Vehicular Networking

With this essential guide to vehicular networking, you'll learn about everything from conceptual approaches and state of the art protocols to system designs and their evaluation.

Covering both in-car and inter-vehicle communication, this comprehensive work outlines the foundations of vehicular networking and demonstrates its commercial applications, from improved vehicle performance to entertainment and traffic information systems. All of this is supported by in-depth case studies and detailed information on proposed protocols and solutions for access technologies and information dissemination, as well as topics on rulemaking, regulations, and standardization. Importantly, for a field that is attracting increasing commercial interest, you'll learn about the future trends of this technology, its problems, and solutions to overcome them.

Whether you are a student, a communications professional, or a researcher, this is an invaluable resource.

Christoph Sommer is Assistant Professor in the Distributed Embedded Systems Group at the University of Paderborn. He created and gave tutorials and keynotes about Veins, one of the best-known vehicular networking simulation frameworks. He has about 50 papers in this field alone and has been active in this community as a general chair of IEEE/IFIP WONS and as co-founder of FG-IVC.

Falko Dressler is Professor and head of the Distributed Embedded Systems Group at the University of Paderborn. He is a Senior Member of the IEEE and ACM, as well as an IEEE Distinguished Lecturer in the fields of inter-vehicular communication, self-organization, and bio-inspired and nano-networking. He was TPC and general chair of a dozen international conferences on vehicular networking, created a Dagstuhl seminar series, and has given tutorial lectures at all major IEEE conferences on this topic.

"Sommer and Dressler have done a painstakingly thorough and solid review of the highly dispersed field of vehicular networking – all the way from in-vehicle networks to V2X, and to privacy and security issues. Destined to be an authoritative book in this area."

Onur Altintas, Toyota InfoTechnology Center

"This book provides an excellent coverage of all the important aspects of vehicular networking. It is very well written and of great value for a broad spectrum of readers including researchers, engineers in the automotive industry, and people who are not in this area but who would like to learn the basics of this exciting new field."

Ozan K. Tonguz, Carnegie Mellon University

"This is the best comprehensive guide to existing and emerging automotive networks. Whether interested in connecting components inside vehicles or networking vehicles with the outside world – it is worth reading for anyone trying to understand technology options and research results in this field."

Marco Gruteser, Rutgers University

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Preface

The intensive use of networked embedded systems is one of the key success factors in the automotive industry, also triggering a massive shortening of innovation cycles. Hundreds of so-called electronic control units (ECUs), connected by kilometers of electrical wiring, operate in today's modern car, enabling a huge variety of new functionalities ranging from safety to comfort applications. All this functionality can be realized only if the ECUs are able to communicate and to cooperate using a real-time enabled communication network in the car.

Today we are at the verge of another leap forward: This in-car network is being extended to not only connect local ECUs but also to connect the whole car to other cars and its environment using inter-vehicle communication (IVC). Relying on existing wireless Internet access using cellular networks of the third (3G) or fourth generation (4G), or novel networking technologies that are being designed specifically for use in the vehicular context such as IEEE WAVE, ETSI ITS-G5, and the IEEE 802.11p protocol, it becomes possible to use spontaneous connections between vehicles to exchange information, promising novel and sometimes futuristic applications.

Using such IVC, safety-relevant information can be exchanged that could not have been obtained using local sensors, enabling a driver to virtually see traffic through large trucks or buildings. This new idea of networked vehicles creates opportunities to not only increase road traffic safety but also improve our driving experience. Traffic jams can be prevented altogether (or at least we would be informed of jams well in advance) – and we might even be able to enable the driver to enjoying fully automated rides in a train-like convoy of cooperating vehicles on the road.

Vehicular networking, the fusion of vehicles' networks to exchange information, is the common basis on which all of these visions build.

Being fascinated with all the opportunities and challenges related to vehicular networking, we have been a part of this research community for close to ten years. In this time, many new and sometimes crazy ideas have been formulated regarding how to connect the cars of the future. Many of these ideas have been found not suitable after thorough investigation – yet, several survived and paved the road for what are now close to market-ready solutions.

From a research perspective, we are able to identify many open challenges, both in in-car and in inter-vehicle communication systems. To investigate these further, we co-organized two Dagstuhl seminars inviting leading experts from all over the world and bringing together practitioners from industry and scientists from research institutes and

universities. In this context, we were able to formulate directions guiding the ongoing research activities at least in the medium term.

We also established a complementary seminar series for newcomers to the field, which is being organized in the context of the international FG-IVC series of seminars by the German computer science and electrical engineering societies GI and ITG.

This textbook is based on a tutorial series on the same topic presented at all the major IEEE conferences including IEEE CCNC, IEEE ICC, IEEE GLOBECOM, and IEEE VTC, as well as in the scope of Falko Dressler's IEEE Distinguished Lecturer Tours in Europe, the USA, South America, and the Asia–Pacific region. We also designed a new graduate-level university class, which is being held at different universities in Europe.

This has inspired us to gather our experiences in the form of a textbook, collecting in one place the common concepts of past and future vehicular networking topics for a broad range of readers – from students who want to enter this exciting new field to practitioners looking for a comprehensive overview.

This book would not have been possible without the many people who have inspired and supported us over the last decade in our research activites on vehicular networking – first and foremost the community centering around the IEEE Vehicular Networking Conference, the premier conference in the field. In particular we'd like to name Professors Ozan K. Tonguz (CMU) and Mario Gerla (UCLA) who collaborated with us on investigating some of the aforementioned crazy ideas, and finally identifying valuable and lasting solutions. The tutorial lectures mentioned above were prepared together with Dr. Onur Altintas (Toyota ITC) and Professor Claudio Casetti (Politecnico di Torino). We also wish to express our appreciation for the support we received from the most helpful staff at Cambridge during the preparation of this book. Finally, we would like to sincerely thank our families, friends, and colleagues for their enduring help and support.

We hope you will enjoy reading this textbook as much as we enjoyed preparing its contents for you. We gladly welcome any feedback and invite you to leave us a note or peruse the supplementary material we are offering on this book's companion website http://book.car2x.org/.

Christoph Sommer and Falko Dressler
Paderborn, Germany

Abbreviations

3GPP	Third Generation Partnership Project, *the group that specified GSM, UMTS, and LTE*
3GPP2	Third Generation Partnership Project 2, *a competing group that specified CDMAone, CDMA2000, and UMB*
AAA	American Automobile Association
ABS	Anti-lock braking system
AC	Access category
ACC	Adaptive cruise control
ACK	Acknowledgement
ACO	Ant colony optimization
ADAC	German Automobile Association (Allgemeiner Deutscher Automobilclub)
ADAS	Advanced driver assistance system
ADQR	Adaptive dispersity QoS routing
AHS	Automated highway system
AIFS	Arbitration interframe space
ALDL	Assembly-line diagnostic link
AODV	Ad-hoc on-demand distance vector
AP	Access point
API	Application programming interface
AQOR	Ad-hoc QoS on-demand routing
ARIB	Association of Radio Industries and Businesses
ASTM	American Society for Testing and Materials
ATB	Adaptive traffic beacon
ATIS	Alliance for Telecommunications Industry Solutions
AVB	Audio/video bridging
BGP	Border gateway protocol
BMBF	Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung)
BMVBS	Federal Ministry of Transport, Building and Urban Development (Bundesministerium für Verkehr, Bau und Stadtentwicklung)
BMWi	Federal Ministry of Economics and Technology (Bundesministerium für Wirtschaft und Technologie)
BPSK	Binary phase-shift keying

BSC	Base station controller
BSM	Basic safety message
BSS	Basic service set
BTP	Basic transport protocol
BTS	Base transceiver station
BYOD	Bring your own device
CA	Certificate authority
CACC	Cooperative adaptive cruise control
CAM	Cooperative awareness message
CAN	Content addressable network, *when referring to the distributed hash table*
CAN	Controller area network, *when referring to the bus protocol*
CAS	Collision-avoidance symbol
CCA	Clear channel assessment
CCH	Control channel
CCK	Complementary code keying
CDF	Cumulative distribution function
CDMA	Code-division multiple access
CEPT	European Conference of Postal and Telecommunications Administrations (Conférence Européenne des Postes et Télécommunications)
CME	Certificate management entity
CoCar	Cooperative Cars
CoCarX	Cooperative Cars extended
COM	Component object model
Converge	Communication network vehicle road global extension
CPU	Central processing unit
CRC	Cyclic redundancy check
CRL	Certificate revocation list
CSD	Circuit switched data
CSMA	Carrier sense multiple access
CSMA/BA	Carrier sense multiple access with bitwise arbitration
CSMA/CA	Carrier sense multiple access with collision avoidance
CSMA/CD	Carrier sense multiple access with collision detection
CTS	Clear to send
CW	Contention window
CWS	Collision warning system
D-FPAV	Distributed fair power adjustment for vehicular networks
D2B	Domestic data bus *later domestic digital bus*
DAB	Digital audio broadcasting
DCC	Decentralized congestion control
DCF	Distributed coordination function
DCH	Dedicated channel
DENM	Decentralized environmental notification message

DES	Discrete event simulation
DHT	Distributed hash table
DLL	Dynamic-link library
DNS	Domain name system
DoIP	Diagnostic communication over Internet protocol
DSA	Dynamic spectrum access
DSC	DCC sensitivity control
DSDV	Destination sequenced distance vector
DSR	Dynamic source routing
DSRC	Dedicated short-range communication
DSRC/WAVE	Dedicated short-range communications/wireless access in vehicular environments
DSSS	Direct-sequence spread spectrum
DTN	Delay/disruption-tolerant network
DV-CAST	Distributed vehicular broadcast
DVD	Digital video disc *also digital versatile disc*
DYMO	Dynamic MANET on demand
DynB	Dynamic beaconing
ECC	Electronic Communications Committee
eCDF	Empirical cumulative density function
ECU	Electronic control unit
EDCA	Enhanced distributed channel access
EDGE	Enhanced data rates for GSM evolution
eMBMS	Evolved multimedia broadcast/multicast service
EMI	Electromagnetic interference
ESP	Electronic stability program
ETSI	European Telecommunications Standards Institute
FACH	Forward access channel
FairAD	Fair and adaptive data dissemination
FairDD	Fair data dissemination
FCC	US Federal Communications Commission
FCD	Floating car data
FDD	Frequency-division duplex
FDMA	Frequency-division multiple access
FHWA	Federal Highway Administration
FOT	Field operational test
FPGA	Field-programmable gate array
GGSN	Gateway GPRS support node
GHT	Geographic hash table
GIDR	Geographical inter-domain routing
GLOSA	Green-light optimal speed advisory
GPRS	General packet radio service
GPS	Global positioning system
GPSR	Greedy perimeter stateless routing

GRWLI	Geographic routing without location information
GSM	Global system for mobile communications
GUI	Graphical user interface
HLA	High-level architecture
HMI	Human–machine interface
HSCSD	High-speed circuit switched data
HSDPA	High-speed downlink packet access
HSPA	High-speed packet access
HSUPA	High-speed uplink packet access
IBSS	Independent basic service set
ICWS	Intersection collision warning system
IDE	Integrated development environment
IEEE	Institute of Electrical and Electronic Engineers
IETF	Internet Engineering Task Force
IFS	Interframe space
ILOC	Intersection location
IoT	Internet of things
IP	Internet protocol
ISM bands	Industrial–scientific–medical radio bands
ISO	International Organization for Standardization
ITS	Intelligent transportation system
ITS-G5	Intelligent transportation systems access layer for the 5-GHz band, *as specified by the ETSI*
ITSA	Intelligent Transportation Society of America
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication Sector
ITU-T	ITU Telecommunication Standardization Sector
IVC	Inter-vehicle communication
IVHS	Intelligent vehicle–highway system
LAN	Local area network
LDM	Local dynamic map
LER	Last encounter routing
LIDAR	Light detection and ranging
LIN	Local interconnect network
LLC	Logical link control
LOS	Line of sight
LTE	Long Term Evolution
MAC	Medium access control
MANET	Mobile ad-hoc network
MBMS	Multimedia broadcast/multicast service
MBSFN	Multicast-broadcast single-frequency network
MCD	Minimum cost distribution
METIS	Mobile and wireless communications enablers for the 2020 information society

MFD	Multi-function display
MIC	Ministry of Internal Affairs and Communications
MIMO	Multiple-input multiple-output
mmW	Millimeter-wave
MNO	Mobile network operator
MOST	Media-oriented systems transport
MSC	Mobile switching center
MTU	Maximum transmission unit
MVNO	Mobile virtual network operator
NHTSA	National Highway Traffic Safety Administration
NLOS	Non-line-of-sight
NRZ	Non-return-to-zero
OAD	Obstacle-aware distribution
OBU	On-board unit
OCB	Outside the context of a BSS
OD	Origin–destination
OEM	Original equipment manufacturer
OFDM	Orthogonal frequency-division multiplexing
OFDMA	Orthogonal frequency-division multiple access
OLSR	Optimized link state routing protocol
OPEN	One-pair Ethernet
P2P	Peer-to-peer
PAPR	Peak-to-average power ratio
PATH	Partners for advanced transit and highways
PCF	Point coordination function
PCI	Peripheral component interconnect
PDR	Packet delivery ratio
PeerTIS	Peer-to-peer traffic information system
PHY	Physical layer
PKI	Public key infrastructure
PoE	Power over Ethernet
POF	Plastic optic fiber
PRNG	Pseudo-random-number generator
PSID	Provider service identifier
PSSME	Provider service security management entity
QAM	Quadrature amplitude modulation
QoS	Quality of service
QPSK	Quadrature phase-shift keying
RACH	Random access channel
RAN	Radio access network
RB	Resource block
RDS	Radio data system
RERR	Route error
RF	Radio frequency

RFC	Request for comments
RIP	Routing information protocol
RMSE	Root mean square error
RNC	Radio network controller
ROI	Region of interest
RREP	Route reply
RREQ	Route request
RSS	Received signal strength
RSU	Roadside unit
RTPGE	Reduced twisted pair Gigabit Ethernet
RTS	Ready to send
SAE	Society of Automotive Engineers
SAM	Service announcement message
SARTRE	Safe road trains for the environment
SCFDMA	Single-carrier FDMA
SCH	Service channel
SDR	Software-defined radio
SFN	Single frequency network
SGSN	Serving GPRS support node
SIFS	Short interframe space
SNR	Signal-to-noise ratio
SODAD	Segment oriented data abstraction and dissemination
SOTIS	Self-organizing traffic information system
SPAT	Signal phase and timing
SRP	Stream reservation protocol
SSU	Stationary support unit
SUMO	Simulation of urban mobility
TAC	Transmit access control
TCP	Transmission control protocol
TD-CDMA	Time-division CDMA
TDC	Transmit data rate control
TDD	Time-division duplex
TDMA	Time-division multiple access
TIC	Traffic information center
TIS	Traffic information system
TMC	Traffic messaging channel
TO-GO	Topology-assisted geo-opportunistic routing
TOPO	Road topology
TPC	Transmit power control
TPEG	Transport Protocol Expert Group
TPM	Trusted platform module
TraCI	Traffic control interface
TRC	Transmit rate control
TSF	Time synchronization function

TSN	Time-sensitive networking
TTCAN	Time-triggered CAN
TTL	Time to live
TVWS	TV white space
TXOP	Transmission opportunity
U-NII bands	Unlicensed national information infrastructure bands
UART	Universal asynchronous receiver/transmitter
UDP	User datagram protocol
UDS	Unified diagnostic service
UE	User equipment
UMB	Ultra-mobile broadband
UMTS	Universal mobile telecommunications system
US DOT	US Department of Transportation
USRP	Universal software radio peripheral
UTC	Coordinated universal time
UV-CAST	Urban vehicular broadcast
V2I	Vehicle to infrastructure
V2V	Vehicle to vehicle
V2X	Vehicle to X
VANET	Vehicular ad-hoc network
VCP	Virtual coordinate protocol
Veins	Vehicles in network simulation
VLAN	Virtual LAN
VoIP	Voice over IP
VRR	Virtual ring routing
VSimRTI	V2X simulation runtime infrastructure
VTL	Virtual traffic light
W-CDMA	Wideband CDMA
WAVE	Wireless access in vehicular environments
WiMAX	Worldwide interoperability for microwave access
WLAN	Wireless LAN
WME	WAVE management entity
WRAN	Wireless regional area network
WSA	WAVE service advertisement
WSM	WAVE short message
WSM-S	WAVE short message with safety supplement
WSMP	WAVE short message protocol
WSN	Wireless sensor network
WSU	Wireless safety unit
WUP	Wake-up pattern
XML	Extensible markup language