Internet of Vehicles

XUEMIN (Sherman) SHEN, ***Fellow IEEE***
Guest Editor

ROMANO FANTACCI, ***Fellow IEEE***
Guest Editor

SHANZHI CHEN, ***Fellow IEEE***
Guest Editor

Vehicular communication networks have emerged to enable numerous vehicular data services and applications. Conventional vehicular *ad hoc* networks (VANETs) are often operated in the *ad hoc* mode and mainly focus on road safety applications based on the connections between vehicles and roadside units (RSUs). To support vehicular communications, dedicated short-range communication (DSRC) and car-to-car communication consortium (C2C-CC) have been initiated in the United States and Europe, respectively. With the new era of the Internet of Things (IoT), the conventional VANETs have evolved to the Internet of Vehicles (IoV). In IoV, each vehicle is envisioned as an intelligent object, equipped with sensing platforms, computing facilities, control units, and storages and is connected to any entity (other vehicles, RSUs, charging/gas stations, cloud, and so on) via vehicle-to-everything (V2X) communications. Intelligent vehicles can take different roles, i.e., being both a client and a server, taking and providing big data services, leading to numerous new IoV applications, from assisted/autonomous driving and platooning, secure information sharing and learning to traffic control and optimization.

This special issue provides a comprehensive overview of Internet-of-Vehicles-related technologies and solutions which address the current challenges in this field.

IoV technologies are anticipated to address the grand challenges of modern transportation to enhance road safety, mitigate traffic congestion, reduce fuel consumption and pollution, and enable car-sharing services to save space and costs. Furthermore, each vehicle can be an information hub or an edge server for people and IoT devices on the road. It has a large scale and profound impact on a wide range of industry sectors, including transportation, vehicle manufacturing, energy, automation, software, and information and communication technology. There is no doubt that IoV stands in the center of the coming Industrial Revolution.

Although IoV enables a myriad of promising applications, its heterogeneous architecture, complex resources, and varied service requirements necessitate novel designs, ranging from new radio technologies to new network architecture and protocols. IoV is different from the traditional Internet and other IoT networks. Each vehicle, from driver-assisted to automated one, will generate a flood of information, up to thousands of times of that by a person. Vehicle density may change drastically over time (off versus peak hours) and location (main versus side streets). Emergency messages and real-time cooperative control messages have stringent delay constraints (a few milliseconds), while infotainment applications may tolerate a certain degree of latency. Service guarantee for reliable and scalable IoV is of paramount importance while technically challenging.

To support IoV applications with different quality of service requirements, various radio technologies have been emerging and are under development, e.g., DSRC, WiFi, 4G/LTE, 5G, TV white space, microwave, millimeter-wave, and visible light communications (VLCs). New network architecture is needed to integrate heterogeneous access technologies and enable the interoperation

Digital Object Identifier 10.1109/JPROC.2020.2964107

among multiple coexisting wireless networks. Software-defined networking (SDN), network function virtualization (NFV), and network slicing have been developed as a promising paradigm for programmable control and management of network resources flexibly and systematically. In the IoV era, where the network is becoming increasingly dynamic, complex, and heterogeneous, it is also desirable to apply advanced AI techniques, data science, and distributed computing to make the network more intelligent to meet the various requirements of ultralow latency, high reliability, seamless wide-area coverage, high-capacity hot-spot, massive-connections, and so on.

Despite appealing advantages, IoV also brings new and challenging security and privacy threats toward drivers, passengers, and pedestrians. Security defense systems and privacy protection strategies against various cyberattacks are critical to be investigated in-depth to provide early-stage guidelines. New safeguard solutions are beckoned to make future IoV fully dependable and secure.

A multitude of research studies, both in academia and industry, have been carried out over the years to address the IoV challenges. Furthermore, great efforts have been made in defining International Standards to push forward the deployment of IoV technologies. This special issue covers the recent developments in the area of IoV, where the communication, computing, control, and caching functions of connected vehicles facilitate a wide spectrum of vehicular applications. The scope of the issue spans many related topics, including advanced IoV applications, new V2X radio technologies, novel network protocol and architecture design, performance analysis, optimization and evaluation, IoV security and privacy, and test-bed and simulation tools.

I. OVERVIEW OF THE SPECIAL ISSUE

Our primary focus of this special issue is to give the readers a comprehensive overview of the field, presenting the state-of-the-art technologies and solutions which address the IoV challenges. We classify the contributions into four categories, i.e., IoV applications, IoV network architectures, V2X radio technologies, and IoV security issues. The articles of this special issue deal with both theoretical and practical aspects of IoV, aiming to attract the attention of academic researchers, application experts, and practitioners, and stimulate collaborations among them, leading to major scientific and technical breakthroughs to make IoV a reality sooner.

A. Advanced IoV Applications

"Mobile edge intelligence and computing for the Internet of Vehicles" by Zhang and Letaief overviews the edge information system (EIS), including edge caching, edge computing, and edge AI, which will enable a plethora of new exciting intelligent IoV applications. Key design issues, methodologies, and hardware platforms are introduced. Typical use cases for intelligent vehicles are illustrated, including edge-assisted perception, mapping, and localization. For edge caching, edge computing, and edge AI, both Vehicle-as-a-Client (VaaC) and Vehicle-as-a-Server (VaaS) applications are surveyed.

"Learning driving models from parallel end-to-end driving data set" by Chen *et al.* concerns how simulated-world data and real-world data can be efficiently used to improve the performance of parallel end-to-end autonomous driving, which takes perceptual information (images, point clouds, and so on) and other vehicle information (speed, navigation command, and so on) as the inputs to the model and directly outputs the decision information (steering angle, and so on). The article introduces a parallel end-to-end driving data set (PED), containing real-world images, corresponding simulated-world images, and vehicle information. Experimental results demonstrate that using PED is effective and achieves superior performance, and transforming the simulated-world image into the real-world image and then combining it with the real-world image to train the driving model is a desirable way to utilize the simulated-world data.

B. Novel IoV Network Architectures

"SDN/NFV-empowered future IoV with enhanced communication, computing, and caching" by Zhuang *et al.* presents an overview of SDN/NFV-enabled IoV, a new network architecture for IoV. Here, SDN/NFV technologies are leveraged to enhance the performance of IoV and enable diverse IoV scenarios and applications. The state-of-the-art research work is surveyed comprehensively and categorized into topics according to the role that SDN/NFV technologies play in IoV, i.e., enhancing the performance of data communication, computing, and caching, respectively. It also discusses open research issues of the new SDN/NFV-based IoV architecture, including joint resource slicing and access control, VNF chaining and placement for computation offloading, joint multidimensional resource orchestration, and hierarchical SDN/NFV controller deployment.

"Future intelligent and secure vehicular network toward 6G: Machine-learning approaches" by Tang *et al.* reveals the potential to apply advanced machine learning into vehicular communications and networking. The article provides a survey on various machine learning techniques applied to communication, networking, and security parts in vehicular networks, and envisions the ways of enabling AI toward future 6G vehicular networks including the evolution of intelligent radio (IR), network intelligentization, and self-learning with proactive exploration.

C. New V2X Radio Technologies

"Evolutionary V2X technologies toward the Internet of Vehicles: Challenges and opportunities" by Zhou *et al.* surveys the historical process and status quo of V2X technologies, while listing the major V2X communication technology standards in North America, Europe,

and Asia. It introduces the development roadmap of 802.11 V2X and cellular V2X (C-V2X), respectively, and compares the pros and cons of the two mainstream V2X technologies. Key technical challenges and opportunities toward the big data-driven IoV and cloud-based IoV are discussed.

"Toward reliable and scalable Internet of Vehicles: Performance analysis and resource management" by Ni *et al.* concerns how to ensure reliable and scalable wireless transmissions for IoV based on performance modeling and analysis. For single-hop beacon broadcasting, the strength and weakness of C-V2X medium access control (MAC) protocol and IEEE 802.11p MAC protocol are compared, and the distributed congestion control mechanisms are discussed. For multihop V2V relay in both 1-D and 2-D networks, the closed form of fundamental network connectivity is given. Considering carry-and-forward transmissions with and without the assistance of roadside infrastructure (dropbox or RSU), the delay of V2V or hybrid V2I/V2V networks is analyzed to deploy different types of infrastructures optimally.

"Deep-learning-based wireless resource allocation with application to vehicular networks" by Liang *et al.* discusses the key motivations and roadblocks of using deep learning for wireless resource allocation with applications to vehicular networks. It reviews major recent studies that mobilize the deep-learning philosophy in wireless resource allocation and achieve impressive results. It also describes in detail how to leverage deep learning to solve difficult optimization problems for resource allocation and deep reinforcement learning for direct answers to many resource allocation problems that have not been handled or modeled in the traditional optimization frameworks.

D. IoV Security Issues

"The security of autonomous driving: Threats, defences, and future directions" by Ren *et al.* gives a systematic study on the security threats surrounding autonomous driving, from the angles of perception, navigation, and control. In addition to the in-depth overview of these threats, it also summarizes the corresponding defence strategies. Furthermore, future research directions about the new security threats, especially those related to deep-learning-based self-driving vehicles, are discussed.

"5G Vehicle-to-Everything (V2X) services: Gearing up for security and privacy" by Lu *et al.* first reviews the architecture and the use cases of 5G V2X. Then, a series of trust, security, and privacy issues in 5G V2X services are studied, and the potential attacks on trust, security, and privacy in 5G V2X are discussed. An in-depth analysis of the state-of-the-art strategies for securing 5G V2X services is given, and how to achieve the trust, security, or privacy protection in each strategy is elaborated. The article also points out open problems and future research directions in secure 5G V2X services.

In closing, we hope that this special issue will serve as a good reference for readers in the field of IoV. We would like to thank Jo Sun, Senior Publications Editor, and Vaishali Damle, Managing Editor of the PROCEEDINGS OF THE IEEE, for their support and advice throughout the publication process. ■

ABOUT THE GUEST EDITORS

Xuemin (Sherman) Shen (Fellow, IEEE) received the Ph.D. degree in electrical engineering from Rutgers University, New Brunswick, NJ, USA, in 1990.

He is currently a University Professor with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON, Canada. His research focuses on network resource management, wireless network security, social networks, 5G and beyond, and vehicular *ad hoc* and sensor networks.

Dr. Shen is a Fellow of the Engineering Institute of Canada, the Canadian Academy of Engineering, the Royal Society of Canada, and the Chinese Academy of Engineering Foreign. He received the R.A. Fessenden Award from IEEE, Canada, in 2019; the James Evans Avant Garde Award from the IEEE Vehicular Technology Society in 2018; the Joseph LoCicero Award in 2015; and the Education Award from the IEEE Communications Society in 2017. He also received the Excellent Graduate Supervision Award in 2006; five Outstanding Performance Awards from the University of Waterloo; and the Premier's Research Excellence Award (PREA) from the Province of Ontario, Canada, in 2003. He has served as the Technical Program Committee Chair/Co-Chair of IEEE Globecom'16, IEEE Infocom'14, IEEE VTC'10 Fall, and IEEE Globecom'07; the Symposia Chair of IEEE ICC'10; the Tutorial Chair of IEEE VTC'11 Spring; and the Chair of the IEEE Communications Society Technical Committee on Wireless Communications. He is the Past Editor-in-Chief of the IEEE INTERNET OF THINGS JOURNAL and the Vice-President of Publications of the IEEE Communications Society. He is also a Distinguished Lecturer of the IEEE Vehicular Technology Society and the IEEE Communications Society. He is a Registered Professional Engineer in Ontario.

Romano Fantacci (Fellow, IEEE) is currently a Full Professor with the Department of Information Engineering, University of Florence, Florence, Italy.

Dr. Fantacci is a member of the Institute of Electronics, Information and Communication Engineers (IEICE) and numerous technical committees within the IEEE Communications Society. He was one of the promoters of the IEEE COMSOC Ad-Hoc and Sensor Networks Committee and the Promoter and the first Vice-Chair of the IEEE COMSOC Power Line Communications Committee. He was an Associate Editor of *Telecommunication Systems*, the IEEE TRANSACTIONS ON COMMUNICATIONS, the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, the *International Journal of Communication Systems*, and the IEEE NETWORK; a Regional Editor of *IET Communications*; and a Funder Area Editor of the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS. He serves as an Area Editor for the IEEE INTERNET OF THINGS JOURNAL. He is also active in the organization of numerous scientific conferences (e.g., GLOBECOM, ICC, and VTC) as the Symposium Chair. He received an attestation of appreciation for his organizational activity in the ICC'04 and ICC'05 conferences.

Shanzhi Chen (Fellow, IEEE) received the bachelor's degree from Xidian University, Xi'an, China, in 1991, and the Ph.D. degree from Beijing University of Posts and Telecommunications (BUPT), Beijing, China, in 1997.

He joined Datang Telecom Technology & Industry Group and CATT in Beijing in 1994, where he has been serving as an EVP R&D since 2008 and the Director of the State Key Laboratory of Wireless Mobile Communications, where he conducted research and standardization on LTE-V, 4G TD-LTE, and 5G. He has authored or coauthored four books, including *Mobility Management: Principle, Technology and Applications* (Springer Press); 17 book chapters; approximately 100 journal articles; 50 conference papers; and more than 50 patents. He has contributed to the design, standardization, and development of 4G TD-LTE and 5G mobile communication systems. His current research interests include 5G mobile communications, network architectures, vehicular communication networks, and the Internet of Things (IoT).

Dr. Chen has won multiple top awards and honors from China's central government for his achievements, including the Grand Prize of National Award for Scientific and Technological Progress, China, in 2016 (this grand prize is the highest category and in some years there are no winners due to its high standard). He has served as the TPC Chair and a member of many international conferences. He is also an Area Editor of the IEEE INTERNET OF THINGS JOURNAL; an Editor of IEEE NETWORK; and a Guest Editor for IEEE WIRELESS COMMUNICATIONS, the *IEEE Communications Magazine*, and the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY.