

Parameter	Value
AoI Threshold	150 ms
Segment Precision	1
Channel Model	REALISTIC channel model

Table 7: Parameters for the evaluation of the adaptive data dissemination strategy for cooperative driving.

resources among all vehicles irrespective of their information relevance, which is a disadvantage in the considered scenario.

In Section A.2, we evaluate the cumulative distribution of the information relevance in a cooperative driving scenario. We show that 90 % of the information relevance measurements are below 0.2, meaning that only few vehicles have a high information relevance and require to coordinate a cooperative maneuver.

In summary, we confirmed the results of our numerical analysis in simulations: Based on the information relevance assessment for cooperative driving, our proposed PRIORITY approach counteracts channel congestion and achieves the highest network's AIR in scenarios with high mobility and a REALISTIC channel model. Moreover, we also confirmed our numerical results with simulations and discussed the impact of our REALISTIC channel model on the performance of the considered approaches. Lastly, we demonstrated that our approach increases the network's AIR by 18.6 % over all simulation runs in a cooperative driving scenario compared to the reference approaches.

7.4 ADAPTIVE DATA DISSEMINATION STRATEGY FOR COOPERATIVE DRIVING

In this section, we compare the performance of our adaptive data dissemination strategy presented in Section 5.3 with reference approaches. In this evaluation, we analyze to which extent our approach improves the communication quality of vehicles coordinating a cooperative maneuver. Furthermore, we analyze the impact of communication quality on the average velocity of vehicles coordinating cooperative maneuvers in a congested urban intersection scenario. In the following, we briefly introduce specific parameters for the evaluation and describe the reference approaches.

7.4.1 *Scenario*

The scenario considered for evaluating our adaptive data dissemination strategy is described in the following. In addition to the parameters described in Section 7.1.3, we specify relevant parameters for this evaluation. After that, we briefly outline our considered reference approaches.

Parameters

Specific parameters considered in this evaluation are summarized in Table 7. If a vehicle on ROUTE 2 cooperates with another vehicle on ROUTE 3, the adaptive data dissemination strategy uses 3GPP LTE-V2N communication if the measurement-based assessed AoI is below a threshold AoI. An AoI threshold close to 100 ms increases the communication quality for the cooperative maneuver but also increases the channel load of 3GPP LTE-V2N communication because of λ_{MAX}. That is, vehicles coordinating a cooperative maneuver would always use 3GPP LTE-V2N in addition to Vehicle-to-Vehicle (V2V) communication. In this evaluation, we set the AoI threshold to 150 ms. If decentralized V2X communication can provide high communication quality, the adaptive data dissemination strategy will not use 3GPP LTE-V2N in addition to V2X communication. However, for unreliable V2X communication, a threshold peak AoI of 150 ms enables an immediate adaptation to increase the communication quality with 3GPP LTE-V2N communication if one message of a cooperation partner is lost.

Segment precision

Our LANE-based GEOCAST approach enables to send messages to vehicles on a specific lane. We introduced the segment precision to limit the number of vehicles selected for a LANE-based GEOCAST transmission. Vehicles subscribe to the segment they are driving on. A high segment precision leads to frequent updates of vehicles entering and leaving lane segments. In contrast, for a low segment precision, messages are sent to a large number of vehicles, increasing the channel load in the 3GPP LTE-V2N network. In the considered urban intersection scenario, SUMO divides the *Flachstrasse* from ROUTE 3 into multiple lanes with lane lengths below 100 m. Hence, there is no need to divide the lane into multiple lane segments. Therefore, we consider a segment precision of 1. In this evaluation, we consider the REALISTIC channel model.

Reference Approaches

We denote our proposed data dissemination strategy as ADAPTIVE. We compare the ADAPTIVE approach with the following reference approaches.

PLAIN The PLAIN approach uses the SUMO driver model, which cannot coordinate cooperative maneuvers with V2X communication and only relies on the driver's Line of Sight (LoS). The PLAIN approach denotes the lower traffic efficiency bound in a congested urban intersection scenario.

NAIVE (I) The NAIVE (I) approach sends messages with the maximum message frequency of 10 Hz and coordinates cooperative maneuvers with our cooperative driving application. NAIVE (I) considers an IDEAL channel model, neglecting radio propagation and medium access effects of the REALISTIC channel model. MCMs are not affected by path loss, message collisions, and latency. Thus, cooperative driving can fully exploit its potential to increase traffic efficiency in an urban intersection scenario and is unaffected by impaired communication quality.

NAIVE (R) Lastly, we consider the NAIVE approach with a REALISTIC channel model. NAIVE (R) sends messages with the maximum message frequency of 10 Hz and coordinates cooperative maneuvers with our cooperative driving application.

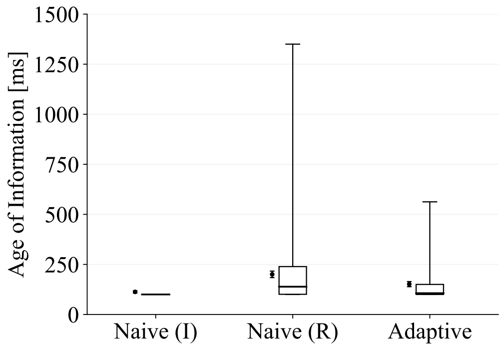


Figure 36: Age of Information for vehicles performing cooperative maneuvers.

LTE unicast

In this evaluation, we do not consider 3GPP LTE-V2N communication as a reference approach. Cooperative driving requires Broadcast transmission to inform vehicles in the vicinity about their future driving intentions. However, Unicast transmissions for 3GPP LTE-V2N communication are not widely deployed and, thus, not usable. As already analyzed in the related work [135, 146, 220, 225], 3GPP LTE-V2N communication cannot sufficiently support periodic Broadcast message dissemination with multiple Unicast transmissions, leading to severe channel congestion in the LTE downlink.

7.4.2 *Communication Quality*

In the previous evaluation, we analyzed the communication quality of vehicles from a V2X network perspective, focusing on the CBR, PDR, normalized throughput, and network's AIR. In the following, we evaluate the measurement-based peak AoI of vehicles requesting, coordinating, and executing a cooperative maneuver.

Figure 36 depicts the peak AoI of vehicles actively involved in a cooperative maneuver to their respective cooperation partners. In this first evaluation, we do not consider the Plain approach because it does not use V2X communication to coordinate cooperative maneuvers.

The Naive (I) approach has a peak AoI of 100 ms because the Naive (I) approach is not affected by limited channel resources, radio propagation, and medium access effects. Hence, for the Naive (I) approach, vehicles coordinating cooperative maneuvers benefit from reliable V2X communication without latency with a maximum message frequency of 10 Hz. In contrast, the peak AoI of vehicles coordinating and executing cooperative maneuvers is significantly higher for the Naive (R) approach with a median peak AoI of 138.75 ms. The mean of means of the peak AoI over all considered simulation runs is 278.44 ms. However, we also notice that the peak AoI partially exceeds 1000 ms during the coordination of a cooperative maneuver. Specifically, path loss and shadowing effects increase the peak AoI of vehicles starting the coordination of a cooperative maneuver. The Adaptive approach improves the peak AoI compared to the Naive (R) approach and achieves a median peak AoI of 106.29 ms. The mean of means of the peak AoI over all considered simulation runs is 151.36 ms, significantly improving the communication quality for vehicles coordinating a cooperative

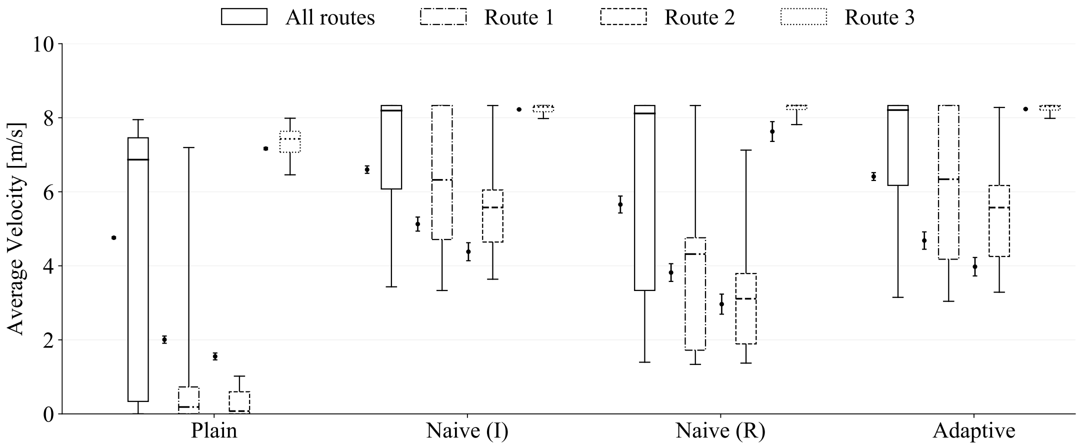


Figure 37: Average velocity per vehicle for the different approaches.

maneuver. Three mechanisms of the Adaptive approach explain the improved communication quality: The Adaptive approach *i)* uses relevance-aware resource allocation to prioritize relevant information, *ii)* increases the communication range with 3GPP LTE-V2N communication to potential cooperation partner for increased awareness, and *iii)* improves the communication with 3GPP LTE-V2N communication during a cooperative maneuver if the communication quality exceeds the peak AoI threshold of 150 ms.

In summary, we have shown that the Adaptive approach decreases the peak AoI of vehicles coordinating a cooperative maneuver by 45.64 % compared to the Naive (R) approach using heterogeneous V2X access technologies.

7.4.3 *Traffic Efficiency*

In the previous evaluation, we have observed that the Adaptive approach improves the communication quality of vehicles coordinating a cooperative maneuver compared to the Naive (R) approach. In the following, we analyze the impact of impaired communication quality on the traffic efficiency of cooperative driving.

Figure 37 depicts the average velocity of vehicles on the different routes depicted in Figure 22b. In this evaluation, we do not report the average velocity of vehicles on Route 4 and Route 5 because these vehicles wait at a red traffic light. The label All Routes in Figure 37 denotes the aggregated average velocity of vehicles on Route 1, Route 2, and Route 3.

Impact of traffic jams

We first analyze the average velocity of vehicles considering the Plain approach. Plain achieves the lowest average velocity on All Routes compared to the other approaches with a mean of means average velocity of 4.76 m/s over all simulation runs. Using the Plain approach, vehicles on Route 3 do not offer cooperation for vehicles on Route 2 to turn left in the intersection. Consequently, we observe a traffic jam on Route 1 and Route 2. In the considered simulation run, most of the vehicles on Route 1 and Route 2 stop in the intersection with a median average velocity of

0.19 m/s and 0.07 m/s, respectively. A vehicle at a standstill requires more time to turn left in the intersection compared to a moving vehicle, increasing the required gap to turn left safely. However, vehicles on Route 3 do not offer cooperation to counteract a traffic jam on Route 1 and Route 2.

The mean of means over all simulation runs on Route 1 and Route 2 is 2.01 m/s and 1.55 m/s, respectively. We also observe a lower mean of means average velocity of 6.89 m/s on Route 3 compared to the other approaches over all simulation runs. The vehicle's LoS to side lanes from the main lane is obstructed by buildings. Hence, the SUMO driver slows down before approaching an intersection on Route 3 to give right-of-way to vehicles turning into the lane. In contrast, our cooperative driving approach relies on V2X communication for environment perception. Without a perceived conflict with other vehicles, the cooperative driving application does not slow down before the intersection and, therefore, achieves a higher average velocity on Route 3 compared to the Plain approach.

Slowing down before intersections

Cooperation increases traffic efficiency

The Naive (I) approach provides the highest communication quality to coordinate cooperative maneuvers early with high reliability. We observe that the traffic jam in the intersection from Route 1 and Route 2 can be reduced, increasing the mean of means average velocity on both routes to 5.13 m/s and 4.38 m/s over all simulation runs, respectively. The mean of means average velocity on All Routes increases to 6.60 m/s over all simulation runs. Hence, cooperative driving with the Naive (I) approach reduces the traffic jam in the intersection and increases the traffic efficiency of vehicles in the considered scenario.

Impact of impaired V2X quality

In contrast to the Naive (I) approach, the Naive (R) approach cannot exploit the full potential of cooperative driving because of impaired communication quality. The mean of means average velocity on All Routes decreases to 5.66 m/s over all simulation runs. We observe that vehicles on Route 1 and Route 2 have a significantly decreased mean of means average velocity of 3.82 m/s and 2.96 m/s over all simulation runs. Hence, the Naive (R) approach only achieves a small traffic efficiency gain compared to the Plain approach. The impaired communication quality because of the congested V2X channel and path loss does not allow for early and reliable maneuver coordination. We also observe a higher average velocity of vehicles on Route 3 for the Naive (R) approach compared to the Naive (I) approach, indicating that vehicles on Route 3 have higher cooperation costs because cooperative maneuvers are coordinated later.

Higher V2X range and quality

In contrast, our Adaptive approach increases the average velocity in the scenario. We observe a mean of means average velocity on All Routes of 6.73 m/s over all simulation runs. Additionally, the traffic jam on Route 1 and Route 2 is significantly reduced, leading to a mean of means average velocity of 5.26 m/s and 5.01 m/s over all simulation runs, respectively. Adaptive improves the cooperative driving efficiency performance through heterogeneous V2X access technologies compared to Naive (R) by extending the communication range and improving the AoI while coordinating a cooperative maneuver.

In summary, a single V2X access technology is insufficient for cooperative driving in challenging scenarios. We have also shown that increasing the communication range before coordinating a cooperative maneuver and improving the communication quality during the execution of a cooperative maneuver increases traffic efficiency for cooperative driving by 18.9 % over all simulation runs.

Notably, even the NAIVE (I) approach cannot fully prevent a traffic jam on ROUTE 1 and ROUTE 2 with cooperative driving. We identified two reasons which are linked to our cooperative driving application and discussed in the following: First, a vehicle only requests a cooperative maneuver with one desired trajectory, which has the lowest costs among all generated trajectories. However, the selected desired trajectory might cause high costs for the vehicle potentially offering cooperation. If the costs exceed the threshold to offer cooperation, the cooperation partner will deny the cooperation request. We can address this problem by sending multiple desired trajectories addressing different cooperation partners. Furthermore, we can obtain the potential costs for the cooperation partner to improve the selection of the desired trajectory.

Desired trajectories

Cooperation costs

Second, we currently require that the costs induced to offer cooperation are lower than the gain achieved by a cooperative maneuver. If a cooperative maneuver is denied, the requesting vehicle requires decelerating while approaching the intersection. With a lower velocity, the requesting vehicle requires an even larger gap to turn left safely, further increasing the costs to offer cooperation. Consequently, also further cooperation requests might be denied because of the high cooperation costs, leading to a traffic jam on ROUTE 1 and ROUTE 2. We can address this problem by considering the overall traffic flow when offering or denying cooperation in addition to the cooperation costs of individual vehicles.

7.5 COMMUNICATION-AWARE COOPERATIVE DRIVING

In the following, we compare the performance of our communication-aware cooperative driving approach, denoted as AWARE, with reference approaches. Adapting cooperative driving to the assessed communication quality is required to maintain safety in scenarios with impaired communication quality. Overall, we analyze if our communication-aware adaptive approach increases the traffic safety for cooperative driving in scenarios with impaired communication quality compared to the reference approaches. Moreover, we analyze to which extent our communication-aware adaptive approach increases traffic efficiency in scenarios with high communication quality.

For the evaluation, we outline the considered scenarios, describe specific parameters, and briefly explain the reference approaches in the following.

7.5.1 *Scenario*

In this evaluation, we consider a simplified PDR channel model. We additionally consider the parameters denoted in Table 8. We vary the PDR between 0.1 and 1 to analyze the impact of different communication qualities on the traffic efficiency and safety of cooperative driving. A PDR of 0 means that no messages can be received, preventing any coordination of cooperative driving maneuvers. For the AWARE approach, we consider a probability to receive at least one message of 0.9999, which is used for the

Parameter	Value
Message Frequency	10 Hz
PDR	0.1, 0.2, ..., 1.0
Probability to receive at least one message	0.9999
Vehicle Velocity	8.33 m/s
Emergency Deceleration	$-10\,\mathrm{m/s^2}$

Table 8: Specific parameters for the evaluation of communication-aware cooperative driving.

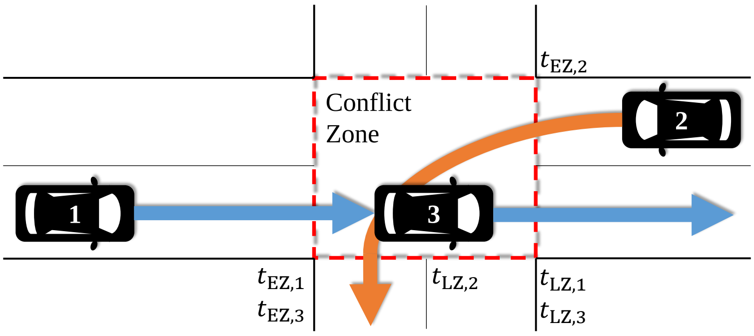


Figure 38: Conflict zone for the left-turning at an intersection use case, denoting the times when vehicles enter and leave the conflict zone.

model-based AoI assessment. Irrespective of the considered approach, cooperative driving always sends MCMs with the maximum message frequency of 10 Hz.

Scenario description

In this evaluation, we focus on the traffic efficiency and safety of individual vehicles performing cooperative driving maneuvers. Hence, we consider a scenario with three vehicles to avoid interference from other vehicles. For reference, the vehicle notation in the following refers to Figure 38. In the considered scenarios, vehicles 1 and 3 approach the intersection on ROUTE 3 and vehicle 2 approaches the intersection on ROUTE 2. All vehicles initially drive with a velocity of 8.33 m/s and the vehicle's maximum deceleration is limited to $-10\,\mathrm{m/s^2}$. Without coordinating a cooperative maneuver, vehicles 1 and 2 will arrive simultaneously in the intersection. Furthermore, vehicle 3 leaves the intersection before vehicle 1 and 2 enter it. Hence, vehicle 2 requires coordinating a cooperative maneuver with vehicle 1. After agreeing on the cooperative maneuver, vehicle 1 opens a sufficiently large gap for vehicle 2 to its preceding vehicle 3.

Traffic efficiency scenario

We consider the following two scenarios. In the first scenario, we focus on the minimum velocity of vehicle 1 while coordinating a cooperative maneuver for different communication qualities. A decreased minimum velocity indicates high cooperation costs for vehicle 1, negatively impacting its traffic efficiency. Our presented AWARE approach adapts the cooperative maneuvers to the assessed communication quality and increases the safety margin to other vehicles in scenarios with impaired communication quality. In the evaluation, we analyze to which extent the velocity of vehicle

1 must be decreased to offer cooperation in scenarios with impaired communication quality compared to the reference approaches.

Traffic safety scenario

The second scenario is similar to the first scenario, where vehicle 1 offers vehicle 2 cooperation. However, in the second scenario, vehicle 3 interferes with the cooperative maneuver because of an emergency in the intersection. After recognizing the emergency, vehicle 3 immediately informs other vehicles with MCMs, decelerates with the maximum deceleration of $-10\,\mathrm{m/s^2}$ (cf. Case 3 in Equation 46), and blocks the intersection. Consequently, after receiving an emergency MCM of vehicle 3, vehicle 1 and 2 abort the cooperation and stop before the intersection to prevent a collision with vehicle 3. For a low PDR, the time until vehicle 1 and 2 reliably receive a message from vehicle 3 increases. In the evaluation, we analyze to which extent our presented approach maintains traffic safety in scenarios with impaired communication qualities compared to the reference approaches. We measure the traffic safety using the collision velocity of vehicle 2. If vehicle 2 cannot stop before the intersection, the collision velocity denotes the vehicle's velocity at the time of the collision with vehicle 3. Traffic safety is maintained if the collision velocity is $0\,\mathrm{m/s}$, i. e., the collision was mitigated.

Reference approaches

We consider cooperative driving with a velocity-dependent safety margin to other vehicles as reference approaches. We use a safety time of $0\,\mathrm{s}$, $1\,\mathrm{s}$, and $2\,\mathrm{s}$, where the reference approaches are denoted as M-0, M-1, and M-2, respectively. The reference approaches maintain a safety margin to other vehicles using the respective safety time multiplied by the vehicle's current velocity. A safety time of $0\,\mathrm{s}$ is a theoretical example and used as an upper bound for the traffic efficiency gain of cooperative driving.

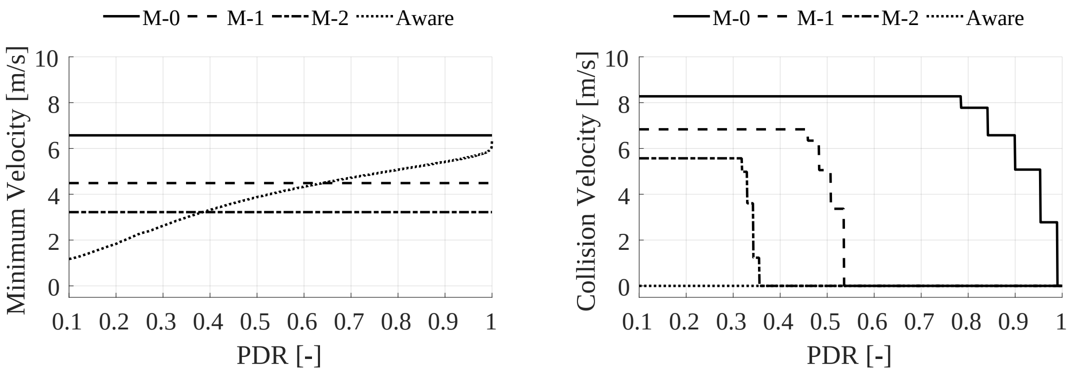
7.5.2 *Numerical Analysis*

A key design parameter of the Aware approach is the considered probability to receive at least one message. Using a small probability to receive at least one message decreases the assessed peak AoI and, therewith, the safety margin to other vehicles. Hence, the traffic efficiency gain of the Aware approach increases for a small probability to receive at least one message. However, a small probability to receive at least one message also decreases the robustness to message loss, potentially affecting traffic safety of vehicles in critical scenarios. In the following, we perform numerical analysis to understand the behavior of the approaches for different communication qualities and the considered probability to receive at least one message in a controlled environment.

Robustness to message loss

We first analyze the traffic efficiency scenario, focusing on the minimum velocity of vehicle 1. Hence, we analyze to which extent the Aware approach decreases the velocity of vehicle 1 compared to the reference approaches.

After that, we analyze the traffic safety scenario, focusing on the collision velocity of vehicle 2. To avoid a collision in the intersection, vehicle 2 must receive at least one message of vehicle 3 informing about its emergency. For a fair comparison in the numerical analysis, vehicle 2 must receive a message of vehicle 3 with a probability of 0.9999 before aborting the cooperation. In Section A.3, we compare the approaches for a probability of 0.9 and 0.99 to receive at least one message. Figure 39 depicts the traffic efficiency and safety scenario analysis.



(a) Efficiency analysis of vehicle 1.

(b) Safety analysis of vehicle 2.

Figure 39: Numerical analysis of a traffic safety and efficiency scenario for cooperative driving at an intersection.

Traffic Efficiency

First, we focus on the traffic efficiency scenario, where the results are depicted in Figure 39a. The safety margins of the reference approaches only depend on their respective safety time and the vehicle's velocity. Figure 39a depicts a minimum velocity of 6.57 m/s, 4.49 m/s, and 3.22 m/s for M-0, M-1, M-2, respectively. As the reference approaches do not consider the PDR, the minimum velocity is independent of the PDR. In this scenario, vehicle 1 must reduce its velocity to the mentioned values to offer vehicle 2 cooperation. The velocity of vehicle 1 decreases with the safety time of the respective approach, increasing the costs for the cooperative maneuver. In contrast, the Aware approach adapts the cooperative maneuver to the assessed AoI obtained from the PDR. For a PDR of 0.1, the Aware approach achieves a minimum velocity of 1.18 m/s to provide a sufficiently large safety margin to vehicle 3. Notably, the Aware approach requires a significantly larger safety margin to other vehicles for a low PDR compared to the reference approaches. However, the Aware approach increases the traffic efficiency compared to the M-2 approach for a PDR higher than 0.39 and the M-1 approach for a PDR higher than 0.64. For a PDR of 1.0, the Aware approach achieves a minimum velocity of 6.35 m/s. In contrast, the M-0 approach achieves a minimum velocity of 6.57 m/s, independent of the PDR. The Aware approach cannot achieve the traffic efficiency gain of the M-0 approach because the AoI is lower bounded by the maximum message frequency of 10 Hz, resulting in a minimum safety time of 100 ms for a PDR of 1.0.

Adapting to the assessed AoI

Performance limitations of the Aware approach

In summary, we conclude that the Aware approach decreases the traffic efficiency of vehicles coordinating a cooperative maneuver to increase the safety margin between vehicles. However, the Aware approach increases traffic efficiency in scenarios with high communication quality, outperforming a static safety margin of 1 s and 2 s for a PDR above 0.64 and 0.39, respectively.

Traffic Safety

Figure 39b depicts the results of the traffic safety scenario. We assume that vehicle 1 and 2 adapt to the emergency of vehicle 3 if they have received at least one MCM of vehicle 3 with a probability of 0.9999, where we consider the requirements of traffic efficiency applications summarized in Table 2. Figure 39b shows that the reference approaches cannot maintain safety for low PDRs. For the M-0 approach, vehicle 2 collides in the intersection with a velocity of 8.28 m/s below a PDR of 0.78. Here, vehicle 2 has not received an MCM of vehicle 3, informing about its emergency before entering the intersection. For a higher PDR, the collision velocity of vehicle 2 decreases similar to a step function. According to Equation 26, the probability to receive at least one message increases with the PDR and the number of sent messages. In the considered safety scenario, a collision is mitigated if vehicle 2 can directly adapt to vehicle 3's emergency, i. e., requires less messages sent by vehicle 3 to receive at least one message reliably. In Figure 39b, the collision velocity is decreased for each message cycle vehicle 2 receives an emergency MCM earlier. In this context, the PDR must exceed a certain threshold such that vehicle 2 reliably receives an emergency MCM earlier. For the M-0 approach, a collision is only mitigated for a PDR of 1.0.

For the M-2 and M-1 approaches, traffic safety is maintained above a PDR of 0.35 and 0.54, respectively. In contrast to the reference approaches, the AWARE approach maintains traffic safety for all considered PDRs and outperforms M-0, M-1, and M-2 for a PDR lower than 1.0, 0.54, and 0.35, respectively.

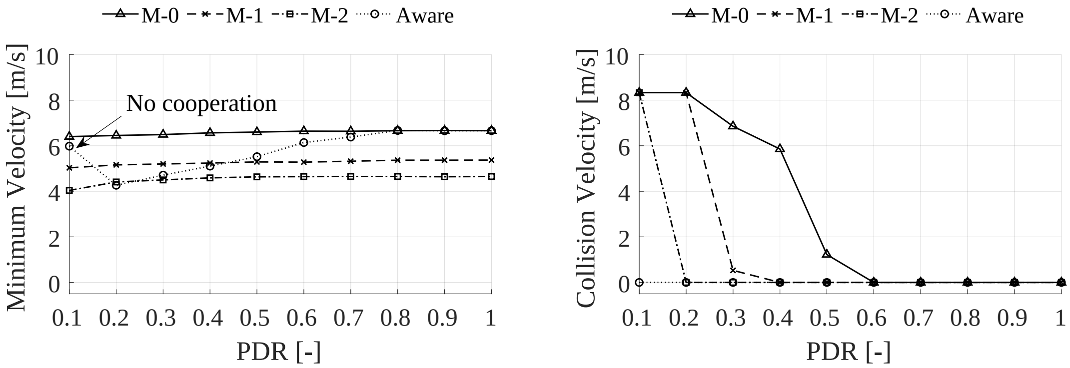
Adapting to the PDR

In Section A.3, we present an extended numerical analysis for different probabilities to receive at least one message. The evaluation shows that the traffic efficiency of the AWARE approach is significantly increased for a probability to receive at least one message of 0.9 and 0.99. Hence, the AWARE approach achieves a minimum velocity of 2.95 m/s and 1.78 m/s, respectively, for a PDR of 0.1. However, a lower probability to receive at least one message also decreases the message loss robustness.

In summary, our presented AWARE approach provides traffic safety in scenarios with unreliable communication by adapting the cooperative maneuver to the assessed communication quality.

7.5.3 *Simulation Analysis*

In the following, we evaluate the performance of the AWARE approach in simulations. In simulations, we use the considered PDR as an input for our model-based AoI assessment because the PDR is assumed to remain constant over time and distance in this analysis. Similar to the numerical analysis, the reference approaches increase the safety margin to other vehicles based on their current velocity and the respective safety time. Figure 40 depicts the analysis for the traffic efficiency and safety scenario in simulations.



(a) Median minimum velocity of vehicle 1.

(b) 97.5th percentile of the collision velocity of vehicle 2 .

Figure 40: Simulation analysis of a traffic safety and efficiency scenario for cooperative driving at an intersection.

Traffic Efficiency

First, we focus on the traffic efficiency scenario. Similar to the numerical analysis, we analyze the minimum velocity of vehicle 1, which offers vehicle 2 cooperation. The markers in Figure 40a show the median minimum velocity of vehicle 1 over 30 simulation runs for a PDR between 0.1 and 1.0. Similar to our numerical results, we observe that the PDR only marginally affects the reference approaches. The approaches only adapt the safety margin to other vehicles based on the safety time and vehicle velocity. For a PDR of 0.1, the M-0 approach achieves a median minimum velocity of 6.40 m/s and increases to 6.67 m/s for a PDR of 1.0. The minimum velocity increases with the PDR because MCMs required to coordinate a cooperative maneuver are received more reliably, allowing for an earlier and, thus, more efficient coordination.

Early and reliable coordination

The M-1 approach achieves a lower median minimum velocity of 5.03 m/s for a PDR of 0.1 compared to the M-0 approach. Furthermore, the M-2 approach achieves a median minimum velocity of 4.04 m/s for the same PDR. For a PDR of 1.0, the median minimum velocity increases to 5.37 m/s and 4.65 m/s for the M-1 and M-2 approaches, respectively. Notably, the Aware approach achieves a median minimum velocity of 5.98 m/s for a PDR of 0.1. For a PDR of 0.1, the cooperative maneuver between vehicles 1 and 2 cannot be coordinated because of the impaired communication quality and the required safety margin to vehicle 3 to turn left safely in the intersection. That is, vehicle 2 has a trajectory conflict with vehicle 3 until arriving in the intersection. Therefore, the requesting vehicle 2 stops in the intersection and waits for vehicles 1 and 3 to pass the intersection. For a PDR higher than 0.1, cooperative maneuvers are successfully performed using the Aware approach. For a PDR of 0.2, the Aware approach achieves a median minimum velocity of 4.26 m/s, which is lower compared to the M-2 approach. The Aware approach achieves a higher median minimum velocity of 4.71 m/s and 5.52 m/s compared to the M-2 and M-0 approaches for a PDR higher than 0.3 and 0.5, respectively. We achieve comparable performance to the M-0 approach for a PDR of

0.8 with a median minimum velocity of 6.67 m/s. That is, for a high communication quality, the AWARE approach significantly increases traffic efficiency.

Traffic Safety

In the following, we analyze the traffic safety scenario, where vehicle 3 unexpectedly decelerates in the intersection because of an emergency. For this purpose, we extend our maneuver planning module and, more specifically, the trajectory assignment in the cooperation logic. After vehicle 3 has entered the intersection, the cooperation logic assigns an emergency trajectory as the planned trajectory for maneuver execution. For vehicle 3, an emergency trajectory is assigned 2 s after entering the intersection. That way, vehicle 3 blocks the intersection after decelerating to a standstill such that vehicle 2 cannot turn left in the intersection.

Unexpected behavior modeling

Figure 40b compares the traffic safety performance of the approaches. Similar to the numerical analysis, we report the collision velocity of the requesting vehicle 2. The markers in Figure 40b show the 97.5th percentile of the collision velocity over 30 simulation runs for a PDR between 0.1 and 1.0. Traffic safety is maintained for a collision velocity of 0 m/s.

Severe vehicle collisions

We observe that the M-0 approach has collisions up to a PDR of 0.6. For a PDR below 0.2, vehicle 2 does not receive an emergency MCM of vehicle 3 and, hence, collides with the maximum vehicle velocity of 8.33 m/s. The reason is that a safety time of 0 s does not allow reacting to unexpected events in time if the communication quality is insufficient. In contrast, the M-1 approach shows higher robustness to impaired communication quality and mitigates collisions up to a PDR of 0.4. However, we observe severe collisions with the maximum vehicle velocity for a PDR below 0.2. The M-2 approach mitigates collisions above a PDR of 0.1.

Similar to the numerical analysis, we observe no collision for the AWARE approach in Figure 40b. Hence, the AWARE approach maintains safety even in scenarios with impaired communication quality. Notably, if a higher probability to receive at least one message than 0.9999 is required, we also need to increase the trajectory's time horizon. A probability of 0.9999 to receive at least one message with a PDR of 0.1 leads to a peak AoI of approximately 8.84 s, almost exceeding the trajectory's time horizon. Hence, for a higher message loss robustness, the trajectory's time horizon must be increased for the AWARE approach.

Adapting the time horizon

In summary, in our numerical and simulation evaluation, we have shown the importance of considering communication quality to coordinate cooperative driving maneuvers. Our evaluation shows that communication-aware cooperative driving is superior to the reference approaches, providing higher traffic efficiency in scenarios with high communication quality and maintaining traffic safety in scenarios with impaired communication quality.

Vehicle dynamics simulators

In future work, different scenarios with significantly more simulation runs must be investigated to further analyze traffic efficiency and safety for cooperative driving considering impaired communication quality. Additionally, our CoDA.KOM framework uses the traffic simulator SUMO. Future work should also consider vehicle dynamics simulators to evaluate traffic safety.

In summary, we showed that our relevance-aware resource allocation and adaptive data dissemination strategy increase the communication quality in highly congested channels for cooperative driving. Furthermore, we demonstrated the need for communication-aware cooperative driving to adapt cooperative maneuvers to the available communication quality to increase traffic efficiency and maintain safety on the road.

8 SUMMARY, CONCLUSIONS, AND OUTLOOK

Finally, we conclude our work by summarizing the content of the previous chapters and highlighting our main contributions. We link our evaluation results to our identified research challenges to draw final conclusions in the scope of this thesis. In the end, we outline open issues and indicate potential future work.

8.1 SUMMARY OF THE THESIS

In Chapter 1, we identified the challenges for cooperative driving from the Vehicle-to-Everything (V2X) communication perspective. We motivated the need for relevance-aware V2X network adaptations and communication-aware cooperative driving in scenarios with high vehicle density. Chapter 2 identified and compared the applicability of different V2X access technologies for cooperative driving based on our communication requirements analysis. We discussed existing cooperative driving mechanisms and message protocols and identified relevant approaches to maintain traffic safety under impaired communication quality conditions. Additionally, we studied existing mechanisms for V2X network adaptations and their applicability to cooperative driving, focusing on resource allocation and heterogeneous V2X communication. In our problem formulation in Chapter 3, we discussed factors for communication quality impairment in V2X networks. Furthermore, we analyzed the effects of impaired communication quality on the cooperative driving performance. Consequently, we introduced necessary components from the V2X communication perspective to coordinate cooperative maneuvers safely and efficiently. Based on the identified research gaps and problem formulation, we summarize our research contributions of this thesis in the following.

8.1.1 *Contributions*

The foundation of this thesis is the communication quality and information relevance assessment in decentralized V2X networks, constituting our *first contribution* in Chapter 4. Communication quality and information relevance assessment is required for relevance-aware V2X network adaptations and communication-aware cooperative driving. In this context, we derived a numerical model to assess radio propagation and medium access effects for the IEEE 802.11p access technology. We analyzed the computational complexity of our approach and proposed an approximated model with low computational complexity for communication quality assessment in decentralized V2X networks. Thereupon, we introduced a measurement- and model-based approach to assess the Age of Information (AoI) in decentralized V2X networks. Additionally, we addressed the challenge of information relevance assessment for cooperative driv-

V2X quality assessment

Information relevance

ing. Based on previous results related to the vehicles' *instantaneous approaching times* targeting the V2X applications *collective perception*, we proposed the Perceived Awareness over Time Horizon (PATH) for *cooperative driving*. The PATH obtains the vehicle's relevance to coordinate a cooperative maneuver, assigning more relevance to critical maneuvers. Finally, we linked the PATH to the information relevance of a Maneuver Coordination Message (MCM). Our design allows predicting the communication quality and information relevance for an upcoming cooperative maneuver.

Relevance-aware resource allocation

In Chapter 5 and based on our communication quality and information relevance assessment, we proposed our *second contribution*. We presented V2X network adaptations to improve communication quality in scenarios with high vehicle density. In this context, we introduced the network's Accessible Information Relevance (AIR), which quantifies the perceived information relevance in a decentralized V2X network. Based on our definition of the network's AIR, we derived an optimization problem to enable relevance-aware resource allocation in decentralized V2X networks. Messages of vehicles with high information relevance are prioritized over messages of vehicles with low information relevance in congested V2X channels. Furthermore, we proposed our adaptive data dissemination strategy using heterogeneous V2X access technologies to enable early and reliable coordination of cooperative driving maneuvers. Our approach uses GEOCAST communication to extend the communication range of decentralized Vehicle-to-Vehicle (V2V) communication with centralized Vehicle-to-Network (V2N) communication for vehicles requiring to coordinate cooperative maneuvers. While coordinating a cooperative maneuver, our approach additionally uses cellular V2N UNICAST communication if the communication quality of decentralized V2V communication is insufficient.

Heterogeneous data dissemination

Adaptive cooperative driving

Our *third contribution* adapts cooperative driving to physical constraints of the V2X communication quality. We analyzed traffic safety of cooperative driving under impaired communication quality conditions and suggested communication-aware cooperative driving, based on the model-based assessment of the AoI in Chapter 4. Our approach forms a general framework for trajectory-based cooperative driving and adapts the safety margins of vehicles to the assessed AoI. In scenarios with impaired communication quality, our approach increases the safety margins between coordinating vehicles to increase the reaction time for unexpected events.

Evaluation framework

Finally, we presented our simulation framework CoDA.KOM in Chapter 6, which supports heterogeneous V2X access technologies, offers a generic interface for V2X applications, and provides a SIMPLE and REALISTIC channel model to consider radio propagation effects. Moreover, we discussed our prototypical realization of the cooperative driving application left-turning at an intersection, where we explain the coordination and execution of cooperative maneuvers in detail. The CoDA.KOM framework and our contributions for relevance-aware V2X network adaptations and communication-aware cooperative driving present the foundation of our evaluation in Chapter 7.

8.1.2 *Conclusions*

We assessed the performance of our contributions in a numerical and simulation evaluation to analyze the effects of relevance-aware V2X network adaptations and communication-aware cooperative driving. We showed that our relevance-aware resource allocation prioritizes relevant information in congested decentralized V2X networks. Moreover, we improve the coordination of cooperative maneuvers from the communication perspective to maintain safety and increase efficiency on the road. Consequently, by implementing our approaches in V2X-enabled vehicles with cooperative driving, our contributions adapt to highly dynamic network conditions. That way, our approach increases the impaired communication quality robustness for cooperative driving.

V2X model validation

We validated our proposed numerical model for communication quality assessment with simulations, showing high similarity of the Channel Busy Ratio (CBR), Packet Delivery Ratio (PDR), normalized throughput, and AoI.

Prioritizing relevant information

In a numerical and simulation evaluation, we analyzed the performance of our novel relevance-aware resource allocation approach in decentralized V2X networks. Our approach optimizes the network's AIR by adapting the vehicle's message frequency to the assessed information relevance and message frequency of other vehicles in a decentralized V2X network. We showed that optimizing the network's AIR improves the AoI of vehicles with relevant information in congested channels compared to reference approaches. Furthermore, we showed that the limited communication range of V2V networks does not allow for early coordination of cooperative maneuvers. Our adaptive data dissemination strategy increases the communication range and communication quality of coordinating vehicles, improving traffic efficiency in an intersection scenario compared to V2V communication.

Combining V2X access technologies

Finally, in Section 7.5, we showed in a numerical and simulation evaluation that communication-unaware cooperative driving negatively affects traffic safety and can lead to severe vehicle collisions when coordinating cooperative maneuvers in scenarios with impaired communication quality. More precisely, we specifically analyzed traffic efficiency and safety performance of cooperative driving in an urban intersection with different communication qualities and compared our proposed approach with communication-unaware approaches. Our evaluation results show that our approach provides high traffic efficiency in scenarios with high communication quality. Our approach increases the safety margins between vehicles in scenarios with impaired communication quality. In contrast to the reference approaches, we showed that our approach maintains traffic safety even in a scenario where the cooperation needs to be canceled because of an unexpected event.

8.2 OUTLOOK

The contributions in this thesis improve the V2X communication and application performance significantly and motivate the extension to other V2X networks and application use cases. Our numerical model for communication quality assessment can be extended to enable relevance-aware resource allocation for other V2X access

5G New Radio

technologies, despite the IEEE 802.11p as presented in this thesis. In this context, the 3GPP 5G-NR with relevance-aware resource allocation offers great potential to improve the communication quality for cooperative driving.

V2X applications supporting autonomous driving

Given the limited channel resources in V2X networks and the increasing number of V2X applications supporting traffic safety and efficiency, the need for relevance-aware resource allocation increases, paving the way towards autonomous driving. In this work, we focused on the assessment of information relevance for cooperative driving. However, for other V2X applications, e. g., collective perception, a different information relevance assessment is required. Moreover, if these applications operate in the same channel, an information relevance weighting of different V2X applications needs to be considered.

In addition, we focused on the cooperative driving use case left-turning at an intersection. As highlighted in this thesis, our adaptive data dissemination strategy and communication-aware cooperative driving can be applied to other cooperative driving use cases such as merging on highways and, in general, to autonomous driving.

Functional safety

Lastly, we evaluated our communication-aware approach for cooperative driving concerning traffic efficiency and safety. Our evaluation concept can be extended to represent the Automotive Safety Integration Level (ASIL) of ISO 26262 [109]. Communication-aware cooperative driving presented in this thesis allows to maintain traffic safety by decreasing efficiency in scenarios with impaired communication quality. The resulting lower severity rating because of a reduced vehicle collision probability presents a promising opportunity to decrease the ASIL rating of cooperative driving. Consequently, the required functional safety validation effort for the vehicle manufacturer and suppliers can be reduced.

Our contributions for trajectory-based communication quality and information relevance assessment and their applicability to relevance-aware V2X network adaptations and communication-aware adaptations are the foundations for safe and efficient cooperative driving and enable further research in this area.

ACKNOWLEDGMENTS

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[1] 5G. *Service Requirements for Enhanced V2X Scenarios (3GPP TS 22.186 Version 16.2.0 Release 16)*. Technical Specification TS 122 186. V16.2.0. European Telecommunications Standards Institute (ETSI), Nov. 2020.

[2] Fakhar Abbas, Pingzhi Fan, and Zahid Khan. "A Novel Low-Latency V2V Resource Allocation Scheme Based on Cellular V2X Communications." In: *IEEE Transactions on Intelligent Transportation Systems* 20.6 (2019), pp. 2185–2197. DOI: `10.1109/TITS.2018.2865173`.

[3] Mohamed K. Abdel-Aziz, Sumudu Samarakoon, Mehdi Bennis, and Walid Saad. "Ultra-Reliable and Low-Latency Vehicular Communication: An Active Learning Approach." In: *IEEE Communications Letters* 24.2 (2020), pp. 367–370. DOI: `10.1109/LCOMM.2019.2956929`.

[4] Mahmoud A. Alawi, Rashid. A. Saeed, and Aisha A. Hassan. "Cluster-Based Multi-Hop Vehicular Communication with Multi-Metric Optimization." In: *2012 International Conference on Computer and Communication Engineering (ICCCE)*. IEEE. 2012, pp. 22–27. DOI: `10.1109/ICCCE.2012.6271145`.

[5] Christoph Allig and Gerd Wanielik. "Dynamic Dissemination Method for Collective Perception." In: *2019 IEEE Intelligent Transportation Systems Conference (ITSC)*. IEEE. 2019, pp. 3756–3762. DOI: `10.1109/ITSC.2019.8917266`.

[6] Akram A. Almohammedi, Nor K. Noordin, Aduwati Sali, Fazirulhisyam Hashim, and Sabri Saeed. "A Comprehensive Performance Analysis of IEEE 802.11p Based MAC for Vehicular Communications Under Non-Saturated Conditions." In: *Journal of ICT Research and Applications* 11.1 (2017), pp. 1–22. DOI: `10.5614/itbj.ict.res.appl.2017.11.1.6`.

[7] Aljawharah Alnasser, Hongjian Sun, and Jing Jiang. "Cyber Security Challenges and Solutions for V2X Communications: A Survey." In: *Computer Networks* 151 (2019), pp. 52–67. DOI: `10.1016/j.comnet.2018.12.018`.

[8] Zubair Amjad, Axel Sikora, Benoit Hilt, and Jean-Philippe Lauffenburger. "Low Latency V2X Applications and Network Requirements: Performance Evaluation." In: *2018 IEEE Intelligent Vehicles Symposium (IV)*. IEEE. 2018, pp. 220–225. DOI: `10.1109/IVS.2018.8500531`.

[9] Silvia Ancona, Razvan Stanica, and Marco Fiore. "Performance Boundaries of Massive Floating Car Data Offloading." In: *2014 11th Annual Conference on Wireless On-Demand Network Systems and Services (WONS)*. IEEE. 2014, pp. 89–96. DOI: `10.1109/WONS.2014.6814727`.

[10] Konstantinos Antonakoglou, Nadia Brahmi, Taimoor Abbas, Antonio Eduardo Fernandez Barciela, Mate Boban, Kai Cordes, Mikael Fallgren, Laurent Gallo, Apostolos Kousaridas, Zexian Li, et al. "On the Needs and Requirements Arising from Connected and Automated Driving." In: *Journal of Sensor and Actuator Networks* 9.2 (2020), p. 24. DOI: 10.3390/jsan9020024.

[11] Fabio Arena and Giovanni Pau. "An Overview of Vehicular Communications." In: *Future Internet* 11.2 (2019), p. 27. DOI: 10.3390/fi11020027.

[12] Sergei S. Avedisov, Chin-Wei Lin, Tamás G. Molnár, Onur Altintas, Ahmed H. Sakr, and Gábor Orosz. "Perceived Safety: A New Metric for Evaluating Safety Benefits of Collective Perception for Connected Road Users." In: *2020 IEEE Vehicular Networking Conference (VNC)*. IEEE. 2020, pp. 1–4. DOI: 10.1109/VNC51378.2020.9318360.

[13] Andrea Baiocchi and Ion Turcanu. "A Model for the Optimization of Beacon Message Age-of-Information in a VANET." In: *2017 29th International Teletraffic Congress (ITC 29)*. IEEE. 2017, pp. 108–116. DOI: 10.23919/ITC.2017.8064345.

[14] Luca Baldesi, Leonardo Maccari, and Renato Lo Cigno. "Keep It Fresh: Reducing the Age of Information in V2X Networks." In: *Proceedings of the 1st ACM MobiHoc Workshop on Technologies, MOdels, and Protocols for Cooperative Connected Cars*. ACM. 2019, pp. 7–12. DOI: 10.1145/3331054.3331547.

[15] Gaurav Bansal, John B. Kenney, and Charles E. Rohrs. "LIMERIC: A Linear Adaptive Message Rate Algorithm for DSRC Congestion Control." In: *IEEE Transactions on Vehicular Technology* 62.9 (2013), pp. 4182–4197. DOI: 10.1109/TVT.2013.2275014.

[16] Gaurav Bansal, Hongsheng Lu, John B. Kenney, and Christian Poellabauer. "EMBARC: Error Model Based Adaptive Rate Control for Vehicle-to-Vehicle Communications." In: *Proceeding of the Tenth ACM International Workshop on Vehicular Inter-Networking, Systems, and Applications*. ACM. 2013, pp. 41–50. DOI: 10.1145/2482967.2482972.

[17] Basel Barakat, Hachem Yassine, Simeon Keates, Ian Wassell, and Kamran Arshad. "How to Measure the Average and Peak Age of Information in Real Networks?" In: *European Wireless 2019; 25th European Wireless Conference*. IEEE. 2019, pp. 1–5.

[18] Alessandro Bazzi. "Congestion Control Mechanisms in IEEE 802.11p and Sidelink C-V2X." In: *2019 53rd Asilomar Conference on Signals, Systems, and Computers*. IEEE. 2019, pp. 1125–1130. DOI: 10.1109/IEEECONF44664.2019.9048738.

[19] Alessandro Bazzi, Claudia Campolo, Barbara M. Masini, and Antonella Molinaro. "How to Deal with Data Hungry V2X Applications?" In: *Proceedings of the Twenty-First International Symposium on Theory, Algorithmic Foundations, and Protocol Design for Mobile Networks and Mobile Computing*. ACM. 2020, pp. 333–338. DOI: 10.1145/3397166.3413465.

[20] Alessandro Bazzi, Barbara M. Masini, Alberto Zanella, and Ilaria Thibault. "Beaconing from Connected Vehicles: IEEE 802.11p vs. LTE-V2V." In: *2016 IEEE 27th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*. IEEE. 2016, pp. 1–6. DOI: 10.1109/PIMRC.2016.7794598.

[21] Alessandro Bazzi, Barbara M. Masini, Alberto Zanella, and Ilaria Thibault. "On the Performance of IEEE 802.11p and LTE-V2V for the Cooperative Awareness of Connected Vehicles." In: *IEEE Transactions on Vehicular Technology* 66.11 (2017), pp. 10419–10432. DOI: 10.1109/TVT.2017.2750803.

[22] Abderrahim Benslimane, Tarik Taleb, and Rajarajan Sivaraj. "Dynamic Clustering-Based Adaptive Mobile Gateway Management in Integrated VANET; 3G Heterogeneous Wireless Networks." In: *IEEE Journal on Selected Areas in Communications* 29.3 (2011), pp. 559–570. DOI: 10.1109/JSAC.2011.110306.

[23] Laura Bernadó, Thomas Zemen, Fredrik Tufvesson, Andreas F. Molisch, and Christoph F. Mecklenbräuker. "Delay and Doppler Spreads of Nonstationary Vehicular Channels for Safety-Relevant Scenarios." In: *IEEE Transactions on Vehicular Technology* 63.1 (2014), pp. 82–93. DOI: 10.1109/TVT.2013.2271956.

[24] Yougang Bian, Shengbo Eben Li, Wei Ren, Jianqiang Wang, Keqiang Li, and Henry X. Liu. "Cooperation of Multiple Connected Vehicles at Unsignalized Intersections: Distributed Observation, Optimization, and Control." In: *IEEE Transactions on Industrial Electronics* 67.12 (2019), pp. 10744–10754. DOI: 10.1109/TIE.2019.2960757.

[25] Giuseppe Bianchi. "Performance Analysis of the IEEE 802.11 Distributed Coordination Function." In: *Journal on Selected Areas in Communications* 18.3 (2000), pp. 535–547. DOI: 10.1109/49.840210.

[26] Daniel Bischoff, Harald Berninger, Steffen Knapp, Tobias Meuser, Björn Richerzhagen, Lars Häring, and Andreas Czylwik. "Safety-Relevant V2X Beaconing in Realistic and Scalable Heterogeneous Radio Propagation Fading Channels." In: *5th International Conference on Vehicle Technology and Intelligent Transport Systems (VEHITS 19)*. Scitepress. 2019, pp. 1–8. DOI: 10.5220/0007712904040411.

[27] Daniel Bischoff and Tobias Meuser. "Geo-Based Backend Dissemination for Safety-Relevant V2X Applications." In: *AmE 2019 - Automotive meets Electronics; 10th GMM-Symposium*. IEEE. 2019, pp. 1–6.

[28] Daniel Bischoff, Florian Schiegg, Tobias Meuser, Dieter Schuller, Nils Dycke, and Ralf Steinmetz. "What Cooperation Costs: Quality of Communication and Cooperation Costs for Cooperative Vehicular Maneuvering in Large-Scale Scenarios." In: *Proceedings of the 6th International Conference on Vehicle Technology and Intelligent Transport Systems (VEHITS 20)*. Scitepress. 2020, pp. 394–405.

[29] Daniel Bischoff, Florian Schiegg, Tobias Meuser, and Ralf Steinmetz. "Impact of Imperfect Communication on Cooperative Vehicular Maneuvering at Intersections." In: *2020 IEEE 91th Vehicular Technology Conference (VTC Spring)*. IEEE. 2020, pp. 1–5. DOI: 10.1109/VTC2020-Spring48590.2020.9128485.

[30] Daniel Bischoff, Florian A. Schiegg, Tobias Meuser, Dieter Schuller, and Ralf Steinmetz. "Adaptive Heterogeneous V2X Communication for Cooperative Vehicular Maneuvering." In: *Smart Cities, Green Technologies, and Intelligent Transport Systems*. Ed. by Cornel Klein, Markus Helfert, Karsten Berns, and Oleg Gusikhin. Springer. Cham: Springer International Publishing, 2021, pp. 228–254. DOI: 10.1007/978-3-030-89170-1_12.

[31] Daniel Bischoff, Florian A. Schiegg, Dieter Schuller, Jens Lemke, Benjamin Becker, and Tobias Meuser. "Prioritizing Relevant Information: Decentralized V2X Resource Allocation for Cooperative Driving." In: *IEEE Access* (2021), pp. 135630–135656. DOI: 10.1109/ACCESS.2021.3116317.

[32] Mate Boban, Apostolos Kousaridas, Konstantinos Manolakis, Josef Eichinger, and Wen Xu. "Connected Roads of the Future: Use Cases, Requirements, and Design Considerations for Vehicle-to-Everything Communications." In: *IEEE Vehicular Technology Magazine* 13.3 (2018), pp. 110–123. DOI: 10.1109/MVT.2017.2777259.

[33] Mate Boban, Konstantinos Manolakis, Mohamed Ibrahim, Samer Bazzi, and Wen Xu. "Design Aspects for 5G V2X Physical Layer." In: *2016 IEEE Conference on Standards for Communications and Networking (CSCN)*. IEEE. 2016, pp. 1–7. DOI: 10.1109/CSCN.2016.7785161.

[34] Mate Boban, Tiago Vinhoza, Michel Ferreira, Joao Barros, and Ozan K. Tonguz. "Impact of Vehicles as Obstacles in Vehicular Ad Hoc Networks." In: *Journal on Selected Areas in Communications* 29.1 (2011), pp. 15–28. DOI: 10.1109/JSAC.2011.110103.

[35] Amal Bouaziz, Ahlem Saddoud, Lamia Chaari Fourati, and Hakima Chaouchi. "Adaptive V2X User Selection and Resource Allocation for Ultra-Dense 5G HetNet Network." In: *2021 International Wireless Communications and Mobile Computing (IWCMC)*. IEEE. 2021, pp. 1454–1459. DOI: 10.1109/IWCMC51323.2021.9498912.

[36] Gabriel Rodrigues de Campos, Paolo Falcone, and Jonas Sjöberg. "Autonomous Cooperative Driving: A Velocity-Based Negotiation Approach for Intersection Crossing." In: *16th International IEEE Conference on Intelligent Transportation Systems (ITSC 2013)*. IEEE. 2013, pp. 1456–1461. DOI: 10.1109/ITSC.2013.6728435.

[37] Giammarco Cecchini, Alessandro Bazzi, Barbara M. Masini, and Alberto Zanella. "Performance Comparison between IEEE 802.11p and LTE-V2V In-Coverage and Out-of-Coverage for Cooperative Awareness." In: *2017 IEEE Vehicular Networking Conference (VNC)*. IEEE. 2017, pp. 109–114. DOI: 10.1109/VNC.2017.8275637.

[38] Chen Chen, Jinna Hu, Tie Qiu, Mohammed Atiquzzaman, and Zhiyuan Ren. "CVCG: Cooperative V2V-Aided Transmission Scheme Based on Coalitional Game for Popular Content Distribution in Vehicular Ad-Hoc Networks." In: *IEEE Transactions on Mobile Computing* 18.12 (2019), pp. 2811–2828. DOI: 10.1109/TMC.2018.2883312.

[39] Gang Chen, Langying Chen, Yizhen Wang, Yixiao Zhang, and Tingting Zhang. "Centralized Vehicle Coordination Strategies Based on Improved Age of Information." In: *2021 International Wireless Communications and Mobile Computing (IWCMC)*. IEEE. 2021, pp. 1105–1110. DOI: `10.1109/IWCMC51323.2021.9498660`.

[40] Maohong Chen, Yong Xiao, Qiang Li, and Kwang-cheng Chen. "Minimizing Age-of-Information for Fog Computing-Supported Vehicular Networks with Deep Q-Learning." In: *ICC 2020 - 2020 IEEE International Conference on Communications (ICC)*. IEEE. 2020, pp. 1–6. DOI: `10.1109/ICC40277.2020.9149054`.

[41] Xianfu Chen, Celimuge Wu, Tao Chen, Honggang Zhang, Zhi Liu, Yan Zhang, and Mehdi Bennis. "Age of Information Aware Radio Resource Management in Vehicular Networks: A Proactive Deep Reinforcement Learning Perspective." In: *IEEE Transactions on Wireless Communications* 19.4 (2020), pp. 2268–2281. DOI: `10.1109/TWC.2019.2963667`.

[42] Lin Cheng, Benjamin E. Henty, Daniel D. Stancil, Fan Bai, and Priyantha Mudalige. "Mobile Vehicle-to-Vehicle Narrow-Band Channel Measurement and Characterization of the 5.9 GHz Dedicated Short Range Communication (DSRC) Frequency Band." In: *IEEE Journal on Selected Areas in Communications* 25.8 (2007), pp. 1501–1516. DOI: `10.1109/JSAC.2007.071002`.

[43] Xiaolu Cheng and Baohua Huang. "A Center-Based Secure and Stable Clustering Algorithm for VANETs on Highways." In: *Wireless communications and mobile computing* 2019 (2019), pp. 1–11. DOI: `10.1155/2019/8415234`.

[44] Elena Cinque, Francesco Valentini, Arianna Persia, Sandro Chiocchio, Fotunato Santucci, and Marco Pratesi. "V2X Communication Technologies and Service Requirements for Connected and Autonomous Driving." In: *2020 AEIT International Conference of Electrical and Electronic Technologies for Automotive (AEIT AUTOMOTIVE)*. IEEE. 2020, pp. 1–6. DOI: `10.23919/AEITAUTOMOTIVE50086.2020.9307388`.

[45] Alejandro Correa, Robert Alms, Javier Gozalvez, Miguel Sepulcre, Michele Rondinone, Robbin Blokpoel, Leonhard Lücken, and Gokulnath Thandavarayan. "Infrastructure Support for Cooperative Maneuvers in Connected and Automated Driving." In: *2019 IEEE Intelligent Vehicles Symposium (IV)*. IEEE. 2019, pp. 20–25. DOI: `10.1109/IVS.2019.8814044`.

[46] Alejandro Correa, Franz Andert, Robbin Blokpoel, Nicolai Wojke, Gokulnath Thandavarayan, Baldomero Coll Perales, Miguel Sepulcre, Javier Gozalvez, Anton Wijbenga, Julian Schindler, et al. *Deliverable 5.2: V2X-Based Cooperative Sensing and Driving in Transition Areas (Second Iteration)*. Project Report Horizon 2020. V2.0. Transition Areas for Infrastructure-Assisted Driving (TransAID), Mar. 2020.

[47] Felipe Cunha, Leandro Villas, Azzedine Boukerche, Guilherme Maia, Aline Viana, Raquel Mini, and Antonio Loureiro. "Data Communication in VANETs: Protocols, Applications and Challenges." In: *Ad Hoc Networks* 44 (2016), pp. 90–103. DOI: `10.1016/j.adhoc.2016.02.017`.

[48] Quentin Delooz and Andreas Festag. “Network Load Adaptation for Collective Perception in V2X Communications.” In: *2019 IEEE International Conference on Connected Vehicles and Expo (ICCVE)*. IEEE. 2019, pp. 1–6. DOI: 10.1109/ICCVE45908.2019.8964988.

[49] Quentin Delooz, Raphael Riebl, Andreas Festag, and Alexey Vinel. “Design and Performance of Congestion-Aware Collective Perception.” In: *2020 IEEE Vehicular Networking Conference (VNC)*. IEEE. 2020, pp. 1–8. DOI: 10.1109/VNC51378.2020.9318335.

[50] Thierry Delot, Nicolas Cenerario, and Sergio Ilarri. “Estimating the Relevance of Information in Inter-Vehicle Ad Hoc Networks.” In: *2008 Ninth International Conference on Mobile Data Management Workshops, MDMW*. IEEE. 2008, pp. 151–158. DOI: 10.1109/MDMW.2008.7.

[51] Jürgen Detlefsen and Uwe Siart. *Grundlagen der Hochfrequenztechnik 3.A.* Oldenbourg Wissenschaftsverlag, 2010. DOI: doi:10.1524/9783486598575. URL: https://doi.org/10.1524/9783486598575.

[52] Dahou Djilali, Youssef. Bakhtil, Belkacem Kouninef, and Benaoumeur Senouci. “Performances Evaluation Study of VANET Communication Technologies for Smart and Autonomous Vehicles.” In: *2018 Tenth International Conference on Ubiquitous and Future Networks (ICUFN)*. IEEE. 2018, pp. 79–84. DOI: 10.1109/ICUFN.2018.8436661.

[53] Falko Dressler, Florian Klingler, Michele Segata, and Renato Lo Cigno. “Cooperative Driving and the Tactile Internet.” In: *Proceedings of the IEEE* 107.2 (2019), pp. 436–446. DOI: 10.1109/JPROC.2018.2863026.

[54] Nils Dreyer, Andreas Moller, Zeeshan Hameed Mir, Fethi Filali, and Thomas Kurner. “A Data Traffic Steering Algorithm for IEEE 802.11p/LTE Hybrid Vehicular Networks.” In: *2016 IEEE 84th Vehicular Technology Conference (VTC-Fall)*. IEEE. 2016, pp. 1–6. DOI: 10.1109/VTCFall.2016.7880850.

[55] Weiqiang Du, Qian Liu, Zhenguo Gao, and Guozhen Tan. “Seamless Vertical Handoff Protocol for LTE-802.11p Hybrid Vehicular Communications over the Tactile Internet.” In: *2018 IEEE International Symposium on Haptic, Audio and Visual Environments and Games (HAVE)*. IEEE. 2018, pp. 1–5. DOI: 10.1109/HAVE.2018.8548055.

[56] Michael During and Karsten Lemmer. “Cooperative Maneuver Planning for Cooperative Driving.” In: *IEEE Intelligent Transportation Systems Magazine* 8.3 (2016), pp. 8–22. DOI: 10.1109/MITS.2016.2549997.

[57] Michael Düring, Kai Franke, Reza Balaghiasefi, Mark Gonter, Markus Belkner, and Karsten Lemmer. “Adaptive Cooperative Maneuver Planning Algorithm for Conflict Resolution in Diverse Traffic Situations.” In: *2014 International Conference on Connected Vehicles and Expo (ICCVE)*. IEEE. 2014, pp. 242–249. DOI: 10.1109/ICCVE.2014.7297550.

[58] Michael Düring and Patrick Pascheka. "Cooperative Decentralized Decision Making for Conflict Resolution Among Autonomous Agents." In: *2014 IEEE International Symposium on Innovations in Intelligent Systems and Applications (INISTA) Proceedings*. IEEE. 2014, pp. 154–161. DOI: 10.1109/INISTA.2014.6873612.

[59] Electronic Communications Committee (ECC). *ECC Decision of 15 March 2002 on the Frequency Bands to be Designated for the Coordinated Introduction of Road Transport and Traffic Telematic Systems*. ECC Decision ECC/DEC/02. (02)01. European Conference of Postal and Telecommunications Administrations (CEPT), Mar. 2002.

[60] Electronic Communications Committee (ECC). *ECC Decision of 02 November 2012 on the Withdrawal of ECC Decision (02)01*. ECC Decision ECC/DEC/12. (12)04. European Conference of Postal and Telecommunications Administrations (CEPT), Nov. 2012.

[61] European Commission. *Total Length of Motorways in Germany from 1990 to 2018 (in Kilometers)*. Available: https://www.statista.com/statistics/449621/germany-timeline-of-total-motorway-length/. [Accessed Aug. 03, 2021]. Nov. 2020.

[62] Jana Fank, Leon Santen, Christian Knies, and Frank Diermeyer. ""Should We Allow Him to Pass?" Increasing Cooperation Between Truck Drivers Using Anthropomorphism." In: *Advances in Human Factors of Transportation*. Springer International Publishing. 2020, pp. 475–484. DOI: 10.1007/978-3-030-20503-4_43.

[63] Federal Ministry of Transport and Digital Infrastructure. *Länge der Straßen des Überörtlichen Verkehrs in Deutschland von 1995 bis 2020*. Available: https://www.statista.com/statistics/449621/germany-timeline-of-total-motorway-length/. [Accessed Aug. 03, 2021]. Nov. 2021.

[64] Federal Motor Transport Authority (KBA). *Number of Registered Cars in Germany from 1960 to 2020*. Available: https://www.statista.com/statistics/587764/number-of-registered-cars-germany/. [Accessed Aug. 03, 2021]. Mar. 2021.

[65] Antonio Eduardo Fernandez, Alain Servel, Jerome Tiphene, Mikael Fallgren, Wanlu Sun, Nadia Brahmi, Erik Ström, Tommy Svensson, Diego Bernardez, Jesus Alonso-Zarate, Apostolos Kousaridas, Mate Boban, Markus Dillinger, Massimo Condoluci, Toktam Mahmoodi, Zexian Li, Juergen Otterbach, Mathieu Lefebvre, Guillaume Vivier, Taimoor Abbas, and Peter Wingård. *Deliverable D2.1 5GCAR Scenarios, Use Cases, Requirements and KPIs*. Project Report 5GCAR. V1.0. Fifth Generation Communication Automotive Research and Innovation (5G PPP), Aug. 2017.

[66] Kai Franke, Mark Gonter, Michael Düring, Karsten Lemmer, Reza Balaghiasefi, and Ferit Kücükay. "A Reference Architecture for CISS/CDAS within the Field of Cooperative Driving." In: *2014 International Conference on Connected Vehicles and Expo (ICCVE)*. IEEE. 2014, pp. 357–363. DOI: 10.1109/ICCVE.2014.7297571.

[67] Harald T. Friis. "A Note on a Simple Transmission Formula." In: *Proceedings of the IRE* 34.5 (1946), pp. 254–256. DOI: 10.1109/JRPROC.1946.234568.

[68] Kaito Furukawa, Mineo Takai, and Susumu Ishihara. "Controlling Sensor Data Dissemination Method for Collective Perception in VANET." In: *2019 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops)*. IEEE. 2019, pp. 753–758. DOI: 10.1109/PERCOMW.2019.8730601.

[69] Julian Garbiso, Ada Diaconescu, Marceau Coupechoux, and Bertrand Leroy. "Dynamic Cluster Size Optimization in Hybrid Cellular-Vehicular Networks." In: *2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC)*. IEEE. 2016, pp. 557–563. DOI: 10.1109/ITSC.2016.7795609.

[70] Keno Garlichs, Caglar Kaya, and Lars Wolf. "Leveraging the Collective Perception Service for CAM Information Aggregation at Intersections." In: *2020 IEEE 92nd Vehicular Technology Conference (VTC2020-Fall)*. IEEE. 2020, pp. 1–5. DOI: 10.1109/VTC2020-Fall49728.2020.9348840.

[71] General German Automobile Club (ADAC). *Germany has Never Seen so Many Traffic Jams*. Available: https://www.statista.com/chart/12695/germany-has-never-seen-so-many-traffic-jams/. [Accessed Aug. 03, 2021]. Jan. 2018.

[72] Muhammad Uzair Ghazi, Muazzam A. Khan Khattak, Balawal Shabir, Asad W. Malik, and Muhammad Sher Ramzan. "Emergency Message Dissemination in Vehicular Networks: A Review." In: *IEEE Access* 8 (2020), pp. 38606–38621. DOI: 10.1109/ACCESS.2020.2975110.

[73] Marco Giordani, Takamasa Higuchi, Andrea Zanella, Onur Altintas, and Michele Zorzi. "A Framework to Assess Value of Information in Future Vehicular Networks." In: *Proceedings of the 1st ACM MobiHoc Workshop on Technologies, MOdels, and Protocols for Cooperative Connected Cars*. ACM. 2019, pp. 31–36. DOI: 10.1145/3331054.3331551.

[74] Marco Giordani, Andrea Zanella, Takamasa Higuchi, Onur Altintas, and Michele Zorzi. "Emerging Trends in Vehicular Communication Networks." In: *Emerging Wireless Communication and Network Technologies: Principle, Paradigm and Performance*. Ed. by Karm Veer Arya, Robin Singh Bhadoria, and Narendra S. Chaudhari. Singapore: Springer Singapore, 2018. Chap. Wireless Technology and CommunicationsExplorations & Trends, pp. 37–57. DOI: 10.1007/978-981-13-0396-8_3. URL: https://doi.org/10.1007/978-981-13-0396-8_3.

[75] Marco Giordani, Andrea Zanella, Takamasa Higuchi, Onur Altintas, and Michele Zorzi. "Investigating Value of Information in Future Vehicular Communications." In: *2019 IEEE 2nd Connected and Automated Vehicles Symposium (CAVS)*. IEEE. 2019, pp. 1–5. DOI: 10.1109/CAVS.2019.8887791.

[76] Manuel Gonzalez-Martín, Miguel Sepulcre, Rafael Molina-Masegosa, and Javier Gozalvez. "Analytical Models of the Performance of C-V2X Mode 4 Vehicular Communications." In: *IEEE Transactions on Vehicular Technology* 68.2 (2019), pp. 1155–1166. DOI: 10.1109/TVT.2018.2888704.

[77] Smriti Gopinath, Lars Wischhof, Christoph Ponikwar, and Hans-Joachim Hof. "Hybrid Solutions for Data Dissemination in Vehicular Networks." In: *2016 Wireless Days (WD)*. IEEE. 2016, pp. 1–4. DOI: 10.1109/WD.2016.7461519.

[78] Yang Guan, Yangang Ren, Shengbo Eben Li, Qi Sun, Laiquan Luo, Koji Taguchi, and Keqiang Li. "Centralized Conflict-Free Cooperation for Connected and Automated Vehicles at Intersections by Proximal Policy Optimization." In: *arXiv preprint* (2019), pp. 12597–12608. eprint: 1912.08410.

[79] Hendrik-Jörn Günther, Sandra Kleinau, Oliver Trauer, and Lars Wolf. "Platooning at Traffic Lights." In: *2016 IEEE Intelligent Vehicles Symposium (IV)*. IEEE. 2016, pp. 1047–1053. DOI: 10.1109/IVS.2016.7535518.

[80] Hendrik-Jörn Günther, Björn Mennenga, Oliver Trauer, Raphael Riebl, and Lars Wolf. "Realizing Collective Perception in a Vehicle." In: *2016 IEEE Vehicular Networking Conference (VNC)*. IEEE. 2016, pp. 1–8. DOI: 10.1109/VNC.2016.7835930.

[81] Hendrik-Jörn Günther, Raphael Riebl, Lars Wolf, and Christian Facchi. "The Effect of Decentralized Congestion Control on Collective Perception in Dense Traffic Scenarios." In: *Computer Communications* 122 (2018), pp. 76–83. DOI: 10.1016/j.comcom.2018.03.009.

[82] Hendrik-Jörn Günther, Oliver Trauer, and Lars Wolf. "The Potential of Collective Perception in Vehicular Ad-Hoc Networks." In: *2015 14th International Conference on ITS Telecommunications (ITST)*. IEEE. 2015, pp. 1–5. DOI: 10.1109/ITST.2015.7377190.

[83] Mohamed Hadded, Pierre Merdrignac, Sacha Duhamel, and Oyunchimeg Shagdar. "Security Attacks Impact for Collective Perception Based Roadside Assistance: A Study of a Highway On-Ramp Merging Case." In: *2020 International Wireless Communications and Mobile Computing (IWCMC)*. IEEE. 2020, pp. 1284–1289. DOI: 10.1109/IWCMC48107.2020.9148235.

[84] Dalton A. Hahn, Arslan Munir, and Vahid Behzadan. "Security and Privacy Issues in Intelligent Transportation Systems: Classification and Challenges." In: *IEEE Intelligent Transportation Systems Magazine* 13.1 (2021), pp. 181–196. DOI: 10.1109/MITS.2019.2898973.

[85] Juergen Hauenstein, Jakob Gromer, Jan Mertens, Frank Diermeyer, and Sven Kraus. "Collective Perception: Impact on Fuel Consumption for Heavy Trucks." In: *7th International Conference on Vehicle Technology and Intelligent Transport Systems (VEHITS 21)*. Scitepress. 2021, pp. 350–361. DOI: 10.5220/0010405503500361.

[86] Takamasa Higuchi, Marco Giordani, Andrea Zanella, Michele Zorzi, and Onur Altintas. "Value-Anticipating V2V Communications for Cooperative Perception." In: *2019 IEEE Intelligent Vehicles Symposium (IV)*. IEEE. 2019, pp. 1947–1952. DOI: 10.1109/IVS.2019.8814110.

[87] Laurens Hobert, Andreas Festag, Ignacio Llatser, Luciano Altomare, Filippo Visintainer, and Andras Kovacs. "Enhancements of V2X Communication in Support of Cooperative Autonomous Driving." In: *IEEE Communications Magazine* 53.12 (2015), pp. 64–70. DOI: 10.1109/MCOM.2015.7355568.

[88] Ching-Ling Huang, Yaser Pourmohammadi Fallah, Raja Sengupta, and Hariharan Krishnan. "Intervehicle Transmission Rate Control for Cooperative Active Safety System." In: *IEEE Transactions on Intelligent Transportation Systems* 12.3 (2011), pp. 645–658. DOI: 10.1109/TITS.2010.2070873.

[89] Hui Huang, Huiyun Li, Cuiping Shao, Tianfu Sun, Wenqi Fang, and Shaobo Dang. "Data Redundancy Mitigation in V2X Based Collective Perceptions." In: *IEEE Access* 8 (2020), pp. 13405–13418. DOI: 10.1109/ACCESS.2020.2965552.

[90] IEEE. "IEEE Standard for Information Technology–Telecommunications and Information Exchange between Systems - Local and Metropolitan Area Networks–Specific Requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications." In: *IEEE Std 802.11-2020 (Revision of IEEE Std 802.11-2016)* (2021), pp. 1–4379. DOI: 10.1109/IEEESTD.2021.9363693.

[91] Intelligent Maneuver Automation Cooperative Hazard Avoidance in Realtime (IMAGinE). *Solutions for Cooperative Driving*. Available: https://www.imagine-online.de/en/home. [Accessed Oct. 01, 2021]. Oct. 2017.

[92] Intelligent Transport Systems (ITS). *Vehicular Communications; Basic Set of Applications; Definitions*. Technical Specification TS 102 638. V1.1.1. European Telecommunications Standards Institute (ETSI), June 2009.

[93] Intelligent Transport Systems (ITS). *Communications Architecture*. European Standard EN 302 665. V1.1.1. European Telecommunications Standards Institute (ETSI), Sept. 2010.

[94] Intelligent Transport Systems (ITS). *Framework for Public Mobile Networks in Cooperative ITS (C-ITS)*. Technical Report TR 102 962. V1.1.1. European Telecommunications Standards Institute (ETSI), Feb. 2012.

[95] Intelligent Transport Systems (ITS). *Basic Set of Applications; Local Dynamic Map (LDM)*. European Standard EN 302 895. V1.1.1. European Telecommunications Standards Institute (ETSI), Sept. 2014.

[96] Intelligent Transport Systems (ITS). *Specification of Cooperative Awareness Basic Service*. European Standard EN 302 637-2. V1.3.1. European Telecommunications Standards Institute (ETSI), Sept. 2014.

[97] Intelligent Transport Systems (ITS). *Specifications of Decentralized Environmental Notification Basic Service*. European Standard EN 302 637-3. V1.2.1. European Telecommunications Standards Institute (ETSI), Sept. 2014.

[98] Intelligent Transport Systems (ITS). *Vehicular Communications; GeoNetworking; Part 1: Requirements*. European Standard EN 302 363-1. V1.2.1. European Telecommunications Standards Institute (ETSI), Feb. 2014.

[99] Intelligent Transport Systems (ITS). *Vehicular Communications; GeoNetworking; Part 3: Network Architecture*. European Standard EN 302 636-3. V1.2.1. European Telecommunications Standards Institute (ETSI), Dec. 2014.

[100] Intelligent Transport Systems (ITS). *Radio Communications Equipment Operating in the 5 855 MHz to 5 925 MHz Frequency Band; Harmonised Standard Covering the Essential Requirements of Article 3.2 of Directive 2014/53/EU*. Harmonised European Standard EN 302 571. V2.1.1. European Telecommunications Standards Institute (ETSI), Feb. 2017.

[101] Intelligent Transport Systems (ITS). *Vehicular Communications; GeoNetworking; Part 5: Transport Protocols; Sub-Part 1: Basic Transport Protocol*. European Standard EN 302 636-5-1. V2.1.0. European Telecommunications Standards Institute (ETSI), May 2017.

[102] Intelligent Transport Systems (ITS). *Decentralized Congestion Control Mechanisms for Intelligent Transport Systems Operating in the 5 GHz Range; Access Layer Part*. Technical Specification TS 102 687. V1.2.1. European Telecommunications Standards Institute (ETSI), Apr. 2018.

[103] Intelligent Transport Systems (ITS). *ITS-G5 Access Layer Specification for Intelligent Transport Systems Operating in the 5 GHz Frequency Band*. European Standard EN 302 663. V1.3.1. European Telecommunications Standards Institute (ETSI), Oct. 2019.

[104] Intelligent Transport Systems (ITS). *Vehicular Communications; Basic Set of Applications; Analysis of the Collective Perception Service (CPS); Release 2*. Technical Report TR 103 562. V2.1.1. European Telecommunications Standards Institute (ETSI), Dec. 2019.

[105] Intelligent Transport Systems (ITS). *Vehicular Communications; GeoNetworking; Part 4: Geographical Addressing and Forwarding for Point-to-Point and Point-to-Multipoint Communications; Sub-Part 1: Media-Independent Functionality*. European Standard EN 302 636-4-1. V1.4.1. European Telecommunications Standards Institute (ETSI), May 2019.

[106] Intelligent Transport Systems (ITS). *Innovating for the Transport of the Future*. Available: `https://ec.europa.eu/transport/themes/its/`. [Accessed Oct. 01, 2021]. May 2020.

[107] Intelligent Transport Systems (ITS). *Vehicular Communications; GeoNetworking; Part 4: Geographical Addressing and Forwarding for Point-to-Point and Point-to-Multipoint Communications; Sub-Part 2: Media-Dependent Functionalities for ITS-G5*. Technical Specification TS 102 636-4-2. V1.2.1. European Telecommunications Standards Institute (ETSI), Apr. 2020.

[108] Intelligent Transport Systems (ITS). *Vehicular Communications; GeoNetworking; Part 4: Geographical Addressing and Forwarding for Point-to-Point and Point-to-Multipoint Communications; Sub-Part 3: Media-Dependent Functionalities for LTE-V2X*. Technical Specification TS 102 636-4-3. V1.1.1. European Telecommunications Standards Institute (ETSI), Aug. 2020.

[109] ISO/TC 22/SC 32. *Road Vehicles - Functional Safety - Part 9: Automotive Safety Integrity Level (ASIL)-Oriented and Safety-Oriented Analyses*. ISO Norm ISO 26262-9:2018. Edition 2. International Organization for Standardization (ISO), Dec. 2018.

[110] Richard Jacob, Waqar Anwar, Gerhard Fettweis, and Joshwa Pohlmann. “Exploiting Multi-RAT Diversity in Vehicular Ad-Hoc Networks to Improve Reliability of Cooperative Automated Driving Applications.” In: *2019 IEEE 90th Vehicular Technology Conference (VTC2019-Fall)*. IEEE. Sept. 2019, pp. 1–7. DOI: `10.1109/VTCFall.2019.8891072`.

[111] William C. Jakes and Donald C. Cox. *Microwave Mobile Communications*. Wiley-IEEE Press, 1994.

[112] Stefan Jesenski, Jan Erik Stellet, Florian Schiegg, and J. Marius Zöllner. “Generation of Scenes in Intersections for the Validation of Highly Automated Driving Functions.” In: *2019 IEEE Intelligent Vehicles Symposium (IV)*. IEEE. 2019, pp. 502–509. DOI: `10.1109/IVS.2019.8813776`.

[113] Dongyao Jia and Dong Ngoduy. “Platoon Based Cooperative Driving Model with Consideration of Realistic Inter-Vehicle Communication.” In: *Transportation Research Part C: Emerging Technologies* 68 (2016), pp. 245–264. DOI: `10.1016/j.trc.2016.04.008`.

[114] Stefan Joerer, Bastian Bloessl, Michele Segata, Christoph Sommer, Renato Lo Cigno, Abbas Jamalipour, and Falko Dressler. “Enabling Situation Awareness at Intersections for IVC Congestion Control Mechanisms.” In: *IEEE Transactions on Mobile Computing* 15.7 (2016), pp. 1674–1685. DOI: `10.1109/TMC.2015.2474370`.

[115] Stefan Joerer, Michele Segata, Bastian Bloessl, Renato Lo Cigno, Christoph Sommer, and Falko Dressler. “A Vehicular Networking Perspective on Estimating Vehicle Collision Probability at Intersections.” In: *IEEE Transactions on Vehicular Technology* 63.4 (2014), pp. 1802–1812. DOI: `10.1109/TVT.2013.2287343`.

[116] Steven G. Johnson. *The NLopt Nonlinear-Optimization Package*. Available: `http://github.com/stevengj/nlopt`. [Accessed Oct. 18, 2021]. Nov. 2020.

[117] Igor Kadota, Abhishek Sinha, Elif Uysal-Biyikoglu, Rahul Singh, and Eytan Modiano. “Scheduling Policies for Minimizing Age of Information in Broadcast Wireless Networks.” In: *IEEE ACM Transactions on Networking* 26.6 (2018), pp. 2637–2650. DOI: `10.1109/TNET.2018.2873606`.

[118] Mohammed Saeed Al-kahtani. “Survey on Security Attacks in Vehicular Ad hoc Networks (VANETs).” In: *2012 6th International Conference on Signal Processing and Communication Systems*. IEEE. 2012, pp. 1–9. DOI: `10.1109/ICSPCS.2012.6507953`.

[119] Athanasios Kanavos, Dimitrios Fragkos, and Alexandros Kaloxylos. “V2X Communication over Cellular Networks: Capabilities and Challenges.” In: *Telecom* 2.1 (2021), pp. 1–26. DOI: `10.3390/telecom2010001`.

[120] Johan Karedal, Fredrik Tufvesson, Taimoor Abbas, Oliver Klemp, Alexander Paier, Laura Bernadó, and Andreas F. Molisch. "Radio Channel Measurements at Street Intersections for Vehicle-to-Vehicle Safety Applications." In: *2010 IEEE 71st Vehicular Technology Conference*. IEEE. 2010, pp. 1–5. DOI: 10.1109/VETECS.2010.5493955.

[121] Johan Karedal, Fredrik Tufvesson, Nicolai Czink, Alexander Paier, Charlotte Dumard, Thomas Zemen, Christoph Mecklenbrauker, and Andreas Molisch. "A Geometry-Based Stochastic MIMO Model for Vehicle-to-Vehicle Communications." In: *IEEE Transactions on Wireless Communications* 8.7 (2009), pp. 3646–3657. DOI: 10.1109/TWC.2009.080753.

[122] Mouna Karoui, Antonio Freitas, and Gerard Chalhoub. "Performance Comparison Between LTE-V2X and ITS-G5 under Realistic Urban Scenarios." In: *2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring)*. IEEE. 2020, pp. 1–7. DOI: 10.1109/VTC2020-Spring48590.2020.9129423.

[123] Seiya Kato, Matti Hiltunen, Kaustubh Joshi, and Richard Schlichting. "Enabling Vehicular Safety Applications over LTE Networks." In: *2013 International Conference on Connected Vehicles and Expo (ICCVE)*. IEEE. 2013, pp. 747–752. DOI: 10.1109/ICCVE.2013.6799889.

[124] Sanjit Kaul, Marco Gruteser, Vinuth Rai, and John Kenney. "Minimizing Age of Information in Vehicular Networks." In: *2011 8th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks*. IEEE. 2011, pp. 350–358. DOI: 10.1109/SAHCN.2011.5984917.

[125] Mehdi Khabazian, Sonia Aissa, and Mustafa Mehmet-Ali. "Performance Modeling of Message Dissemination in Vehicular Ad Hoc Networks with Priority." In: *IEEE Journal on Selected Areas in Communications* 29.1 (2011), pp. 61–71. DOI: 10.1109/JSAC.2011.110107.

[126] I. Khan, G. M. Hoang, and J. Härri. "Rethinking Cooperative Awareness for Future V2X Safety-Critical Applications." In: *2017 IEEE Vehicular Networking Conference (VNC)*. IEEE. 2017, pp. 73–76. DOI: 10.1109/VNC.2017.8275645.

[127] Mohammad Irfan Khan and Jérôme Härri. "Integration Challenges of Facilities-Layer DCC for Heterogeneous V2X Services." In: *2018 IEEE Intelligent Vehicles Symposium (IV)*. IEEE. 2018, pp. 1131–1136. DOI: 10.1109/IVS.2018.8500572.

[128] Mohammad Irfan Khan, Jérôme Härri, and Stefania Sesia. "Enhancing ETSI DCC for Multi-Service Vehicular Safety Communication." In: *2020 IEEE 92nd Vehicular Technology Conference (VTC2020-Fall)*. IEEE. 2020, pp. 1–5. DOI: 10.1109/VTC2020-Fall49728.2020.9348644.

[129] Mohammad Irfan Khan, Miguel Sepulcre, and Jérôme Härri. "Cooperative Wireless Congestion Control for Multi-Service V2X Communication." In: *2020 IEEE Intelligent Vehicles Symposium (IV)*. IEEE. 2020, pp. 1357–1363. DOI: 10.1109/IV47402.2020.9304838.

[130] Uzma Khan, Shikha Agrawal, and Sanjay Silakari. "Detection of Malicious Nodes (DMN) in Vehicular Ad-Hoc Networks." In: *Procedia Computer Science* 46 (2015), pp. 965–972. DOI: 10.1016/j.procs.2015.01.006.

[131] Sahrish Khan Tayyaba, Hasan Ali Khattak, Ahmad Almogren, Munam Ali Shah, Ikram Ud Din, Ibrahim Alkhalifa, and Mohsen Guizani. "5G Vehicular Network Resource Management for Improving Radio Access Through Machine Learning." In: *IEEE Access* 8 (2020), pp. 6792–6800. DOI: 10.1109/ACCESS.2020.2964697.

[132] Byungjun Kim, Seongwon Kim, Hoyoung Yoon, Sunwook Hwang, M. Xavier Punithan, Byeong Rim Jo, and Sunghyun Choi. "Nearest-First: Efficient Relaying Scheme in Heterogeneous V2V Communication Environments." In: *IEEE Access* 7 (2019), pp. 23615–23627. DOI: 10.1109/ACCESS.2019.2899111.

[133] Björn Koopmann, Stefan Puch, Günter Ehmen, and Martin Fränzle. "Cooperative Maneuvers of Highly Automated Vehicles at Urban Intersections: A Game-Theoretic Approach." In: *6th International Conference on Vehicle Technology and Intelligent Transport Systems (VEHITS 20)*. Scitepress. 2020, pp. 15–26. DOI: 10.5220/0009351500150026.

[134] Daniel Krajzewicz, Georg Hertkorn, C. Rössel, and Peter Wagner. "SUMO (Simulation of Urban MObility); An Open-Source Traffic Simulation." In: *Proceedings of the 4th middle East Symposium on Simulation and Modeling (MESM2002)*. DLR. 2002, pp. 183–187. URL: https://elib.dlr.de/6661/.

[135] Sebastian Kuehlmorgen, Patrick Schmager, Andreas Festag, and Gerhard Fettweis. "Simulation-Based Evaluation of ETSI ITS-G5 and Cellular-VCS in a Real-World Road Traffic Scenario." In: *2018 IEEE 88th Vehicular Technology Conference (VTC-Fall)*. IEEE. 2018, pp. 1–6. DOI: 10.1109/VTCFall.2018.8691011.

[136] Saurabh Kumar and Hyungwon Kim. "Packet Rate Adaptation Protocol Based on Bloom Filter for Hidden Node Avoidance in Vehicular Ad-Hoc Networks." In: *IEEE Access* 7 (2019), pp. 137446–137460. DOI: 10.1109/ACCESS.2019.2942971.

[137] Bernd Lehmann, Hendrik-Jörn Günther, and Lars Wolf. "A Generic Approach Towards Maneuver Coordination for Automated Vehicles." In: *2018 21st International Conference on Intelligent Transportation Systems (ITSC)*. IEEE. 2018, pp. 3333–3339. DOI: 10.1109/ITSC.2018.8569442.

[138] Bernd Lehmann and Lars Wolf. "Safety Analysis of a Maneuver Coordination Protocol." In: *2020 IEEE Vehicular Networking Conference (VNC)*. IEEE. 2020, pp. 1–8. DOI: 10.1109/VNC51378.2020.9318359.

[139] Yuyi Li, Kai Ying, Peng Cheng, Hui Yu, and Hanwen Luo. "Cooperative Data Dissemination in Cellular-VANET Heterogeneous Wireless Networks." In: *2012 4th International High Speed Intelligent Communication Forum*. IEEE. 2012, pp. 1–4. DOI: 10.1109/HSIC.2012.6212991.

[140] Bingyi Liu, Dongyao Jia, Jianping Wang, Kejie Lu, and Libing Wu. "Cloud-Assisted Safety Message Dissemination in VANET Cellular Heterogeneous Wireless Network." In: *IEEE Systems Journal* 11.1 (2017), pp. 128–139. DOI: 10.1109/JSYST.2015.2451156.

[141] Xiaofeng Liu and Arunita Jaekel. "Congestion Control in V2V Safety Communication: Problem, Analysis, Approaches." In: *Electronics* 8.5 (2019), pp. 1–24. DOI: 10.3390/electronics8050540.

[142] Ignacio Llatser, Thomas Michalke, Maxim Dolgov, Florian Wildschütte, and Hendrik Fuchs. "Cooperative Automated Driving Use Cases for 5G V2X Communication." In: *2019 IEEE 2nd 5G World Forum (5GWF)*. IEEE. 2019, pp. 120–125. DOI: 10.1109/5GWF.2019.8911628.

[143] Hien P. Luong, Suong H. Nguyen, Hai L. Vu, and Bao Quoc Vo. "One-Hop vs. Multi-Hop Broadcast Protocol for DSRC Safety Applications." In: *Proceeding of IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks 2014*. 2014, pp. 1–3. DOI: 10.1109/WoWMoM.2014.6919007.

[144] Petri Luoto, Mehdi Bennis, Pekka Pirinen, Sumudu Samarakoon, Kari Horneman, and Matti Latva-aho. "Vehicle Clustering for Improving Enhanced LTE-V2X Network Performance." In: *2017 European Conference on Networks and Communications (EuCNC)*. IEEE. 2017, pp. 1–5. DOI: 10.1109/EuCNC.2017.7980735.

[145] David Malone, Ken Duffy, and Doug Leith. "Modeling the 802.11 Distributed Coordination Function in Nonsaturated Heterogeneous Conditions." In: *IEEE ACM Transactions on Networking* 15.1 (2007), pp. 159–172. DOI: 10.1109/TNET.2006.890136.

[146] Valerian Mannoni, Vincent Berg, Stefania Sesia, and Eric Perraud. "A Comparison of the V2X Communication Systems: ITS-G5 and C-V2X." In: *2019 IEEE 89th Vehicular Technology Conference (VTC2019-Spring)*. IEEE. 2019, pp. 1–5. DOI: 10.1109/VTCSpring.2019.8746562.

[147] David Martín-Sacristán, Sandra Roger, David Garcia-Roger, Jose F. Monserratt, Panagiotis Spapis, Apostolos Kousaridas, and Chan Zhou. "Low-Latency V2X Communication Through Localized MBMS with Local V2X Servers Coordination." In: *2018 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*. 2018, pp. 1–8. DOI: 10.1109/BMSB.2018.8436758.

[148] Barbara M. Masini, Alberto Zanella, Gianni Pasolini, Alessandro Bazzi, Flavio Zabini, Oreste Andrisano, Mirko Mirabella, and Paolo Toppan. "Toward the Integration of ADAS Capabilities in V2X Communications for Cooperative Driving." In: *2020 AEIT International Conference of Electrical and Electronic Technologies for Automotive (AEIT AUTOMOTIVE)*. IEEE. 2020, pp. 1–6. DOI: 10.23919/AEITAUTOMOTIVE50086.2020.9307433.

[149] Juergen Maurer, Thomas Fugen, Thomas Schafer, and Werner Wiesbeck. "A New Inter-Vehicle Communications (IVC) Channel Model." In: *IEEE 60th Vehicular Technology Conference, 2004. VTC2004-Fall. 2004*. IEEE. 2004, pp. 9–13. DOI: 10.1109/VETECF.2004.1399905.

[150] Christoph F. Mecklenbrauker, Andreas F. Molisch, Johan Karedal, Fredrik Tufvesson, Alexander Paier, Laura Bernado, Thomas Zemen, Oliver Klemp, and Nicolai Czink. "Vehicular Channel Characterization and Its Implications for Wireless System Design and Performance." In: *Proceedings of the IEEE* 99.7 (2011), pp. 1189–1212. DOI: 10.1109/JPROC.2010.2101990.

[151] Amjad Mehmood, Akbar Khanan, Abdul Hakim H. M. Mohamed, Saeed Mahfooz, Houbing Song, and Salwani Abdullah. "ANTSC: An Intelligent Naïve Bayesian Probabilistic Estimation Practice for Traffic Flow to Form Stable Clustering in VANET." In: *IEEE Access* 6 (2018), pp. 4452–4461. DOI: 10.1109/ACCESS.2017.2732727.

[152] Agon Memedi, Florian Hagenauer, Falko Dressler, and Christoph Sommer. "Cluster-Based Transmit Power Control in Heterogeneous Vehicular Networks." In: *2015 IEEE Vehicular Networking Conference (VNC)*. IEEE. 2015, pp. 60–63. DOI: 10.1109/VNC.2015.7385547.

[153] Jan Cedric Mertens, Christian Knies, Frank Diermeyer, Svenja Escherle, and Sven Kraus. "The Need for Cooperative Automated Driving." In: *Electronics* 9.5 (2020), p. 754. DOI: 10.3390/electronics9050754.

[154] Tobias Meuser. "Data Management in Vehicular Networks - Relevance-Aware Networking for Advanced Driver Assistance Systems." PhD thesis. Darmstadt: Technische Universität, 2020. URL: http://tuprints.ulb.tu-darmstadt.de/11378/.

[155] Tobias Meuser, Daniel Bischoff, Björn Richerzhagen, and Ralf Steinmetz. "Cooperative Offloading in Context-Aware Networks: A Game-Theoretic Approach." In: *Proceedings of the 13th ACM International Conference on Distributed and Event-Based Systems*. ACM. 2019, pp. 55–66. DOI: 10.1145/3328905.3338535.

[156] Tobias Meuser, Oluwasegun Taiwo Ojo, Daniel Bischoff, Antonio Fernández Anta, Ioannis Stavrakakis, and Ralf Steinmetz. "Hide Me: Enabling Location Privacy in Heterogeneous Vehicular Networks." In: *Networked Systems*. Springer International Publishing. 2021, pp. 11–27. DOI: 10.1007/978-3-030-67087-0_2.

[157] Tobias Meuser, Björn Richerzhagen, Ioannis Stavrakakis, The An Binh Nguyen, and Ralf Steinmetz. "Relevance-Aware Information Dissemination in Vehicular Networks." In: *2018 IEEE 19th International Symposium on "A World of Wireless, Mobile and Multimedia Networks" (WoWMoM)*. IEEE. 2018, pp. 588–599. DOI: 10.1109/WoWMoM.2018.8449751.

[158] Tobias Meuser, Martin Wende, Patrick Lieser, Björn Richerzhagen, and Ralf Steinmetz. "Adaptive Decision Making based on Temporal Information Dynamics." In: *4th International Conference on Vehicle Technology and Intelligent Transport Systems (VEHITS 18)*. Scitepress. 2018, pp. 91–102. DOI: 10.5220/0006687900910102.

[159] Vicente Milanés, Jorge Godoy, Jorge Villagrá, and Joshué Pérez. “Automated On-Ramp Merging System for Congested Traffic Situations.” In: *IEEE Transactions on Intelligent Transportation Systems* 12.2 (2011), pp. 500–508. DOI: 10.1109/TITS.2010.2096812.

[160] Zeeshan Hameed Mir and Fethi Filali. “LTE and IEEE 802.11p for Vehicular Networking: A Performance Evaluation.” In: *EURASIP Journal on Wireless Communications and Networking* 2014.1 (2014), p. 89. DOI: 10.1186/1687-1499-2014-89.

[161] Zeeshan Hameed Mir and Fethi Filali. “On the Performance Comparison between IEEE 802.11p and LTE-Based Vehicular Networks.” In: *2014 IEEE 79th Vehicular Technology Conference (VTC Spring)*. IEEE. 2014, pp. 1–5. DOI: 10.1109/VTCSpring.2014.7023017.

[162] Zeeshan Hameed Mir and Fethi Filali. “Applications, Requirements, and Design Guidelines for Multi-Tiered Vehicular Network Architecture.” In: *2018 Wireless Days (WD)*. IEEE. 2018, pp. 15–20. DOI: 10.1109/WD.2018.8361686.

[163] Zeeshan Hameed Mir, Jamal Toutouh, Fethi Filali, and Enrique Alba. “QoS-Aware Radio Access Technology (RAT) Selection in Hybrid Vehicular Networks.” In: *Communication Technologies for Vehicles*. Springer International Publishing. 2015, pp. 117–128. DOI: 10.1007/978-3-319-17765-6_11.

[164] Rafael Molina-Masegosa, Miguel Sepulcre, and Javier Gozalvez. “Geo-Based Scheduling for C-V2X Networks.” In: *IEEE Transactions on Vehicular Technology* 68.9 (2019), pp. 8397–8407. DOI: 10.1109/TVT.2019.2924698.

[165] Andreas Moller, Jorg Nuckelt, Dennis M. Rose, and Thomas Kurner. “Physical Layer Performance Comparison of LTE and IEEE 802.11p for Vehicular Communication in an Urban NLOS Scenario.” In: *2014 IEEE 80th Vehicular Technology Conference (VTC2014-Fall)*. IEEE. 2014, pp. 1–5. DOI: 10.1109/VTCFall.2014.6966129.

[166] Johannes Müller, Tobias Meuser, Ralf Steinmetz, and Michael Buchholz. “A Trust Management and Misbehaviour Detection Mechanism for Multi-Agent Systems and Its Application to Intelligent Transportation Systems.” In: *2019 IEEE 15th International Conference on Control and Automation (ICCA)*. IEEE. 2019, pp. 325–331. DOI: 10.1109/ICCA.2019.8899968.

[167] A. Murali, K. Bhanupriya, S. B. Smitha, and G. N. Kumar. “Performance Evaluation of IEEE 802.11p for Vehicular Traffic Congestion Control.” In: *2011 11th International Conference on ITS Telecommunications*. IEEE. 2011, pp. 732–737. DOI: 10.1109/ITST.2011.6060151.

[168] John A. Nelder and Roger Mead. “A Simplex Method for Function Minimization.” In: *The Computer Journal* 7 (1965), pp. 308–316. DOI: 10.1093/comjnl/7.4.308.

[169] Tien Viet Nguyen, Patil Shailesh, Baghel Sudhir, Gulati Kapil, Libin Jiang, Zhibin Wu, Durga Malladi, and Junyi Li. "A Comparison of Cellular Vehicle-to-Everything and Dedicated Short Range Communication." In: *2017 IEEE Vehicular Networking Conference (VNC)*. IEEE. 2017, pp. 101–108. DOI: 10.1109/VNC.2017.8275618.

[170] Jie Ni, Jingwen Han, and Fei Dong. "Multivehicle Cooperative Lane Change Control Strategy for Intelligent Connected Vehicle." In: *Journal of Advanced Transportation* 2020 (2020), pp. 1–10. DOI: 10.1155/2020/8672928.

[171] Lei Ni, Yuxin Wang, Haoyang Tang, Zhao Yin, and Yanming Shen. "Accurate Localization Using LTE Signaling Data." In: *2017 IEEE International Conference on Computer and Information Technology (CIT)*. 2017, pp. 268–273. DOI: 10.1109/CIT.2017.59.

[172] Gustavo Niemeyer. *Geohash*. Available: http://geohash.org/. [Accessed Oct. 01, 2021]. Feb. 2008.

[173] Mikael G. Nilsson, Carl Gustafson, Taimoor Abbas, and Fredrik Tufvesson. "A Measurement-Based Multilink Shadowing Model for V2V Network Simulations of Highway Scenarios." In: *IEEE Transactions on Vehicular Technology* 66.10 (2017), pp. 8632–8643. DOI: 10.1109/TVT.2017.2709258.

[174] Jinho Park, Won-Hwa Lee, and Sang-Sun Lee. "An Intelligent Interface Selection Scheme for Vehicular Communication System using LTE and IEEE 802.11p." In: *2016 International Conference on Information and Communication Technology Convergence (ICTC)*. IEEE. 2016, pp. 868–870. DOI: 10.1109/ICTC.2016.7763318.

[175] Moumita Patra, Anik Sengupta, and C. Siva Ram Murthy. "On Minimizing the System Information Age in Vehicular Ad-Hoc Networks via Efficient Scheduling and Piggybacking." In: *Wireless Networks* 22.5 (2016), pp. 1625–1639. DOI: 10.1007/s11276-015-1056-3.

[176] Jonathan Petit, Florian Schaub, Michael Feiri, and Frank Kargl. "Pseudonym Schemes in Vehicular Networks: A Survey." In: *IEEE Communications Surveys Tutorials* 17.1 (2015), pp. 228–255. DOI: 10.1109/COMST.2014.2345420.

[177] Andreas Pfadler, Guillaume Jornod, Ahmad El Assaad, and Peter Jung. "Predictive Quality of Service: Adaptation of Platoon Inter-Vehicle Distance to Packet Inter-Reception Time." In: *2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring)*. IEEE. 2020, pp. 1–5. DOI: 10.1109/VTC2020-Spring48590.2020.9129097.

[178] Daniel Plöger, Michele Segata, Renato Lo Cigno, and Andreas Timm-Giel. "Markov-Modulated Models to Estimate the Age of Information in Cooperative Driving." In: *2019 IEEE Vehicular Networking Conference (VNC)*. IEEE. 2019, pp. 1–4. DOI: 10.1109/VNC48660.2019.9062802.

[179] Filippo Rebecchi, Marcelo Dias de Amorim, Vania Conan, Andrea Passarella, Raffaele Bruno, and Marco Conti. "Data Offloading Techniques in Cellular Networks: A Survey." In: *IEEE Communications Surveys Tutorials* 17.2 (2015), pp. 580–603. DOI: `10.1109/COMST.2014.2369742`.

[180] Guillaume Remy, Sidi-Mohammed Senouci, Francois Jan, and Yvon Gourhant. "LTE4V2X: LTE for a Centralized VANET Organization." In: *2011 IEEE Global Telecommunications Conference - GLOBECOM 2011*. IEEE. 2011, pp. 1–6. DOI: `10.1109/GLOCOM.2011.6133884`.

[181] Raphael Riebl, Hendrik-Jörn Günther, Christian Facchi, and Lars Wolf. "Artery: Extending Veins for VANET Applications." In: *2015 International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS)*. IEEE. 2015, pp. 450–456. DOI: `10.1109/MTITS.2015.7223293`.

[182] Jackeline Rios-Torres and Andreas A. Malikopoulos. "Automated and Cooperative Vehicle Merging at Highway On-Ramps." In: *IEEE Transactions on Intelligent Transportation Systems* 18.4 (2017), pp. 780–789. DOI: `10.1109/TITS.2016.2587582`.

[183] Fidel Alejandro Rodríguez-Corbo, Leyre Azpilicueta, Mikel Celaya-Echarri, Ana Vazquez Alejos, and Francisco Falcone. "Propagation Models in Vehicular Communications." In: *IEEE Access* 9 (2021), pp. 15902–15913. DOI: `10.1109/ACCESS.2021.3049884`.

[184] Michele Rondinone and Alejandro Correa. *Deliverable 5.1: Definition of V2X Message Sets*. Project Report Horizon 2020. V2.0. Transition Areas for Infrastructure-Assisted Driving (TransAID), Aug. 2018.

[185] Michele Rondinone, Javier Gozalvez, Jérémie Leguay, and Vania Conan. "Exploiting Context Information for V2X Dissemination in Vehicular Networks." In: *2013 IEEE 14th International Symposium on "A World of Wireless, Mobile and Multimedia Networks" (WoWMoM)*. IEEE. 2013, pp. 1–9. DOI: `10.1109/WoWMoM.2013.6583373`.

[186] SAE On-Road Automated Vehicle Standards Committee. "Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems." In: *SAE Standard* 3016 (2014), pp. 1–16. DOI: `10.4271/J3016_201806`.

[187] Pierpaolo Salvo, Ion Turcanu, Francesca Cuomo, Andrea Baiocchi, and Izhak Rubin. "LTE Floating Car Data Application Off-Loading via VANET Driven Clustering Formation." In: *2016 12th Annual Conference on Wireless On-Demand Network Systems and Services (WONS)*. IEEE. 2016, pp. 1–8.

[188] Oliver Sawade, Matthias Schulze, and Ilja Radusch. "Robust Communication for Cooperative Driving Maneuvers." In: *IEEE Intelligent Transportation Systems Magazine* 10.3 (2018), pp. 159–169. DOI: `10.1109/MITS.2018.2842241`.

[189] Florian A. Schiegg, Ignacio Llatser, Daniel Bischoff, and Georg Volk. "Collective Perception: A Safety Perspective." In: *Sensors* 21.1 (2021), pp. 1–23. DOI: `10.3390/s21010159`.

[190] Miguel Sepulcre, Manuel Gonzalez-Martin, Javier Gozalvez, and Rafael Molina-Masegosa. "Analytical Models of the Performance of IEEE 802.11p Vehicle to Vehicle Communications." In: *arXiv preprint* (2021), pp. 1–11. eprint: 2104.07923.

[191] Miguel Sepulcre and Javier Gozalvez. "Coordination of Congestion and Awareness Control in Vehicular Networks." In: *Electronics* 7.11 (2018), p. 335. DOI: 10.3390/electronics7110335.

[192] Miguel Sepulcre and Javier Gozalvez. "Heterogeneous V2V Communications in Multi-Link and Multi-RAT Vehicular Networks." In: *IEEE Transactions on Mobile Computing* 20.1 (2021), pp. 162–173. DOI: 10.1109/TMC.2019.2939803.

[193] Miguel Sepulcre, Javier Gozalvez, Onur Altintas, and Haris Kremo. "Adaptive Beaconing for Congestion and Awareness Control in Vehicular Networks." In: *2014 IEEE Vehicular Networking Conference (VNC)*. IEEE. 2014, pp. 81–88. DOI: 10.1109/VNC.2014.7013313.

[194] Miguel Sepulcre, Javier Gozalvez, Jérôme Härri, and Hannes Hartenstein. "Application-Based Congestion Control Policy for the Communication Channel in VANETs." In: *IEEE Communications Letters* 14.10 (2010), pp. 951–953. DOI: 10.1109/LCOMM.2010.091010.100345.

[195] Miguel Sepulcre, Jorge Mira, Gokulnath Thandavarayan, and Javier Gozalvez. "Is Packet Dropping a Suitable Congestion Control Mechanism for Vehicular Networks?" In: *2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring)*. IEEE. 2020, pp. 1–5. DOI: 10.1109/VTC2020-Spring48590.2020.9128822.

[196] Chenhao Shi, Yi Zhou, Wei Li, Huanhuan Li, Ning Lu, Nan Cheng, and Tingting Yang. "A Centralized Clustering Based Hybrid Vehicular Networking Architecture for Safety Data Delivery." In: *GLOBECOM 2017 - 2017 IEEE Global Communications Conference*. IEEE. 2017, pp. 1–6. DOI: 10.1109/GLOCOM.2017.8254086.

[197] Galina Sidorenko, Johan Thunberg, Katrin Sjöberg, and Alexey Vinel. "Vehicle-to-Vehicle Communication for Safe and Fuel-Efficient Platooning." In: *2020 IEEE Intelligent Vehicles Symposium (IV)*. IEEE. 2020, pp. 795–802. DOI: 10.1109/IV47402.2020.9304719.

[198] Christoph Sommer, Reinhard German, and Falko Dressler. "Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis." In: *IEEE Transactions on Mobile Computing* 10.1 (2011), pp. 3–15. DOI: 10.1109/TMC.2010.133.

[199] Heecheol Song and Hwang Soo Lee. "A Survey on How to Solve a Decentralized Congestion Control Problem for Periodic Beacon Broadcast in Vehicular Safety Communications." In: *2013 15th International Conference on Advanced Communications Technology (ICACT)*. IEEE. 2013, pp. 649–654.

[200] Statista-Umfrage. *Welche Faktoren Stressen Sie Rund ums Autofahren?* Available: https://de.statista.com/prognosen/856943/umfrage-in-deutschland-zu-stressoren-rund-ums-autofahren. [Accessed Aug. 03, 2021]. Dec. 2018.

[201] Elias Strigel, Daniel Meissner, Florian Seeliger, Benjamin Wilking, and Klaus Dietmayer. "The Ko-PER Intersection Laserscanner and Video Dataset." In: *17th International IEEE Conference on Intelligent Transportation Systems (ITSC)*. IEEE. 2014, pp. 1900–1901. DOI: 10.1109/ITSC.2014.6957976.

[202] Wanlu Sun, Di Yuan, Erik G. Ström, and Fredrik Brännström. "Cluster-Based Radio Resource Management for D2D-Supported Safety-Critical V2X Communications." In: *IEEE Transactions on Wireless Communications* 15.4 (2016), pp. 2756–2769. DOI: 10.1109/TWC.2015.2509978.

[203] Technical Specification Group Services and System Aspects. *Release 12 Description*. Technical Report TR 21.912. V12.0.0. Third Generation Partnership Project (3GPP), Sept. 2015.

[204] Technical Specification Group Services and System Aspects. *Release 14 Description*. Technical Report TR 21 914. V14.0.0. Third Generation Partnership Project (3GPP), May 2018.

[205] Technical Specification Group Services and System Aspects. *Enhancement of 3GPP Support for V2X Scenarios; Stage 1*. Technical Specification TS 22.186. V16.2.0. Third Generation Partnership Project (3GPP), June 2019.

[206] Technical Specification Group Services and System Aspects. *Release 15 Description*. Technical Report TR 21.915. V15.0.0. Third Generation Partnership Project (3GPP), Sept. 2019.

[207] Gokulnath Thandavarayan, Miguel Sepulcre, and Javier Gozalvez. "Analysis of Message Generation Rules for Collective Perception in Connected and Automated Driving." In: *2019 IEEE Intelligent Vehicles Symposium (IV)*. IEEE. 2019, pp. 134–139. DOI: 10.1109/IVS.2019.8813806.

[208] Gokulnath Thandavarayan, Miguel Sepulcre, and Javier Gozalvez. "Generation of Cooperative Perception Messages for Connected and Automated Vehicles." In: *Transactions on Vehicular Technology* 69.12 (2019), pp. 16336–16341. DOI: 10.1109/TVT.2020.3036165.

[209] Gokulnath Thandavarayan, Miguel Sepulcre, and Javier Gozalvez. "Cooperative Perception for Connected and Automated Vehicles: Evaluation and Impact of Congestion Control." In: *IEEE Access* 8 (2020), pp. 197665–197683. DOI: 10.1109/ACCESS.2020.3035119.

[210] The CAMP Vehicle Safety Communications Consortium. *Identify Intelligent Vehicle Safety Applications Enabled by DSRC*. Technical Report DOT HS 809 859. Final. National Highway Traffic Safety Administration (NHTSA), Mar. 2005.

[211] Manfred Thumm, Werner Wiesbeck, and Stefan Kern. *Hochfrequenzmesstechnik*. Vieweg+Teubner Verlag, 1998. DOI: 10.1524/9783486598575.

[212] Johan Thunberg, Daniel Bischoff, Florian A. Schiegg, Tobias Meuser, and Alexey Vinel. "Unreliable V2X Communication in Cooperative Driving: Safety Times for Emergency Braking." In: *IEEE Access* (2021), pp. 148024–148036. DOI: 10.1109/ACCESS.2021.3124450.

[213] Johan Thunberg, Nikita Lyamin, Katrin Sjöberg, and Alexey Vinel. "Vehicle-to-Vehicle Communications for Platooning: Safety Analysis." In: *IEEE Networking Letters* 1.4 (2019), pp. 168–172. DOI: 10.1109/LNET.2019.2929026.

[214] Johan Thunberg, Galina Sidorenko, Katrin Sjöberg, and Alexey Vinel. "Efficiently Bounding the Probabilities of Vehicle Collision at Intelligent Intersections." In: *IEEE Open Journal of Intelligent Transportation Systems* 2 (2021), pp. 47–59. DOI: 10.1109/OJITS.2021.3058449.

[215] Behrad Toghi, Md Saifuddin, Hossein Nourkhiz Mahjoub, M. O. Mughal, Yaser P. Fallah, Jayanthi Rao, and Sushanta Das. "Multiple Access in Cellular V2X: Performance Analysis in Highly Congested Vehicular Networks." In: *2018 IEEE Vehicular Networking Conference (VNC)*. IEEE. 2018, pp. 1–8. DOI: 10.1109/VNC.2018.8628416.

[216] Lung-Chih Tung, Jorge Mena, Mario Gerla, and Christoph Sommer. "A Cluster Based Architecture for Intersection Collision Avoidance using Heterogeneous Networks." In: *2013 12th Annual Mediterranean Ad Hoc Networking Workshop (MED-HOC-NET)*. IEEE. 2013, pp. 82–88. DOI: 10.1109/MedHocNet.2013.6767414.

[217] Seyhan Ucar, Sinem Coleri Ergen, and Oznur Ozkasap. "Multihop-Cluster-Based IEEE 802.11p and LTE Hybrid Architecture for VANET Safety Message Dissemination." In: *IEEE Transactions on Vehicular Technology* 65.4 (2016), pp. 2621–2636. DOI: 10.1109/TVT.2015.2421277.

[218] Felipe Valle, Sandra Céspedes, and Abdelhakim Senhaji Hafid. "Automated Decision System to Exploit Network Diversity for Connected Vehicles." In: *IEEE Transactions on Vehicular Technology* 70.1 (2021), pp. 858–871. DOI: 10.1109/TVT.2020.3046413.

[219] András Varga and Rudolf Hornig. "An Overview of the OMNeT++ Simulation Environment." In: *Proceedings of the 1st International Conference on Simulation Tools and Techniques for Communications, Networks and Systems & Workshops*. ACM. 2008, pp. 1–10.

[220] Alexey Vinel. "3GPP LTE Versus IEEE 802.11p/WAVE: Which Technology is Able to Support Cooperative Vehicular Safety Applications?" In: *IEEE Wireless Communications Letters* 1.2 (2012), pp. 125–128. DOI: 10.1109/WCL.2012.022012.120073.

[221] Alexey Vinel, Nikita Lyamin, and Pavel Isachenkov. "Modeling of V2V Communications for C-ITS Safety Applications: A CPS Perspective." In: *IEEE Communications Letters* 22.8 (2018), pp. 1600–1603. DOI: 10.1109/LCOMM.2018.2835484.

[222] Antonio Virdis, Giovanni Stea, and Giovanni Nardini. "Simulating LTE/LTE-Advanced Networks with SimuLTE." In: *Simulation and Modeling Methodologies, Technologies and Applications*. Springer. 2015, pp. 83–105. DOI: 10.1007/978-3-319-26470-7_5.

[223] Wantanee Viriyasitavat, Mate Boban, Hsin-Mu Tsai, and Athanasios Vasilakos. "Vehicular Communications: Survey and Challenges of Channel and Propagation Models." In: *IEEE Vehicular Technology Magazine* 10.2 (2015), pp. 55–66. DOI: 10.1109/MVT.2015.2410341.

[224] Jiadai Wang, Jiajia Liu, and Nei Kato. "Networking and Communications in Autonomous Driving: A Survey." In: *IEEE Communications Surveys Tutorials* 21.2 (2019), pp. 1243–1274. DOI: 10.1109/COMST.2018.2888904.

[225] Min Wang, Martin Winbjork, Zhang Zhang, Ricardo Blasco, Hieu Do, Stefano Sorrentino, Marco Belleschi, and Yunpeng Zang. "Comparison of LTE and DSRC-Based Connectivity for Intelligent Transportation Systems." In: *2017 IEEE 85th Vehicular Technology Conference (VTC Spring)*. IEEE. 2017, pp. 1–5. DOI: 10.1109/VTCSpring.2017.8108284.

[226] Ruyan Wang, Jiaxing Wu, and Junjie Yan. "Resource Allocation for D2D-Enabled Communications in Vehicle Platooning." In: *IEEE Access* 6 (2018), pp. 50526–50537. DOI: 10.1109/ACCESS.2018.2868839.

[227] Xu Wang and Randall A. Berry. "MAC Trade-Offs Between Age and Reachability of Information in Vehicular Safety Applications." In: *IEEE INFOCOM 2020 - IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*. IEEE. 2020, pp. 689–695. DOI: 10.1109/INFOCOMWKSHPS50562.2020.9162922.

[228] Axel Wegener, Micha Piórkowski, Maxim Raya, Horst Hellbrück, Stefan Fischer, and Jean-Pierre Hubaux. "TraCI: An Interface for Coupling Road Traffic and Network Simulators." In: *Proceedings of the 11th Communications and Networking Simulation Symposium*. ACM. 2008, pp. 155–163. DOI: 10.1145/1400713.1400740.

[229] Geeth P. Wijesiri N.B.A., Jussi Haapola, and Tharaka Samarasinghe. "A Markov Perspective on C-V2X Mode 4." In: *2019 IEEE 90th Vehicular Technology Conference (VTC2019-Fall)*. IEEE. 2019, pp. 1–6. DOI: 10.1109/VTCFall.2019.8891331.

[230] Wireless Telecommunications. *Dedicated Short Range Communications (DSRC) Service*. Available: https://www.fcc.gov/wireless/bureau-divisions/mobility-division/dedicated-short-range-communications-dsrc-service. [Accessed Oct. 01, 2021]. Apr. 2019.

[231] Michael Wolf, Alexander Willecke, Johannes-Christian Müller, Keno Garlichs, Thomas Griebel, Lars Wolf, Michael Buchholz, Klaus Dietmayer, Rens W. van der Heijden, and Frank Kargl. "Securing CACC: Strategies for Mitigating Data Injection Attacks." In: *2020 IEEE Vehicular Networking Conference (VNC)*. IEEE. 2020, pp. 1–7. DOI: 10.1109/VNC51378.2020.9318396.

[232] Celimuge Wu, Tsutomu Yoshinaga, Xianfu Chen, Lin Zhang, and Yusheng Ji. "Cluster-Based Content Distribution Integrating LTE and IEEE 802.11p with Fuzzy Logic and Q-Learning." In: *IEEE Computational Intelligence Magazine* 13.1 (2018), pp. 41–50. DOI: 10.1109/MCI.2017.2773818.

[233] Christos Xenakis, Christoforos Panos, and Ioannis Stavrakakis. "A Comparative Evaluation of Intrusion Detection Architectures for Mobile Ad hoc Networks." In: *Computers & Security* 30.1 (2011), pp. 63–80. DOI: 10.1016/j.cose.2010.10.008.

[234] Wenbo Xu, Alexander Willecke, Martin Wegner, Lars Wolf, and Rüdiger Kapitza. "Autonomous Maneuver Coordination via Vehicular Communication." In: *2019 49th Annual IEEE/IFIP International Conference on Dependable Systems and Networks Workshops (DSN-W)*. IEEE. 2019, pp. 70–77. DOI: 10.1109/DSN-W.2019.00022.

[235] Zhigang Xu, Xiaochi Li, Xiangmo Zhao, Michael H. Zhang, and Zhongren Wang. "DSRC Versus 4G-LTE for Connected Vehicle Applications: A Study on Field Experiments of Vehicular Communication Performance." In: *Journal of Advanced Transportation* 2017 (2017), pp. 1–11. DOI: 10.1155/2017/2750452.

[236] Jiaxin Yang, Benoît Pelletier, and Benoît Champagne. "Enhanced Autonomous Resource Selection for LTE-Based V2V Communication." In: *2016 IEEE Vehicular Networking Conference (VNC)*. IEEE. 2016, pp. 1–6. DOI: 10.1109/VNC.2016.7835937.

[237] Yang Yang, Ping Wang, Chao Wang, and Fuqiang Liu. "An eMBMS Based Congestion Control Scheme in Cellular-VANET Heterogeneous Networks." In: *17th International IEEE Conference on Intelligent Transportation Systems (ITSC)*. IEEE. 2014, pp. 1–5. DOI: 10.1109/ITSC.2014.6957656.

[238] Tao Yu, Shunqing Zhang, Shan Cao, and Shugong Xu. "Performance Evaluation for LTE-V based Vehicle-to-Vehicle Platooning Communication." In: *2018 24th Asia-Pacific Conference on Communications (APCC)*. IEEE. 2018, pp. 15–20. DOI: 10.1109/APCC.2018.8633551.

[239] Abdennour Zekri and Weijia Jia. "Heterogeneous Vehicular Communications: A Comprehensive Study." In: *Ad Hoc Networks* 75-76 (2018), pp. 52–79. DOI: 10.1016/j.adhoc.2018.03.010.

[240] Fuxin Zhang, Mengchu Zhou, Liang Qi, Yuyue Du, and Haichun Sun. "A Game Theoretic Approach for Distributed and Coordinated Channel Access Control in Cooperative Vehicle Safety Systems." In: *IEEE Transactions on Intelligent Transportation Systems* 21.6 (2020), pp. 2297–2309. DOI: 10.1109/TITS.2019.2916214.

[241] Shan Zhang, Jiayin Chen, Feng Lyu, Nan Cheng, Weisen Shi, and Xuemin Shen. "Vehicular Communication Networks in the Automated Driving Era." In: *IEEE Communications Magazine* 56.9 (2018), pp. 26–32. DOI: 10.1109/MCOM.2018.1701171.

[242] Xiangmo Zhao, Xiaochi Li, Zhigang Xu, and Ting Chen. "An Optimal Game Approach for Heterogeneous Vehicular Network Selection with Varying Network Performance." In: *IEEE Intelligent Transportation Systems Magazine* 11.3 (2019), pp. 80–92. DOI: 10.1109/MITS.2019.2919563.

[243] Jun Zheng and Qiong Wu. "Performance Modeling and Analysis of the IEEE 802.11p EDCA Mechanism for VANET." In: *IEEE Transactions on Vehicular Technology* 65.4 (2016), pp. 2673–2687. DOI: 10.1109/TVT.2015.2425960.

[244] Ghayet el mouna Zhioua, Houda Labiod, Nabil Tabbane, and Sami Tabbane. "A Multi-Metric QoS-Balancing Scheme for Gateway Selection in a Clustered Hybrid VANET Network." In: *2012 IEEE 8th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*. IEEE. 2012, pp. 150–156. DOI: 10.1109/WiMOB.2012.6379068.

[245] Ghayet el mouna Zhioua, Houda Labiod, Nabil Tabbane, and Sami Tabbane. "FQGwS: A Gateway Selection Algorithm in a Hybrid Clustered VANET LTE-Advanced Network: Complexity and Performances." In: *2014 International Conference on Computing, Networking and Communications (ICNC)*. IEEE. 2014, pp. 413–417. DOI: 10.1109/ICCNC.2014.6785370.

[246] Huan Zhou, Hui Wang, Xin Chen, Xiuhua Li, and Shouzhi Xu. "Data Offloading Techniques Through Vehicular Ad Hoc Networks: A Survey." In: *IEEE Access* 6 (2018), pp. 65250–65259. DOI: 10.1109/ACCESS.2018.2878552.

[247] Adam Ziebinski, Rafal Cupek, Hueseyin Erdogan, and Sonja Waechter. "A Survey of ADAS Technologies for the Future Perspective of Sensor Fusion." In: *Computational Collective Intelligence*. Springer International Publishing. 2016, pp. 135–146. DOI: 10.1007/978-3-319-45246-3_13.

[248] Peng Zou, Omur Ozel, and Suresh Subramaniam. "On Age and Value of Information in Status Update Systems." In: *2020 IEEE Wireless Communications and Networking Conference (WCNC)*. IEEE. 2020, pp. 1–6. DOI: 10.1109/WCNC45663.2020.9120792.

A APPENDIX

A.1 EXTENDED EVALUATION OF RELEVANCE-AWARE RESOURCE ALLOCATION

In this section, we show an extended evaluation of resource allocation in decentralized Vehicle-to-Everything (V2X) networks. We consider the parameters and scenario used in Section 7.3.

In the previous evaluation, we considered that the message frequency of vehicles is uniformly distributed in the first iteration. In the following, we analyze the performance of the considered approaches for a message frequency of 1 Hz and 250 vehicles. The scenario is specifically challenging for the adaptive approaches because all vehicles assess a low Channel Busy Ratio (CBR) in the first iteration and simultaneously adapt their message frequency in the next iterations. We want to verify if the adaptive approaches converge to a stable state and to which extent the results in the steady-state are comparable to our evaluation results in Section 7.3.

Channel busy ratio

Figure 41a depicts the CBR for 250 vehicles. We see that the CBR is 0.18 for all approaches in the first iteration because all vehicles send with a message frequency of 1 Hz. In the next iteration, NAIVE, R-DCC, and PRIORITY immediately increase the message frequency of all vehicles to 10 Hz. In contrast, A-DCC slowly increases the vehicles' message frequency, which increases the CBR. In the next iteration, PRIORITY and R-DCC decrease the message frequency of vehicles, which also decreases the CBR to 0.60 and 0.44, respectively. PRIORITY and R-DCC converge to a stable state after 4 iterations with a CBR of 0.72 and 0.44, respectively. The reason for the oscillating behavior of PRIORITY in the first 4 iterations is because of the higher adaptive gain factor β_R compared to A-DCC, allowing vehicles to allocate more resources per iteration. However, our parameterization still fulfills Equation 41 for 250 vehicles.

Normalized throughput

Figure 41b depicts the normalized throughput for 250 vehicles. We see that PRIORITY achieves a normalized throughput of 0.62 after only 4 iterations, also outperfomring the reference approaches in terms of convergence speed.

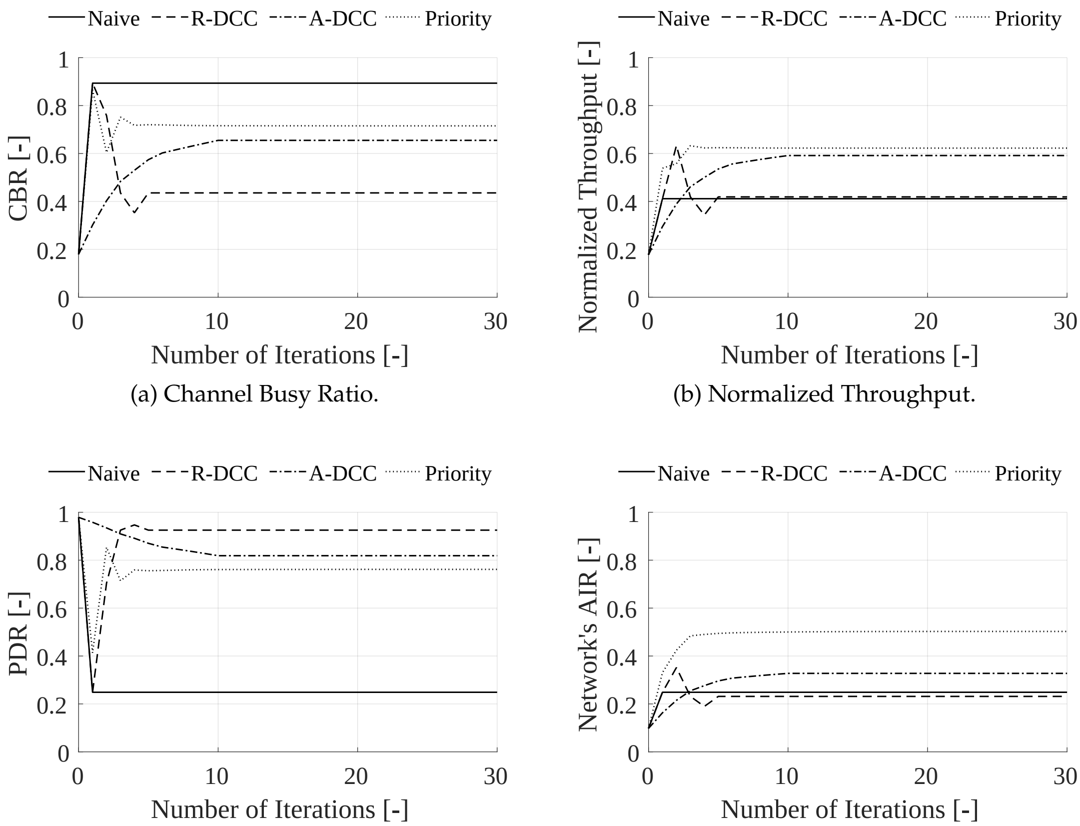
PDR

Figure 41c shows the Packet Delivery Ratio (PDR) for 250 vehicles. We see that all approaches have a high PDR of 0.98 in the first iteration because of the low vehicles' message frequency. However, all approaches achieve a similar performance in the steady-state compared to the evaluation in Figure 31c.

Network's AIR

Figure 41d depicts the network's Accessible Information Relevance (AIR) for 250 vehicles. We see that PRIORITY achieves a network's AIR of 0.50, similar to the results in Figure 31d. In contrast, the reference approaches R-DCC, A-DCC, and NAIVE only achieve a network's AIR of 0.23, 0.33, and 0.25, respectively.

In summary, we obtain results comparable to the evaluation in Section 7.3, where PRIORITY outperforms the reference approaches w. r. t. the normalized throughput and network's AIR. Moreover, we observed that in this challenging scenario, where all



(a) Channel Busy Ratio.

(b) Normalized Throughput.

(c) Packet Delivery Ratio.

(d) Network's AIR.

Figure 41: Evaluation of the communication quality metrics over a series of iterations for 250 vehicles and static information relevance.

vehicles start with a message frequency of 1 Hz, our approach converges to a stable state after only 4 iterations.

A.2 EXTENDED EVALUATION OF THE INFORMATION RELEVANCE DISTRIBUTION

In Section 7.3.3, we compared the achieved network's AIR for the considered approaches in a cooperative driving scenario. Each vehicle obtained its information relevance based on the approaching time of its trajectory towards other trajectories. A vehicle obtains a high information relevance for critical scenarios and a low information relevance otherwise. Figure 42 depicts the cumulative distribution of the vehicles' information relevance for a single simulation run using the PRIORITY approach performed in Section 7.3 with cooperative driving. Vehicles report their currently obtained information relevance in each update cycle, i. e., every 100 ms.

0.05 of the reported information relevance is 0, which is primarily from vehicles waiting at a red traffic light. Notably, vehicles waiting at a red light near the center of

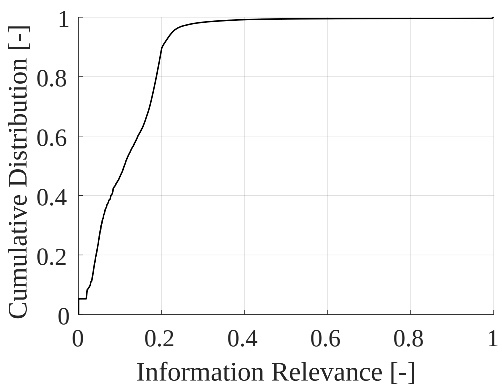


Figure 42: Cumulative distribution of the information relevance in a cooperative driving scenario.

the intersection have an information relevance greater than 0 because moving vehicles at a green light approach them.

Figure 42 also shows that 0.9 and 0.99 of all information relevance measurements are below 0.2 and 0.4, respectively. On the one side, Figure 42 shows that cooperation conflicts can be coordinated and solved early. Considering a safety time of 2 s, an information relevance of 0.2 and 0.4 is equal to an approaching time of 10 s and 5 s, respectively. The result also explains the low performance of the Risk and Risk Dynamic approaches, which trigger the maximum message frequency below an approaching time of 1.5 s.

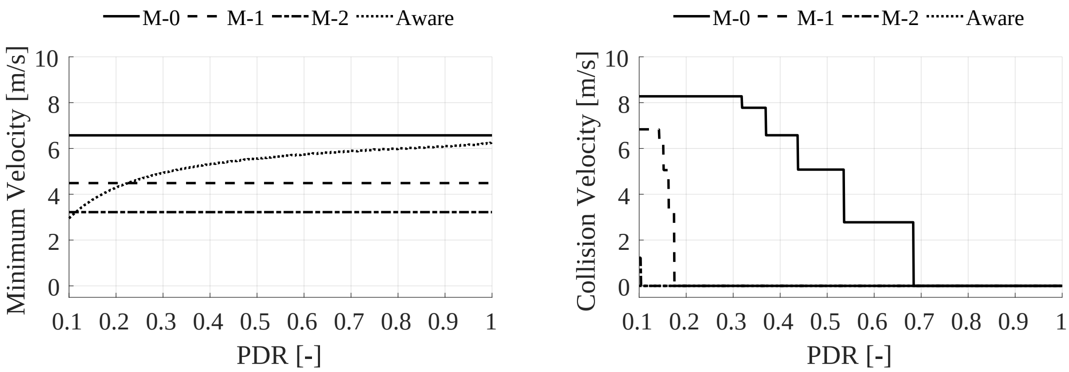
On the other side, Figure 42 confirms our assumption that only a few vehicles have a high information relevance and require to coordinate a cooperative maneuver.

A.3 EXTENDED EVALUATION OF COMMUNICATION-AWARE COOPERATIVE DRIVING

In this section, we present an additional numerical analysis of communication-aware cooperative driving to further analyze the impact of the probability to receive at least one message. The numerical analysis is performed with the same parameters and scenarios explained in Section 7.5. In the following, we analyze the effect of a probability of 0.9 and 0.99 to receive at least one message on traffic efficiency and safety for cooperative driving.

A.3.1 *Increasing the Traffic Efficiency of Communication-Aware Cooperative Driving*

Figure 43 depicts the traffic efficiency and safety performance of the considered approaches for a probability of 0.9 to receive at least one message. In contrast to a probability of 0.9999 to receive at least one message considered in Section 7.5, a probability of 0.9 to receive at least one message allows for higher traffic efficiency for the communication-aware approach even in scenarios with impaired communication quality. That is, the model-based assessed Age of Information (AoI) decreases with the probability to receive at least one message. Figure 43a compares the traffic efficiency



(a) Efficiency analysis of vehicle 1. (b) Safety analysis of vehicle 2.

Figure 43: Numerical analysis of a traffic safety and efficiency scenario for cooperative driving at an intersection for a probability of 0.9 to receive at least one message.

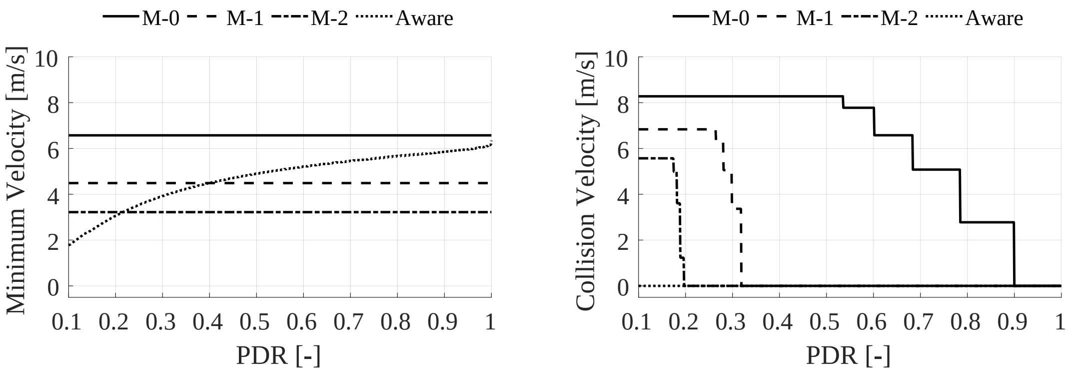
of the different approaches for a PDR between 0.1 and 1.0. We see that the reference approaches achieve the same performance compared to the evaluation reported in Figure 39a. However, the traffic efficiency of the Aware approach significantly increases the minimum velocity of vehicle 1 to 2.95 m/s for a PDR of 0.1. In contrast, for a probability of 0.9999 to receive at least one message, the Aware approach only achieved a minimum velocity of 1.18 m/s.

Figure 43b depicts the collision velocity for the safety scenario of the different approaches. For comparison, we also consider that vehicles must receive one message with a probability of 0.9. As expected, the Aware approach maintains safety for all PDRs. We note that the lower probability to receive at least one message requirement significantly affects the safety performance of the reference approaches. According to Figure 43b all considered approaches maintain traffic safety above a PDR of 0.68. The M-0 approach can reduce the collision severity up to a PDR of 0.32. Furthermore, the M-1 and M-2 approaches maintain traffic safety for a PDR above 0.18 and 0.1, respectively.

A.3.2 *The Sweet-Spot between Traffic Efficiency and Safety*

In the previous evaluation, we have seen that a low probability to receive at least one message increases the traffic efficiency performance of the Aware approach. However, a low probability to receive at least one message also decreases the robustness to message loss in a safety scenario. Figure 44 depicts the traffic efficiency and safety performance for a probability of 0.99 to receive at least one message.

Figure 44a shows the traffic efficiency performance of the different approaches. The Aware approach achieves a minimum velocity of 1.78 m/s for a PDR of 0.1. Interestingly, we only increase the minimum velocity by 0.6 m/s in contrast to a probability of 0.9999 to receive at least one message for a PDR of 0.1. However, the minimum velocity is



(a) Efficiency analysis of vehicle 1.

(b) Safety analysis of vehicle 2.

Figure 44: Numerical analysis of a traffic safety and efficiency scenario for cooperative driving at an intersection for a probability of 0.99 to receive at least one message.

reduced by 1.17 m/s in contrast to a probability of 0.9 to receive at least one message, as depicted in Figure 43a.

Lastly, the collision velocity for the different approaches for a probability of 0.99 to receive at least one message is depicted in Figure 44b. We again confirm that the Aware approach maintains traffic safety for all considered PDRs. The M-0, M-1, M-2 maintain safety for a PDR above 0.9, 0.32, and 0.20, respectively.

3GPP	Third Generation Partnership Project
A-DCC	Adaptive Decentralized Congestion Control
ADAS	Advanced Driver Assistant Systems
AIFS	Arbitration Inter-Frame Spacing
AIR	Accessible Information Relevance
AoI	Age of Information
ASIL	Automotive Safety Integration Level
BTP	Basic Transport Protocol
CAM	Cooperative Awareness Message
CBR	Channel Busy Ratio
CDD	Common Data Dictionary
CMM	Collaborative Maneuver Message
COMPASS	Cross-layer Coordination of Multiple Vehicular Protocols
CPM	Collective Perception Message
CQI	Channel Quality Index
DCC	Decentralized Congestion Control
DCF	Distributed Coordination Function
DENM	Decentralized Environmental Notification Message
DSRC	Dedicated Short Range Communication
ECC	Electronic Communications Committee
EDCA	Enhanced Distributed Channel Access
ERA	Environmental Risk Awareness
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
GAC	GeoAnycast
GBC	GeoBroadcast
GBD	Geometry-based Deterministic
GBS	Geometry-based Stochastic
GUC	GeoUnicast
INTERN	Integration of congestion and awareness control
ITS	Intelligent Transport Systems
LDM	Local Dynamic Map
Limeric	Linear Message Rate Integrated Control
LoS	Line of Sight

LTE	Long Term Evolution
MAC	Medium Access Control
MCM	Maneuver Coordination Message
NGS	Non-Geometry-based Stochastic
NIC	Network Interface Card
NLoS	Non-Line of Sight
OFDM	Orthogonal Frequency-Division Multiplexing
OSI	Open Systems Interconnection
OSM	OpenStreetMap
PATH	Perceived Awareness over Time Horizon
PDR	Packet Delivery Ratio
POTI	Position and Timing
ProSe	Proximity Service
QoS	Quality of Service
R-DCC	Reactive Decentralized Congestion Control
RSU	Roadside Unit
SCO	Single-Channel Operation
SHB	Single-Hop Broadcast
TCP	Transmission Control Protocol
TDRC	Transmission Data Rate Control
TPC	Transmission Power Control
TraCI	Traffic Control Interface
TRC	Transmission Rate Control
TSB	Topologically-Scoped Broadcast
UDP	User Datagram Protocol
URLLC	Ultra-Reliable Low-Latency Communication
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VANETs	Vehicular Adhoc Networks
VDP	Vehicle Data Provider
VoI	Value of Information
VVLC	Vehicular Visible Light Communication

[1] David Baran. "Proactive Adaptation of Heterogeneous V2X Communication Networks for Cooperative Maneuver Coordination." Master Thesis. TU Darmstadt, 2021.

[2] Markus Bommer. "Network-Based Safety and Efficiency Optimization for Cooperative Left-Turning at Intersections." Master Thesis. TU Darmstadt, 2021.

[3] Carsten Englert. "Cooperative Distribution of Channel Information in Vehicular Communication Networks Using Game Theory." Master Thesis. TU Darmstadt, 2020.

[4] Youssef Haridy. "Implementation and Simulative Evaluation of Coordination Algorithms for the Cooperative Maneuver Planning Based on Vehicle-to-Vehicle Communication." Master Thesis. TU Darmstadt, 2020.

[5] Lukas Heidt. "Heterogeneous Communication in Vehicular Networks: Influence Factors on the Performance of 802.11p and LTE-A." Student Research Project. TU Darmstadt, 2018.

[6] Justin Hopp. "Game Theoretical Approach to Obtain Information Relevance and Improving Communication-Based Cooperative Vehicular Maneuver Coordination." Master Thesis. TU Darmstadt, 2020.

[7] Balint Klement. "Generating Computational Efficient Trajectories to Support Large-Scale Simulation for Cooperative Maneuver Coordination." Master Thesis. TU Darmstadt, 2020.

[8] Jens Lemke. "Adaptive Dissemination of Information Using the Condition of Cooperative Maneuver Coordination in Heterogeneous V2X Communication Networks." Bachelor Thesis. TU Darmstadt, 2020.

[9] Michael Matthé. "Context-Based Message Generation Rules for Decentralized Cooperative Maneuvering in Vehicular Adhoc Networks." Master Thesis. TU Darmstadt, 2020.

[10] Lukas Schnarz. "Relevance-Based Efficiency Increase of Adhoc Communication for Cooperative Maneuver Coordination at Intersections." Bachelor Thesis. TU Darmstadt, 2020.

[11] Antonio Schneider. "Framework to Compare Dissemination Strategies in V2X Networks for Cooperative Maneuver Coordination." Bachelor Thesis. TU Darmstadt, 2020.

B

AUTHOR'S PUBLICATIONS

MAIN PUBLICATIONS

[1] Daniel Bischoff. "Poster: Proactive Adaptation of Heterogeneous V2X Communication for Safety-Relevant Applications." In: *Netsys*. IEEE. 2019, pp. 1–2.

[2] Daniel Bischoff, Harald Berninger, Steffen Knapp, Tobias Meuser, Björn Richerzhagen, Lars Häring, and Andreas Czylwik. "Safety-Relevant V2X Beaconing in Realistic and Scalable Heterogeneous Radio Propagation Fading Channels." In: *5th International Conference on Vehicle Technology and Intelligent Transport Systems (VEHITS 2019)*. Scitepress. 2019, pp. 1–8. DOI: 10.5220/0007712904040411.

[3] Daniel Bischoff and Tobias Meuser. "Geo-Based Backend Dissemination for Safety-Relevant V2X Applications." In: *AmE 2019 - Automotive meets Electronics; 10th GMM-Symposium*. IEEE. 2019, pp. 1–6.

[4] Daniel Bischoff, Florian Schiegg, Tobias Meuser, Dieter Schuller, Nils Dycke, and Ralf Steinmetz. "What Cooperation Costs: Quality of Communication and Cooperation Costs for Cooperative Vehicular Maneuvering in Large-Scale Scenarios." In: *Proceedings of the 6th International Conference on Vehicle Technology and Intelligent Transport Systems (VEHITS 2020)*. Scitepress. 2020, pp. 394–405.

[5] Daniel Bischoff, Florian Schiegg, Tobias Meuser, and Ralf Steinmetz. "Impact of Imperfect Communication on Cooperative Vehicular Maneuvering at Intersections." In: *2020 IEEE 91th Vehicular Technology Conference (VTC Spring)*. IEEE. 2020, pp. 1–5. DOI: 10.1109/VTC2020-Spring48590.2020.9128485.

[6] Daniel Bischoff, Florian A. Schiegg, Tobias Meuser, Dieter Schuller, and Ralf Steinmetz. "Adaptive Heterogeneous V2X Communication for Cooperative Vehicular Maneuvering." In: *Smart Cities, Green Technologies, and Intelligent Transport Systems*. Ed. by Cornel Klein, Markus Helfert, Karsten Berns, and Oleg Gusikhin. Springer. Cham: Springer International Publishing, 2021, pp. 228–254. DOI: 10.1007/978-3-030-89170-1_12.

[7] Daniel Bischoff, Florian A. Schiegg, Dieter Schuller, Jens Lemke, Benjamin Becker, and Tobias Meuser. "Prioritizing Relevant Information: Decentralized V2X Resource Allocation for Cooperative Driving." In: *IEEE Access* (2021), pp. 135630–135656. DOI: 10.1109/ACCESS.2021.3116317.

[8] Johan Thunberg, Daniel Bischoff, Florian A. Schiegg, Tobias Meuser, and Alexey Vinel. "Unreliable V2X Communication in Cooperative Driving: Safety Times for Emergency Braking." In: *IEEE Access* (2021), pp. 148024–148036. DOI: 10.1109/ACCESS.2021.3124450.

[9] Florian Jomrich, Daniel Bischoff, Steffen Knapp, Tobias Meuser, Björn Richerzhagen, and Ralf Steinmetz. "Lane Accurate Detection of Map Changes based on Low Cost Smartphone Data." In: *Proceedings of the 5th International Conference on Vehicle Technology and Intelligent Transport Systems (VEHITS 2019)*. Scitepress. 2019, pp. 126–137. DOI: 10.5220/0007709401260137.

[10] Viktor Lizenberg, Daniel Bischoff, Youssef Haridy, Ulrich Eberle, Steffen Knapp, and Frank Koester. "Simulation-Based Evaluation of Cooperative Maneuver Coordination and Its Impact on Traffic Quality." In: *SAE WCX Digital Summit*. SAE. 2021, pp. 1–11. DOI: 10.4271/2021-01-0171.

[11] Tobias Meuser, Daniel Bischoff, Björn Richerzhagen, and Ralf Steinmetz. "Cooperative Offloading in Context-Aware Networks: A Game-Theoretic Approach." In: *Proceedings of the 13th ACM International Conference on Distributed and Event-Based Systems*. ACM. 2019, pp. 55–66. DOI: 10.1145/3328905.3338535.

[12] Tobias Meuser, Daniel Bischoff, and Ralf Steinmetz. "Location Privacy in Heterogeneous Vehicular Networks." In: *Proceedings of the 13th ACM International Conference on Distributed and Event-Based Systems*. DEBS '19. ACM. Darmstadt, Germany: Association for Computing Machinery, 2019, pp. 260–261. DOI: 10.1145/3328905.3332515. URL: https://doi.org/10.1145/3328905.3332515.

[13] Tobias Meuser, Daniel Bischoff, Ralf Steinmetz, and Björn Richerzhagen. "Simulation Platform for Connected Heterogeneous Vehicles." In: *Proceedings of the 5th International Conference on Vehicle Technology and Intelligent Transport Systems (VEHITS 2019)*. Scitepress. 2019, pp. 412–419. DOI: 10.5220/0007713004120419.

[14] Florian A. Schiegg, Daniel Bischoff, Johannes R. Krost, and Ignacio Llatser. "Analytical Performance Evaluation of the Collective Perception Service in IEEE 802.11p Networks." In: *2020 IEEE Wireless Communications and Networking Conference (WCNC)*. 2020, pp. 1–6. DOI: 10.1109/WCNC45663.2020.9120490.

[15] Florian A. Schiegg, Ignacio Llatser, Daniel Bischoff, and Georg Volk. "Collective Perception: A Safety Perspective." In: *Sensors* 21.1 (2021), pp. 1–23. DOI: 10.3390/s21010159.

C

ERKLÄRUNG LAUT DER PROMOTIONSORDNUNG

§8 Abs. 1 lit. c PromO

Ich versichere hiermit, dass die elektronische Version meiner Dissertation mit der schriftlichen Version übereinstimmt.

§8 Abs. 1 lit. d PromO

Ich versichere hiermit, dass zu einem vorherigen Zeitpunkt noch keine Promotion versucht wurde. In diesem Fall sind nähere Angaben über Zeitpunkt, Hochschule, Dissertationsthema und Ergebnis dieses Versuchs mitzuteilen.

§9 Abs. 1 PromO

Ich versichere hiermit, dass die vorliegende Dissertation selbstständig und nur unter Verwendung der angegebenen Quellen verfasst wurde.

§9 Abs. 2 PromO

Die Arbeit hat bisher noch nicht zu Prüfungszwecken gedient.

Darmstadt, 30. November 2021

Daniel Bischoff