1 Introduction

Vehicular networking, the exchange of information in the car and between cars, has been on the mind of researchers since at least the often-cited 1939 New York World's Fair. Here, in its *Futurama* exhibit, General Motors revealed utopian visions of what highways and cities might look like twenty years later. In fact, many of the visions of intelligent transportation systems (ITSs) showcased there, as well as in the exhibit designer's 1940 book *Magic Motorways* (Bel Geddes 1940), such as that "car-to-car radio hook-up might be used to advise a driver nearing an intersection of the approach of another car or even to maintain control of speed and spacing of cars in the same traffic lane", are still being pursued today. Modern vehicles collect huge amounts of information from on-board sensors, and this information is made available to the in-car network and ready for sharing with other cars – not just for the described visions of intersection assistance systems and platooning, i.e., road-train applications, but also for a whole wealth of new applications. Today, with *in*-car networks merging into networks *of* cars, these early visions seem closer to reality than ever.

But why did we have to wait this long?

Hugely many research projects have been undertaken since *Magic Motorways* was written, all of which tried to make visions of ITS a reality (Jurgen 1991). Among the most notable of research initiatives were the Japanese CACS, US ERGS, and European ALI projects for urban route guidance in the late 1960s to late 1970s, the European Prometheus project for autonomous driving (1986–1995), and the US PATH project for cooperative driving (1986–1992). Evidently, the majority of these initiatives led to working prototypes and successful field operational tests; yet, commercial success failed to match the projects' promises.

A possible explanation is given by Chen & Ervin (1990): early approaches were simply too visionary for their time, commonly focusing on infrastructure-less solutions, which could not be supported by current technology. The 1980s then saw a shift of attention from the more long-term goals of complete highway automation to nearer-term goals such as driver-advisory functions. However, for the same reasons, attention shifted also from infrastructure-less to infrastructure-assisted solutions, resulting in what the authors called a *chicken-and-egg* type of standoff in the deployment of what were called intelligent vehicle–highway system (IVHS) solutions:

> The automotive and electronics industries are skeptical as to whether the public infrastructure for IVHS will materialize. (Without an infrastructure, of course, there will be no market for cooperative IVHS products on-board the vehicle or on the highway.)

Highway agencies are skeptical as to whether IVHS technologies will deliver solutions to real highway problems. (Without a sound expectation of public benefit, of course, public investment is unjustified.)

In the years since this 1990 article, however, these premises have changed considerably, causing interest in inter-vehicle communication (IVC) research to re-ignite.

First, with the commercial deployment of latest-generation cellular communication technology, there is now an almost universal communication infrastructure available. In fact, commercially available versions of what could be described as early IVC systems are already on the market, e.g., *On Star* (1995), *BMW Assist* (1999), *FleetBoard* (2000), and *TomTom HD Traffic* (2007), after which the number of IVC systems all but exploded. The new-found optimism with regard to IVC communication research can also be seen expressed in countries' allocation of dedicated short-range communication (DSRC) bands for the sole use of vehicular short-range wireless communication (in 1999 by the US FCC, followed in 2008 by the European ECC). New technologies to work in this spectrum have been conceived and, together with cellular networks, will allow future vehicles to exchange information in order to *cooperate* on the road.

Second, computing power has increased many-fold, enabling modern vehicles to collect and process data under tight temporal constraints, allowing enhanced degrees of *automation*. Radar, laser scanners, infrared and three-dimensional (3D) surround-view systems, fully networked with other systems in the car, are all shipping in modern vehicles or are planned for upcoming generations. In mid 2011, the state of Nevada passed a law allowing autonomous (that is, driver-less) vehicles to drive on its roads, and the first car was licensed roughly one year later (though it is still requiring at least two people on board to take over manual control if needed).

These two trends, increasing automation and increasing cooperation of vehicles, are now promising to merge. Vehicles' in-car networks are extended beyond the boundaries of their bodies, creating truly *intelligent transportation systems*.

When designing future vehicular networks it is therefore important to keep the broad picture of both in-vehicle and inter-vehicle communications in mind, as well as to consider the whole range of available communication paradigms and technologies from wired bus systems to wireless in-car networks and from wireless cellular to short-range radio communication.

From this holistic point of view, the research on vehicular networking solutions has been re-initiated in the second decade of the twenty-first century. This research perspective establishes a multi-disciplinary effort. The vehicular networking community reconvened at Dagstuhl, an internationally renowned meeting and seminar place, in 2013 to reconsider the developments in our field from both an academic and an industrial point of view. The main outcomes include new research directions and a new focus on open challenges that need to be addressed in order to enable day-one IVC applications.

We are now entering an era that might change the game in road-traffic management. The vehicular networking field is shifting from early academic research ideas to application-oriented research and development to global deployment. Large-scale field operational tests (FOTs) are taking place both in Europe and in the USA, helping decision makers such as the National Highway Traffic Safety Administration (NHTSA) and the US Department of Transportation (US DOT) to prepare recommendations to make DSRC technology mandatory for new cars.

This textbook is the first of its kind to investigate the common concepts of all vehicular networking approaches, their limits, what unifies them, and how they differ, as well as to take a detailed look at how the challenges of vehicular networks are met by selected techniques and technologies – both with a look back on how they evolved and with one eye on their potential future.

We also address two issues that are at the heart of research into new vehicular networking approaches: First, how to conduct a rigorous scientific evaluation of their feasibility and performance – both in a way that produces insightful results close to real life and in a way that can help advance science; and second, how to design systems in a way that ensures both the security of the system and the privacy of its users.

Before we do so, however, it might be a good idea to take a brief look at the vocabulary of vehicular networking as well as at the key players in the field.

1.1 Terms and definitions

Much of the terminology that we will be using in this book has a very clear-cut definition, but in many cases the original meaning has been diluted in common use or in the media, mixed with other definitions or supplanted altogether. With this in mind, to avoid misunderstandings in the following, let us briefly go over some of the basic terminology that may lead to confusion, considering its use over the last few decades.

One of the most obvious families of terms that are being used in vehicular networking consists of those referring to the communicating network itself.

Vehicular networking is what we adopted as the most general classifier, referring to the field of computer communications and networking as applied to vehicles. Vehicular networking thus encompasses both in-car and inter-vehicle communication aspects as well as their fusion.

Inter-vehicle communication (IVC) restricts this to exclude wired communication as well as any network (wired or wireless) within vehicles. It thus refers to a system where vehicles are participants in a wireless network. Other participants such as roadside units (RSUs) can explicitly be part of this network.

Vehicular ad-hoc network (VANET) has its origins in the discipline of mobile ad-hoc networks (MANETs), casting VANETs as a novel application domain. Being the basis for what we call IVC today, the term is still somewhat synonymous with IVC, but focuses on spontaneously created ad-hoc networks, much less on pre-deployed infrastructure like using RSUs or cellular networks.

Intelligent transportation system (ITS) describes the overall goal of being able to make better use of transportation networks, for which road networks are one of many such networks and IVC is one means among many. Lately, other modes of transportation have faded into the background and ITS has become synonymous with intelligent *road* networks. The precursor goals to ITS were intelligent vehicle–highway systems (IVHSs), aiming more at making roads smarter, before smart vehicles were considered an option.

Vehicle to vehicle (V2V) as well as **vehicle to infrastructure (V2I)** and **vehicle to X (V2X)**, all refer to the end points of communication, indicating whether information is being exchanged with other vehicles, with infrastructure (also called vehicle-to-roadside), or with arbitrary nodes – independently of the technology being used. Colloquially, some use substitutes the somewhat shorter word *car* for *vehicle* (forming C2C, C2I, and C2X) to refer to the same concepts.

A second group of terms consists of those related to the communication technology employed:

IEEE WAVE and ETSI ITS are complete communication architectures comprising a protocol stack together with needed facilities and regulatory provisions for IVC.

IEEE 802.11 Wireless LAN (WLAN) is the base technology for the most commonly used short-range wireless communication protocols, both for consumer networking and for IVC. The term **WiFi** refers to that subset of IEEE 802.11 that is part of the certification the Wi-Fi Alliance provides for consumer networking devices.

IEEE 802.11p and dedicated short-range communication (DSRC) have become synonymous with the use of IEEE 802.11 for IVC. IEEE 802.11p is the amendment that introduced many of the missing parts of functionality in the IEEE 802.11 family needed for efficient IVC – most notably operation at around 5.9 GHz. This radio band is known in the USA as the dedicated short-range communications (DSRC) radio band.

Finally, we have to deal with generic terminology, which we include mainly for the sake of completeness.

A channel seems to be the most irritating term. In general, it refers to a means of transporting information over a medium, wired or wireless. Multiple channels can be provided on a single medium by subdividing it via multiple access schemes, most commonly into time slots or frequency bands. For convenience, channels provided by frequency-division multiple access (FDMA) are commonly referred to not by their frequency range or their center frequency, but by a channel number, assigned in the respective standards of communication technology. To give an example, IEEE 802.11 specifies for its orthogonal frequency-division multiplexing (OFDM) physical layer a channel number of 178 to refer to a channel centered at 5.890 GHz.

The penetration rate refers to which fraction of all vehicles are equipped with IVC technology. It indicates how vehicle density (on the road) relates to node density (in the network). Other names for this fraction are equipment rate or market penetration.

Self-organization describes a control paradigm supporting a self-governing approach of network participants. No global state is maintained in the network and no centralized coordination is required (Dressler 2007).

1.2 Who is who

Many businesses and organizations worldwide are stakeholders in vehicular networking. From rulemaking, via regulation and standardization, to manufacturing, there are many entities involved that we want to give a brief overview of. Furthermore, we outline the key research dissemination and networking platforms.

1.2.1 Rulemaking, regulation, and standardization

In the context of in-vehicle networking, little rulemaking is needed, since vehicle busses constitute closed systems and vehicle manufacturers are free to follow an industry standardization process. In the context of IVC, extensive rulemaking, regulation, and standardization are required, because one brand's vehicles naturally need to be able to communicate with other manufacturers' vehicles. Moreover, radio spectrum is heavily regulated by countries' governments. In fact, whole books, e.g., that by Williams (2008) to name just one, have been written on the processes of rulemaking and standardization in the context of ITS. In this book, we are focusing on organizations from those countries in which today's top automobile manufacturers are based: Japan (e.g., Toyota, Nissan, Honda), the USA (e.g., General Motors, Ford), and Europe (e.g., Volkswagen, Daimler, BMW).

In Japan, spectrum is managed by its Ministry of Internal Affairs and Communications (MIC). Spectrum allocation is the result of an involved public consultation process, after which spectrum is allocated to specific uses. For implementing studies and implementing standardization processes, the MIC (or, rather, one of its precursor ministries, the Ministry of Posts and Telecommunications), chartered the creation of the Association of Radio Industries and Businesses (ARIB). ARIB counts over 200 companies and organizations as its members: aside from all of the major telecommunication companies, and those involved with research and development of radio technologies, all major automobile manufacturers are members.

In the USA, spectrum allocation and rulemaking is the task of the US Federal Communications Commission (FCC), an independent agency of the government. The FCC frequently adopts standards by reference. Standards are created by independent organizations, such as ASTM International, which are comparable to other national standards bodies like ANSI or DIN. It frequently collaborates with other organizations, in our context most prominently with the IEEE Standards Association, an organization within the Institute of Electrical and Electronics Engineers (IEEE).

In the European Union (EU), spectrum allocation in its constituent countries is governed by the European Commission, which issues decisions that need to be implemented by EU member states and associated countries. For this, the European Commission issues mandates to the European Conference of Postal and Telecommunications Administrations (Conférence Européenne des Postes et Télécommunications, CEPT), one committee of which is the Electronic Communications Committee (ECC), which is tasked with developing rulemaking for communications. For developing standards, the CEPT also created the European Telecommunications Standards Institute (ETSI) as an independent, not-for-profit, standardization organization. Today, the ETSI numbers 750 member organizations from 63 countries around the world. Its output, harmonized standards, serves as input for ECC spectrum regulations, which are the input for European Commission decisions.

Higher-layer standards lend themselves better to international standardization. Among the most active formal international standardization bodies are the International Organization for Standardization (ISO) and the International Telecommunication Union (ITU). The ISO comprises national standards organizations from around the world, with standardization conducted by its technical committees (TCs). The ITU, in particular its ITU Telecommunication Standardization Sector (ITU-T), is a United Nations agency that investigates technical or operational questions with the goal of providing recommendations for standardization worldwide; that is, it does not issue standards itself, even though these ITU-T recommendations are used as *de facto* standards in many domains.

This is complemented by specialized national standardization bodies, e.g., the Society of Automotive Engineers (SAE), and industry special interest groups like the Wi-Fi Alliance (for a particular short-range wireless radio standard) and the AVnu Alliance (for a particular in-vehicle networking standard).

1.2.2 Research

Long-term research activities towards future vehicular networking concepts that are more visionary in nature are discussed in the context of an international research seminar series, the *Dagstuhl Seminar on Inter-Vehicular Communication*, which is hosted at the world-renowned center for computer science of the German computer science community. Its last meetings took place in 2010 and 2013 (Dressler *et al*. 2011a, 2014). Traditionally, this seminar series brings together practitioners from many branches of industry and researchers from computer science, electrical engineering, traffic sciences, business, and other fields.

Research results in the scope of vehicular networking are published in a variety of journals and conference proceedings. Cross-cutting developments are regularly published in one of the many journals and magazines covering general networking topics, such as the

- *IEEE Journal on Selected Areas in Communications*,
- *IEEE/ACM Transactions on Networking*,

- *IEEE Transactions on Mobile Computing*,
- *Elsevier Ad Hoc Networks*,
- *IEEE Communications Letters*, and
- *IEEE Communications Magazine*.

Of special note is that, twice a year, the *IEEE Communications Magazine* publishes an issue of its Automotive Series. Among the periodicals that are focused more on the vehicular domain are the

- *IEEE Transactions on Vehicular Technology*,
- *IEEE Vehicular Technology Magazine*, and
- *IEEE Transactions on Intelligent Transportation Systems*.

Active research is, as always, being presented and published in the context of international conferences. Again, more general approaches are most commonly published at conferences focusing on networking as a whole. These conferences regularly dedicate one or more of their tracks to vehicular networking or host specialized workshops on this topic. The leading conferences are the

- IEEE Conference on Computer Communications (INFOCOM),
- ACM International Conference on Mobile Computing and Networking (MobiCom),
- ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc),
- IEEE International Conference on Communications (ICC), and
- IEEE Global Telecommunications Conference (GLOBECOM).

More focused on vehicular networking is the IEEE Vehicular Technology Conference (VTC), which hosts two complementary yearly editions, in spring and fall. Finally, in 2009 major vehicular networking workshops merged to form a conference, which is also seeing a major influx of attendees from previous flagship workshops such as ACM VANET. This conference is the IEEE Vehicular Networking Conference (VNC).

1.3 How to use this book

In the following, we briefly outline the structure of the book and comment on a recommended reading approach depending on the reader's profile.

1.3.1 Target audience

We decided to design the textbook for a broad range of readers, from graduate students to academics who need a comprehensive overview of the current vehicular networking approaches and future research issues, and practitioners from the communications and automotive industries.

The book is structured in a way that allows beginners and those moving into the field to first get a higher-level overview as well as allowing experts in the domain to use the book as a quick reference providing in-depth studies of selected approaches to vehicular networking. This textbook can readily be used for a university class dedicated to vehicular networking and as supplementary material in any other computer networking and communications class.

Our main focus is first on introducing both in-vehicle networking techniques and approaches for inter-vehicle communication. We summarize these chapters as an "overview for non-experts" in Section 1.3.2. Secondly, we investigate concepts for inter-vehicle communication in detail, also studying methods for evaluating the performance of these approaches as well as security and privacy related concerns. The related chapters are subsequently discussed as "in-depth studies for the experienced reader" in Section 1.3.3.

1.3.2 Overview for non-experts

We organize this overview into two chapters, one focusing on in-vehicle networking, the other on inter-vehicle communication. We highly recommend the reader to start with these chapters – both providing a comprehensive overview of the respective field but not investigating all the little technical details. For the expert reader, it is reasonable to skip these chapters and start with those described in Section 1.3.3.

Intra-vehicle communication (Chapter 2)

After motivating the need for actual networking (i.e., bus systems and message forwarding as opposed to dedicated wire connections), this chapter discusses the makeup and the roles of the individual networking components, with a special focus on electronic control units (ECUs) as parts of automotive bus systems. It continues by describing the evolution of these components as well as of on-board and off-board networking standards, from simple LIN to Gigabit Ethernet. The chapter highlights their fundamental commonalities and differences, as well as lessons learned from less successful standards. A look at recent trends and early implementation efforts concludes the chapter.

- Discussion of networking as such, components (ECUs, gateways)
- Bus systems (LIN, CAN, MOST, FlexRay, trends towards in-car Ethernet)
- Wireless in-vehicle networking

Inter-vehicle communication (Chapter 3)

Communication between vehicles and between vehicles and available infrastructure is the topic of this chapter. Essentially, a basic introduction to IVC is given, identifying the key application domains of safety, efficiency, and entertainment. This chapter derives all the relevant communication concepts and solutions for those applications and, most importantly, identifies the minimum requirements such as maximum delays, minimum dissemination range, or minimum data rates. Furthermore, an overview on the possible communication paradigms is presented, such as whether information is to be exchanged without the help of any available infrastructure or whether infrastructure elements – RSUs, parking vehicles, or even widely deployed cellular networks – can be used for the information exchange.

- Applications: safety, efficiency, entertainment. Sample use cases such as intersection warning/assistance systems, platooning management, traffic information systems, traffic-light information and control, multimedia streaming, multiplayer games.
- Concepts, solutions, requirements: Example applications and proposed solutions, requirements on the communication technology (delays, reliability, dissemination range, data rates).
- Infrastructure-based vs. infrastructure-less: Ad-hoc communication, store–carry–forward, roadside units, stationary support units, cellular networks.

1.3.3 In-depth studies for the experienced reader

Being already familiar with the concept of inter-vehicle communication, we now explore the protocols and concepts in more detail. This part is organized into two chapters on key networking aspects (access and information dissemination) and two additional chapters focusing on performance evaluation and on security and privacy issues. These chapters do not necessarily build upon each other. The material is composed to establish both a general reference and the basis for an in-depth study of vehicular networking solutions, e.g., in the scope of a graduate-level university class or an extended seminar on the topic.

Access technologies (Chapter 4)

Any application relying on inter-vehicle communication demands a particular set of network characteristics. In this chapter, we discuss access technologies that have been considered for IVC. This chapter outlines all relevant aspects of cellular communication technology and introduces dedicated short-range communications/wireless access in vehicular environments (DSRC/WAVE) as a key player in the IVC domain. In this field, specifically IEEE 802.11 is discussed in its WiFi versions as well as in the form of the IEEE 802.11p protocol, which is the basis for DSRC/WAVE. Furthermore, the use of white spaces for IVC as is currently being considered in Japan is discussed.

- Cellular networks: Introduction to GSM, UMTS, and LTE-A; approaches using cellular networks for IVC.
- Short-range radio: IEEE 802.11, EDCA, WAVE, and ITS-G5 concepts, frequencies, IEEE 802.11p.
- White spaces and cognitive radio: Principles, cognitive radio, using white spaces for IVC.

Information dissemination (Chapter 5)

The objective of this chapter is to discuss typical vehicular network layer protocols in detail. The key objective is information exchange between any two vehicles, from one vehicle to all neighboring ones, from one vehicle to infrastructure components, from infrastructure to one or all neighboring vehicles, and dissemination from a vehicle to all those which are interested in the content. This chapter details the basic principles underlying such IVC approaches, namely unicast, local broadcast, anycast, and multicast communication principles as used in vehicular networks. This also includes the current IEEE and ETSI standards such as cooperative awareness messages (CAMs) and decentralized environmental notification messages (DENMs) for local broadcast and geocast for multi-hop transmissions. The main focus is on the most recent beaconing solutions inluding extensions providing congestion control and fair resource sharing. Furthermore, more sophisticated re-broadcasting and delay/disruption-tolerant network (DTN) concepts are described.

- Routing: MANET routing, applicability to IVC, impact of RSUs.
- Beaconing: Static beaconing, adaptive beaconing periods, adaptive transmission power, ATB, ETSI ITS-G5 DCC, DynB.
- Geocast: Geographic routing, convex networks, coordinate transformation, virtual coordinate-based routing, geographically constrained broadcasting.
- DTN concepts: Store–carry–forward, roadside units, heterogeneous vehicular networks.

Performance evaluation (Chapter 6)

The chosen methodology greatly influences the quality of performance evaluation. Field operational tests are being conducted in many areas and have provided some very helpful first results. Yet, large-scale experimentation is conceptually infeasible. Thus, simulation is still the method of choice for most performance studies. This chapter concerns how such simulations should be performed in the field of IVC and which tools are freely available to aid researchers. The key concern is the correct and realistic modeling of the vehicles' mobility. Besides that, the 'correct' choice of the scenario has a strong influence on the expressiveness, the validity, and the comparability of simulation experiments. This chapter also studies the impact of radio signal propagation models, the influence of the human driver's behavior, and suitable metrics for finally assessing the performance.

- Field operational tests: Measurement strategies, examples of field operational tests.
- Network simulation: Basic models and tools for network simulation, the use of these tools for IVC, scalability.
- Road traffic simulation: Road traffic microsimulation, traffic flow simulation, scalability.
- Simulation frameworks: IVC simulation frameworks Veins, iTetris, VSimRTI.
- Scenarios: Intersections, highway scenarios, impact of number of lanes, suburban and urban scenarios.
- Channel models: Freespace, two-ray, Nakagami-m, shadowing by buildings and other vehicles.
- Metrics: Classical network simulation metrics (delay, throughput, etc.) vs. application-dependent metrics (travel time, CO_2 emission, safety).

Security and privacy (Chapter 7)

Especially with the engagement of the major industry players to bring IVC into the market, the need to secure the communication between vehicles and the infrastructure