Beiträge aus der Informationstechnik

Mobile Nachrichtenübertragung
Nr. 102

Richard Jacob

On Reliability Enhancements of Safety-Critical Vehicle-to-Vehicle Communications

VOGT

Dresden 2024

Bibliografische Information der Deutschen Nationalbibliothek
Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über http://dnb.dnb.de abrufbar.

Bibliographic Information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at http://dnb.dnb.de.

Zugl.: Dresden, Techn. Univ., Diss., 2024

Die vorliegende Arbeit stimmt mit dem Original der Dissertation „On Reliability Enhancements of Safety-Critical Vehicle-to-Vehicle Communications“ von Richard Jacob überein.

Gesetzt vom Autor

ISBN 978-3-95947-074-2

Jörg Vogt Verlag
Niederwaldstr. 36
01277 Dresden
Germany

Phone: +49-(0)351-31403921
Telefax: +49-(0)351-31403918
e-mail: info@vogtverlag.de
Internet : www.vogtverlag.de

Technische Universität Dresden

Faculty of Electrical and Computer Engineering
Institute of Communication Technology
Vodafone Chair Mobile Communications Systems

Doctoral Dissertation

On Reliability Enhancements of Safety-Critical Vehicle-to-Vehicle Communications

Richard Jacob

1. Reviewer Prof. Dr.-Ing. Dr. h.c. Gerhard Fettweis
Fakultät Elektro- und Informationstechnik
Technische Universität Dresden

2. Reviewer Prof. Dr.-Ing. Andreas Festag
Fakultät Elektro- und Informationstechnik
Technische Hochschule Ingolstadt

Supervisors Prof. Dr.-Ing. Dr. h.c. Gerhard Fettweis

Date of the submission: 02.10.2023
Date of the defence: 22.12.2023

Richard Jacob
On Reliability Enhancements of Safety-Critical Vehicle-to-Vehicle Communications
Doctoral Dissertation, Date of the submission: 02.10.2023
Date of the defence: 22.12.2023
Reviewers: Prof. Dr.-Ing. Dr. h.c. Gerhard Fettweis and Prof. Dr.-Ing. Andreas Festag
Supervisor: Prof. Dr.-Ing. Dr. h.c. Gerhard Fettweis

Technische Universität Dresden
Vodafone Chair Mobile Communications Systems
Institute of Communication Technology
Faculty of Electrical and Computer Engineering
Helmholtzstr. 18
01062 and Dresden

Abstract

The reliable, low-latency exchange of sensor and control information between vehicles enables cooperative driving which allows to significantly increase road safety and traffic efficiency. Vehicular short-range communication based on IEEE 802.11p was specifically designed for safety-critical Vehicle-to-Vehicle (V2V) communication. Its successor 802.11bd promises reliability enhancements by employing packet repetitions, which allow to exploit the wireless channel diversity through packet combining. However, as the added channel load increases the interference is the root cause of access loss, repetitions require a careful medium allocation. This work provides a novel comprehensive study on the trade-off between combining gain and access loss based on extensive performance modeling of both time- and frequency-domain repetitions. The results show significant combining gains which increase with the channel selectivity, and a benefit of frequency diversity at low vehicle mobility that motivates the use of multi-channel repetitions. However, as the related load increase leads to more collisions, the observed gains quickly diminish in multi-user scenarios, resulting in rising packet loss and access delays. To maximize the gains the trade-off is investigated based on system-level simulations with variable traffic load. A methodology to determine the optimal number of repetitions for a given channel state expressed by the Channel Busy Ratio (CBR) is presented. Based on the CBR thresholds, the distributed allocation under time-varying load conditions is evaluated. The results show a trade-off between allocation stability, achieved by short and steady-state performance, achieved by long observations. To deal with this trade-off, the dynamic adaptation of the CBR observation based on channel behavior is proposed. Further, the multi-channel repetitions are investigated, showing worse oscillations due to the bandwidth increase. Strategies to suppress oscillations are discussed, among which an iterative allocation which estimates the impact of the allocation decision, shows the best results. As with the introduction of the Cellular V2X (C-V2X) technology mixed deployments are inevitable, the coordination of the heterogeneous technologies has become crucial to fulfill the requirements of the diverse vehicular applications. Finally, the redundant operation of 802.11p/bd and C-V2X in ad-hoc mode is investigated as a further option to improve the communication reliability. Overall this work contributes to the understanding of how to enhance the reliability of V2V communications by distributed repetition allocation. It can be concluded that a threshold-based repetition allocation allows to increase the reliability at the cost of a tolerable delay increase.

Acknowledgement

I want to express my deepest gratitude to my family: my mother, my father and my grandparents, for all the love and support they provided on the long journey towards this thesis. Having a family that is always there for you is the greatest gift you can get, that is something I just realized when my mother died. With her positive energy and her unbelievable patience my girlfriend Annie helped me through this worst time of my life, which I am extremely grateful for.

A big thanks goes to my supervisor Professor Gerhard Fettweis for giving me the opportunity to pursue my doctoral studies, the scientific guidance along the way and the generous funding that provided me the freedom to focus on writing this thesis. Further, I want to thank my former group leader Andreas Festag for believing in my skills and guiding me through the beginning of my scientific career. A special thanks goes to my group leader Nick Schwarzenberg who always motivated me to go on with my research, no matter how desperate I was. Without his guidance and constant support finishing this thesis would not have been possible.

I am also grateful for my team members Andreas Traßl, Friedrich Burmeister and Waqar Anwar for all the fruitful discussions that helped me progress with my research. This progress was also driven by the work of my diploma students Joshwa Pohlmann, Shimeng Huang and Lingjie Li, which I highly appreciate. Finally, I want to thank all the lovely colleagues of the Vodafone Chair who made the daily work at the chair a joy and kept me motivated. Thanks for plenty of great memories especially to Martin Danneberg, Sebastian Kühlmorgen, Christoph Jans, Martin Schlüter, Eva Schmitt, Viktor Razilov and Stephan Zeitz.

Contents

1 Introduction

Motivation for Reliable Vehicle-to-Vehicle Communication

Climate change, a growing earth population, and a steadily increasing consumption of the planet's limited resources drive the need for more sustainable, yet efficient and affordable mobility solutions. In recent years, Autonomous Driving (AD) has gained tremendous interest, promising to revolutionize road mobility by making it more convenient and safe. However, current driving systems, as well as those under development, rely on onboard sensor vision and ego path planning only. This means they lack the cooperation with other vehicles that would allow them to coordinate their driving maneuvers making them more efficient and safe. Accordingly, to the opinion of the author, the benefit of these systems is limited to passenger satisfaction, their ecologic as well as economic footprint is too high and safety improvements are questionable. Combining automated driving systems with wireless communication technologies not only allows to facilitate information exchange to decrease reaction times and enable beyond Line of Sight (LOS) vision but also enables cooperative maneuver planning. This vision of Cooperative Automated Driving (CAD) is expected to decrease the number of accidents meanwhile significantly enhancing traffic efficiency in terms of a reduction of driving times and fuel consumption.

To achieve safe cooperation among vehicles in proximity reliable Vehicle-to-Vehicle (V2V) communication is required. Typically, reliability is associated with avoiding packet loss, i.e. achieving a low Packet Error Rate (PER), which is challenging in vehicular propagation environments due to fast-changing channel conditions. However, from an application-perspective, a transmission is only successful if the packet is delivered within the desired time frame. To achieve efficient maneuver cooperation and to guarantee quick reaction times this end-to-end delay needs to be kept reasonably low. Besides low PER and delay, a reliable communication system also needs to provide ubiquitous connectivity to achieve safe driving under all conditions, independent from the availability of a communications infrastructure, e.g. base stations. In contrast, the communication also needs to be scalable to achieve a low PER and delay even in scenarios with high traffic load, e.g. an urban intersection.

State-of-the-Art in Vehicle-to-Vehicle Communication

In 2010 the IEEE 802.11 standard amendment IEEE 802.11p [IEE10] for vehicular short-range communications, further also referred to as 11p, was introduced to address these V2V-specific requirements. Designed as native radio access interface for Dedicated Short Range Communication (DSRC), it enables the generation and geographic dissemination of standardized V2X messages which are adressing safety-critical awareness and warning applications, e.g., emergency brake warning. It uses a downclocked version of the 802.11a Physical Layer (PHY) resulting in $10\,\mathrm{MHz}$ channels, of which 7 were reserved in the $5.9\,\mathrm{GHz}$ band dedicated to V2X communication in Europe. The channels are accessed in a decentralized fashion using Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA), combining carrier sensing to detect concurrent transmissions with collision avoidance based on a backoff procedure. In combination with instantaneous communication achieved by avoiding association procedures, this not only guarantees ubiquitous connectivity independent from network infrastructure but also achieve relatively low access delays below $1\,\mathrm{ms}$. Investigations on IEEE 802.11p have been carried out for more than a decade [JD08]. Due to ubiquitous connectivity combined with low transmission delays, it has proven favorable for V2V communications compared to cellular technologies such as Fourth Generation Cellular Networks (4G) [Xu+17]. Even though it can be considered as a mature technology it has not been deployed on a large scale yet. The reasons are ranging from missing legislation to limited benefits for first-day users at low penetration rates.

Since 2010 not only the targeted warning applications have evolved to CAD use cases, but with the Fifth Generation Cellular Networks (5G) new radio technologies are addressing the automotive market. Cellular V2X (C-V2X), which started as an advanced feature of 4G networks (4G-V2X) and further evolves in 5G-V2X, brings several enhancements to the existing Uu interface (interface between radio access network and user equipment), to improve the reliability of unicast and to enable geographic multicast transmissions. Furthermore, it introduces the PC5 sidelink interface known from Device-to-Device (D2D) communications which enables direct communication between vehicles in proximity, similar to 11p. To address the increased reliability requirements of modern driving applications and to stay competitive against C-V2X, the development of a new generation of vehicular short-range technologies was started in 2018. With the finalization of the new IEEE 802.11bd standard [IEE16a] in 2023, also referred to as 11bd, several features to enhance transmission reliability were introduced. Most prominently the new signal structure with midambles avoids outdated channel estimates and hence fixes 11p's bad performance in doubly selective fading channels occurring in high-mobility environments. To further increase robustness against channel fading causing a degradation of transmission reliability packet repetitions with packet combining were introduced.

Enhancing the Reliability of Vehicle-to-Vehicle Communication

Channel fading describes strong fluctuations of the received power that are caused by the superposition of the signal from several reflection paths. As each reflection observes a different delay according to its path length, as well as a frequency shift caused by the Doppler effect, the channel gain and phase vary with time. In vehicular environments with rich multi-path environments with lots of scatters and high vehicle mobility, these fluctuations can be particularly strong, challenging the receiver to successfully decode the packet. When employing repetitions these undesired fluctuations are being exploited. As each of the redundant copies is sent at a different time instance, each of them observes a different fading realization leading to a different distribution of bit errors over the packet duration. This is also referred to as channel diversity, which can be exploited by combining multiple faulty packets to obtain a decodable version of the original packet. Accordingly, from the link-level perspective, the combining of packet repetitions achieves significant Signal-to-Noise Ratio (SNR) gains [Mar+19] that allow to drastically increase the transmission reliability and range.

However, the link-level perspective only considers a single link and hence omits the multi-user interference which cannot be prevented in CSMA/CA networks. Hidden nodes and the selection of the same resources lead to packet collisions. The higher the channel occupation, the more collisions occur. As for safety-critical V2V communication, the receivers are typically not known, acknowledging transmission is not feasible. Further, even for a group of known transceivers the number of acknowledgments sent would quickly flood the channel leading to channel congestion causing severe packet loss and excessive access delays. Instead of retransmitting packets when no acknowledgement is received, as typically done in IEEE 802.11 networks, the packets are blindly repeated. Still, repeating packets causes a severe increase in interference levels, potentially causing congestion, especially when they are being repeated multiple times. To achieve congestion-awareness and hence to maximize the communication reliability, this trade-off between reliability enhancements achieved by combining individual transmissions and the performance degradation caused by the resulting channel load increase need to be evaluated. Therefore, suited system-level models for repetitions taking into account both PHY and Medium Access Layer (MAC) effects need to be developed, that allow to determine the optimal number of repetitions in dependency of the load state. Based on the models and results, approaches for the allocation of repetitions in a distributed fashion under the time-varying load conditions need to be developed and evaluated.

Heterogeneous Vehicle-to-Vehicle Communication

The vision of CAD not only relies on V2V but also on communication with the roadside infrastructure, referred to as Vehicle-to-Infrastructure (V2I), and the network, referred to as Vehicle-to-Network (V2N). In addition to the different endpoints, the requirements of the different Vehicle-to-Everything (V2X) applications range from best-effort., e.g., driver entertainment, to safety-critical services, e.g., remote control in case of a driving system failure. These heterogeneous services are challenging the communication system with diverse requirements and render a hybrid approach, where short-range are combined with cellular technologies, inevitable. This way for each service or even packet the best-suited technology can be selected among the available ones. In case no technology can achieve the application's Quality of Service (QoS) requirements, multiple can be combined to be either aggregated for higher throughput per user or redundantly operated to increase the system reliability. Concepts for the coordination of short-range and cellular technologies need to be developed to support the diverse performance requirements of the various V2X applications. Besides the coordination of heterogeneous technologies, with the introduction of C-V2X ad-hoc sidelink, the coordination of technologies with similar performance characteristics became relevant. Especially due to the deployment of both technologies by different manufacturers, mixed deployments are becoming inevitable, the redundant operation of both technologies needs to be evaluated.

Contributions

To address the described research problems, this work provides the following contributions: Chapter 2 summarises the background on vehicular communication systems. It gives an introduction to the V2X protocol stack, vehicular short-range technologies based on IEEE 802.11 technology, and how reliability in wireless communications systems can be achieved. Further, the related work is summarized. Next, in Chapter 3 the developed link- and system-level simulation models are introduced, based on which a comprehensive analysis of packet repetitions for IEEE 802.11bd is conducted. On link-level, the performance in terms of PER vs. SNR of both time- and frequency-repetitions is evaluated for V2V-specific fading channels. Using the link-level error curves the Packet Reception Ratio (PRR), describing the ratio between successful and expected receptions, and the packet delay is evaluated on system-level, as a function of the traffic load. Based on the results, approaches to achieve congestion-aware repetition allocation are presented in Chapter 4. Therefore, the allocation under constant load conditions is evaluated and a methodology to derive the optimal number of repetitions for a given channel state, expressed by the Channel Busy Ratio (CBR) thresholds, is presented. It is discussed how to adapt the thresholds for deployment in real-world scenarios. Next, the distributed allocation of repetitions based on the derived CBR thresholds is evaluated by showing the impact of different CBR observation widows on stability and steady-state performance. Finally, to maximize the combining gain, minimize the access delay, and prevent congestion, the allocation of repetitions to multiple frequency channels is proposed. Further, multi-channel allocation strategies based on the single-channel CBR thresholds are discussed. In Chapter 5 approaches for the coordination of heterogeneous V2X technologies are presented. To increase the reliability of V2V technologies, the redundant operation of IEEE 802.11 technology and PC-5-based ad-hoc communication is evaluated. Finally, the work is concluded in Chapter 6.