

# Vehicular Communications

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The case for research, development, and deployment of vehicular communications is a strong one. Arguments are made and elaborated on in numerous papers, including those that make up this Special Issue and our Point of View feature in the 2010 July issue of the PROCEEDINGS [1]. We will therefore be brief here and just recount some of the more compelling reasons for why we should care about this technology.

Consider the question “What was the second most common cause of death for 5–29 year olds in 2002?” If this question was posed in a more general context than here, we doubt that many would know the correct answer: road traffic injuries, according to a World Health Organization (WHO) report [2]. We can quote many other alarming statistics from [2], including

- 1.4 million dead and up to 50 million injured on a yearly basis;
- total estimated economic cost of USD 518 billion, of which the estimated USD 65 billion affecting low-income countries exceeds the amount received in development assistance.

Clearly, we, humans in general and engineers in particular, should do something to reduce these appalling numbers. Reducing the number of ac-

cidents will have many other positive effects including more efficient use of fuel, time, and other resources, i.e., contribute to make the transport system sustainable.

Vehicular communications is defined in this Special Issue as vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications, collectively referred to as V2X communications. With infrastructure in V2I, we mean road infrastructure, such as traffic light, street signs, etc., which is not to be confused with communications infrastructure, such as access points (APs) or base stations. V2X communications is an enabling technology for cooperative traffic safety systems, i.e., systems in which vehicles and road infrastructure cooperates to avoid or mitigate the effects of accidents. For obvious reasons, vehicular communications needs to be wireless. Although free-space optical systems, e.g., infrared communications, are used, radio is dominating. Many existing radio systems, such as traditional cellular and satellite systems, can and are used for vehicular communications. However, new technology is emerging to cover the case when the supported latency or coverage of existing technology is

**Vehicular Communications is vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications, collectively referred to as V2X communications; the focus of this special issue is on key challenges, including modeling of radio channels, physical and medium access techniques, simulation methods, and standardization of V2X systems.**

not good enough. The new technology is based on direct communications without the aid of communication infrastructure, e.g., base stations, satellites or access points.

In this Special Issue, we will focus our attention on key problems in these new systems: modeling of radio channels, physical and medium access techniques, simulation methods, and standardization of V2X systems. Admittedly, this is not a comprehensive coverage of the field, since we are not treating important problems such as security, privacy, and routing in V2X networks. However, a prudent pruning of the scope of the Special Issue was needed for space constraints.

The nine papers that make up this Special Issue will follow a top-down-top approach in which we first explore the current standardization effort carried out by primarily the IEEE and the European Telecommunications Standards Institute (ETSI), then we will dive down to issues related to vehicular radio channels, and work our way up the communication stack by discussing the physical and medium access layers, and finish by describing modeling and simulation approaches.

Standards are crucial for cost-efficient deployment of V2X technology. The first paper by Kenney describes in detail the 75 MHz-wide dedicated spectrum allocation in the United States and the standards IEEE 802.11p, IEEE 1609.1–1609.4, SAE J2735, and SAE J2945-1, that make up the bulk of the V2X protocol stack in the United States, also known as Wireless Access in Vehicular Environments (WAVE). Most of these standards have been published within the past 18 months and are reaching a certain level of a maturity. However, the IEEE 1609.2 (Security Services) and SAE J2945-1 (Minimum Performance Requirements) standards are first expected in late 2011.

The second paper by Ström briefly describes the European Intelligent Transport System (ITS) architecture, which has been developed mainly by ETSI. This architecture is, in general,

different from WAVE. However, both architectures are based on IEEE 802.11p, which is good news for chip and vehicular manufacturers. The focus of Ström's paper is on European spectrum allocation, which is less generous and only partly overlapping with the United States allocation, and ETSI's profile of IEEE 802.11p, called ITS-G5. A common conclusion from Kenney's and Ström's papers is that future work on congestion control is required (which is the topic of the paper by Sepulcre *et al.* described below).

The third paper by Mecklenbräuker *et al.*, describes the key characteristics of V2X channels, i.e., shadowing by other vehicles, high Doppler shifts, and the inherent non-stationarity, which all have a major impact on transmission reliability and latency. The paper provides an overview of the existing V2V and V2I channel measurements, reviews currently available vehicular channel models, and point out their respective merits and deficiencies. Antenna and their placement on the vehicles, which will have a major impact on the achievable performance, are discussed. The paper is concluded by exploring the implications of V2X channels and antennas on wireless system designs in general and on the IEEE 802.11p physical (PHY) layer in particular. The paper points out that further work on channel measurements and channel modeling is needed, as V2X channels are not completely understood. Moreover, a key conclusion is that the PHY layer should be designed with respect to the properties of the propagation channels, in particular to the time-varying joint Doppler and delay spread. In this respect, the IEEE 802.11p PHY layer would profit, e.g., from a better pilot distribution and the introduction of multiple transmit and receive antennas.

The fourth paper by Alexander *et al.* presents the results from extensive V2X field trial campaigns conducted with IEEE 802.11p equipment in Australia, Italy,

Germany, Austria, and the United States, covering over 1100 km of driving in a wide variety of physical environments. The field trials show that commercial off-the-shelf (COTS) equipment sometimes fail to provide good enough performance, especially in nonline-of-sight (NLOS) propagation environments. However, much better results were achieved with IEEE 802.11p-compliant equipment that employs more sophisticated channel estimation and tracking. Hence, the Alexander *et al.* and the Mecklenbräuker *et al.* papers are in complete agreement about the importance of this point. Moreover, the paper presents delay and Doppler spreads statistics based on the accumulated field trial measurements.

The fifth paper by Sturm and Wiesbeck makes a case for a joint radar and communication (RadCom) system. Together with cameras and lidars (Light Detection And Ranging), radars are the most commonly used type of sensor on vehicles. A RadCom system could potentially solve the essential tasks of environmental sensing and V2X communications more efficiently than two separate systems. The authors propose waveform designs, suitable for simultaneously performing both data transmission and radar sensing, and discuss a variety of possible radar processing algorithms. Multiple antenna techniques for direction-of-arrival estimation are also considered.

The sixth paper by Sepulcre *et al.* starts from the observation that, if countermeasures are not undertaken, the V2X radio channel will most likely be saturated even under normal vehicular traffic conditions. Radio channel congestion causes unstable V2X communications, thus putting the whole cooperative vehicular system concept at risk. In the paper, Sepulcre *et al.* surveys and classifies various decentralized methods to control the load on the radio channel and to ensure each vehicle's capacity to detect and communicate with the *relevant* neighboring vehicles. A particular focus is on approaches based on transmit

power and rate control. Open research challenges that are imposed by different application requirements and potential existing contradictions are also discussed at the end of the paper.

Cost-efficient design and analysis of V2X systems requires that computer simulations are complementing field trials. In fact, some design tasks are simply not feasible without efficient and accurate computer simulations, because of the cost and time required by field trials. The final three papers of this Special Issue address the tradeoff between simulation accuracy and efficiency from different perspectives.

The seventh paper by Giordano *et al.* propose a method for classifying the propagation situation between two nodes using a reverse geocoding algorithm based on a digital map and the nodes' geographical positions. The method, named CORNER, estimates the presence of buildings and obstacles along the signal path using information extrapolated from urban digital maps. The classification, into line-of-sight (LOS) and two types of NLOS propagation, can be used with any channel models that are tailored to these situations. The authors validate CORNER (with a specific set of path-loss models) by comparing simulations with on-the-road experiments. The results indicate that

CORNER is able to predict the network connectivity with high accuracy.

The eighth paper by Reichardt *et al.* addresses how the interaction between antennas, vehicles, and the propagation environment can be captured in a computer simulation tool. As stressed earlier in this Special Issue, multiple antennas are important for improving V2X communication performance. However, finding the optimal antenna configuration is a difficult task. A possible solution is to use prototypes and measurement campaigns, but this is expensive, time consuming, and has problems with repeatability. As an alternative, the authors describe a tool that uses environment and vehicular traffic models together with a 3D ray-tracing algorithm to calculate the multipath propagation, including the antennas, between the transmitters and receivers. This tool enables virtual driving through arbitrary scenarios and is therefore called "Virtual Drive." It is shown in the paper that the tool agrees well with V2V channel measurements in an urban and a highway scenario. The tool can also be used for radar applications.

The ninth paper by Mittag *et al.* is concerned with merging network and link simulators with realistic channel models. Many existing V2X communication studies have been conducted

using either network or physical layer simulators; both approaches are problematic because of oversimplified modeling. Network simulators typically abstract physical layer details (coding, modulation, radio channels, receiver algorithms, etc.) while physical layer ones do not consider overall network characteristics (topology, network traffic types, and so on). To overcome these shortcomings, the authors present the integration of a detailed physical layer simulator into the popular NS-3 network simulator, with the aim to allow for more accurate studies on cross-layer optimization. The authors exemplify this approach by integrating an IEEE 802.11p physical layer simulator into NS-3 and validate this against an IEEE 802.11 wireless testbed. The integrated simulator is made available online for the benefit of the research community.

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## REFERENCES

[1] E. G. Ström, H. Hartenstein, P. Santi, and W. Wiesbeck, "Vehicular communications: Ubiquitous networks for sustainable

mobility. *Proc. IEEE*, vol. 98, no. 7, pp. 1111–1112, Jul. 2010.

[2] M. Peden, R. Scurfield, D. Sleet, D. Mohan, A. A. Hyder, E. Jarawan, and C. Mathers, Eds., *World Report on Road Traffic Injury*

*Prevention*, World Health Organization, Geneva, 2004, Accessed Mar. 2011. [Online]. Available: [http://www.who.int/violence\\_injury\\_prevention/publications/road\\_traffic/world\\_report/en/](http://www.who.int/violence_injury_prevention/publications/road_traffic/world_report/en/)

## ABOUT THE GUEST EDITORS

**Erik G. Ström** (Senior Member, IEEE) received the M.S. degree from the Royal Institute of Technology (KTH), Stockholm, Sweden, in 1990 and the Ph.D. degree from the University of Florida, Gainesville, in 1994, both in electrical engineering.

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ment, Stockholm, Sweden. His research interests include signal processing and communication theory in general, and constellation labelings, channel estimation, synchronization, multiple access, medium access, multiuser detection, wireless positioning, and vehicular communications in particular.

Dr. Ström received the Chalmers Pedagogical Prize in 1998 and the Chalmers Ph.D. Supervisor of the Year award in 2009. He is a contributing author and associate editor for Roy Admiralty Publishers FesGas-series, and was a Co-Guest Editor for the *IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS* Special Issues on Signal Synchronization in Digital Transmission Systems (2001) and on Multiuser Detection for Advanced Communication Systems and Networks (2008). He was a member of the board of the IEEE VT/COM Swedish Chapter 2000–2006. He leads the competence area Sensors and Communications at the traffic safety center SAFER hosted by Chalmers.

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Dr. Hartenstein has been TPC Co-Chair and General Chair of various highly selective ACM and IEEE international workshops and symposia on vehicular communications.

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Dr. Santi is Associate Editor of *IEEE TRANSACTIONS ON MOBILE COMPUTING* and *IEEE TRANSACTIONS ON PARALLEL AND DISTRIBUTED SYSTEMS*, he has been General Co-Chair of ACM VANET 2007 and 2008, and he is involved in the organizational and technical program committee of several conferences in the field. He is a Member of IEEE Computer Society and a Senior Member of ACM and SIGMOBILE.



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Dr. Wiesbeck is a member of the IEEE GRS-S AdCom (1992–2000), Chairman of the GRS-S Awards Committee (1994–1998, 2002), Executive Vice President IEEE GRS-S (1998–1999), President IEEE GRS-S (2000–2001), Associate Editor *IEEE-AP Transactions* (1996–1999), past Treasurer of the IEEE German Section (1987–1996, 2003–2007). He has been General Chairman of the 1988 Heinrich Hertz Centennial Symposium, the 1993 Conference on Microwaves and Optics (MIOP '93), the Technical Chairman of International mm-Wave and Infrared Conference 2004, Chairman of the German Microwave Conference GeMIC 2006, and he has been a member of the scientific committees and TPCs of many conferences. For the Carl Cranz Series for Scientific Education, he serves as a permanent lecturer for Radar systems engineering, wave propagation and mobile communication network planning. He is a member of an Advisory Committee of the EU—Joint Research Centre (Ispra/Italy), and he is an Advisor to the German Research Council (DFG), to the Federal German Ministry for Research (BMBF) and to industry in Germany. He is the recipient of a number of awards, lately the IEEE Millennium Award, the IEEE GRS Distinguished Achievement Award, the Honorary Doctorate (Dr.h.c.) from the University Budapest/Hungary, the Honorary Doctorate (Dr.-Ing.E.h.) from the University Duisburg/Germany and the IEEE Electromagnetics Award 2008. He is a Fellow of IEEE, an Honorary Life Member of IEEE GRS-S, a Member of the IEEE Fellow Committee, a Member of the Heidelberger Academy of Sciences and Humanities, and a Member of the German Academy of Engineering and Technology (ACATECH).

