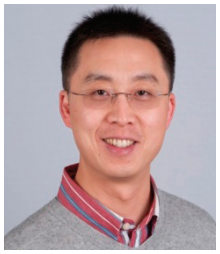
5G Enabled Vehicular Communications and Networking





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Vehicular communications and networking (VCN) is considered a billion-dollar industry. Its development not only possesses economic value, but also has enormous social potential. The earliest vehicular network started from the dedicated short range networks, such as the IEEE 802.11p standard established at the beginning of this century. In recent years, the public access network based VCN has been rapidly advanced. For example, LTE-V based on 4G LTE is under standardization, and VNC is for the first time listed as one of the three representative application scenarios of 5G. It is envisioned that, as the enabler of the modern era of the automobile industry including electric vehicles, intelligent vehicles, and shared vehicles, VCN will undergo unprecedented development in the next decade. In 2020, VCN is expected to reach the level of trillion RBM, 30% of which will be covered by China. At the same time, VCN is also considered a cornerstone to effectively resolve various traffic congestion and safety issues. As estimated by Didi, the per capita transportation cost will be 1k RMB/hr in 2025. With VCN-based technologies, traffic congestion can be reduced by 10%, number of accidents reduced by 20%, together with carbon exhaust cut back and fuel savings.

Currently in China, with the present full-speed efforts towards "Made in China 2025", a VCN specialty leadership team has also been established to coordinate the development of the VCN industry. The leadership team explicitly pointed out that, riding the historical wave of the expedited merge of next-generation information technology and conventional industry, the timely development of VCN would significantly benefit the innovation of the automobile industry, facilitate new transportation services, promote automatic driving technology and application, improve transportation safety and efficiency, and alleviate pollution. This is a critical step towards the realization of "Made in China 2025".

Technically, however, the research and development of VCN are still facing formidable challenges. This is because the vehicular environments are inherently very challenging due to the doubly selective and fast time-varying channels, and the ever-changing network connectivity and topology. Hence, many 5G cellular technologies cannot be directly employed in vehicular networks and will otherwise suffer from significant performance degradation. In addition, vehicles are often constrained in computation, storage, and radio spectrum resources. As such, we have recently witnessed unprecedented efforts and resultant outcomes. These are essential in bringing the many demanding vehicular applications to reality.

This Special Topic Issue contains a collection of papers that provide theoretical advances and practical experiments in terms of vehicular communications and networking. We collected outstanding papers in this Special Topic Issue to showcase recent research and developments related to vehicular communications and networking. We received a large number of manuscripts in response to our call for papers. More importantly, we are honored to receive contributions from the research groups of several renowned VCN experts, including the Canadian academician Prof. Sherman Shen (IEEE Fellow) from University of Waterloo, Canada, the NSFC 5G VCN project leader Prof. Pingzhi Fan (IEEE Fellow) from Southwest Jiaotong University, China, Prof. Ping Zhang form Beijing University of Posts and Telecommunications, China, and Prof. Lin Cai from University of Victoria, Canada. Via a careful peer-review process,

we have accepted nine papers for this Special Issue. The accepted papers can be divided into three categories respectively covering three aspects regarding 5G-enabled vehicular communications and networking, namely vehicular channel modeling and measurements, physical layer techniques, and MAC design and applications.

On the content distribution side, we introduce the first article, "Cooperative Vehicular Content Distribution in Edge Computing Assisted 5G-VANET," is authored by Guiyang Luo *et al*. Many enabling applications in 5G vehicular networks rely on the efficient content sharing among mobile vehicles, which is a very challenging issue due to the extremely large data volume, rapid topology change, and unbalanced traffic. Therefore, the authors investigate content prefetching and distribution in 5G-VANET. The authors first introduce an edge computing based hierarchical architecture for efficient distribution of large-volume vehicular data, and then propose a multi place multi-factor prefetching scheme to meet the rapid topology change and unbalanced traffic. The content requests of vehicles can be served by neighbors, which can improve the sharing efficiency and alleviate the burden of networks. Moreover, the authors exploit a graph theory-based approach to solve the content distribution by transforming it into a maximum weighted independent set problem. Due the novelty and contributions of this article, we recommend it as the cover article of this Special Issue.

Then, we introduce the first two articles focusing on vehicular channel modeling and measurements.

On the V2V channel modeling and measurement side, the second article, "Deterministic and Stochastic Simulators for Non-Isotropic V2V-MIMO Wideband Channels" is co-authored by Yiran Li *et al*. The authors consider a novel geometry-based stochastic model (GBSM) for MIMO vehicle-to-vehicle (V2V) wideband fading channels, which introduces the combination of a two-ring model and a multiple confocal ellipses model. The authors derive some expressions of the channel statistical properties, including space-time correlation function (STCF), Doppler spectral power density (DPSD), envelope level crossing rate (LCR) and average fade duration (AFD). Moreover, the authors compare the statistical properties of the reference model and the two simulation models in different scenarios and investigate the impact of different vehicular traffic densities (VTDs) on the channel statistical properties of the proposed model.

On the vehicular MIMO channel modeling side, the third article, "A Geometry-Based Non-Stationary MIMO Channel Model for Vehicular Communications," is authored by Yuanyuan Ma *et al*. The authors derive a non-stationary MIMO channel model from the one-ring scattering model. The proposed channel model characterizes vehicular radio propagation channels with considerations of both base and mobile stations in motion, which makes the angle of arrivals (AOAs) along with the angle of departures (AODs) time-varying. Moreover, the authors analyze the statistical properties of the proposed channel model including the local time-variant autocorrelation function and the space cross-correlation functions. The channel model developed in this article for non-stationary scenarios also includes the existing one-ring wide-sense stationary channel model as its special case.

And, we further introduce the two papers on physical layer techniques for vehicular communications, both on the channel estimation side.

The forth article, "Joint Channel Estimation and Decoding Design for 5G-enabled V2V Channel," is authored by Xuanfan Shen *et al*. The authors investigate the problem of channel estimation in 5G-enabled V2V channels with high-mobility environments and non-stationary feature. Considering an OFDM system, the authors perform extended Kalman filter (EKF) for channel estimation in conjunction with Iterative Detector and Decoder (IDD) at the receiver to improve the estimation accuracy. The EKF is proposed to jointly estimate the channel frequency response and the time-varying time correlation coefficients. And the IDD structure is adopted to reduce the estimation errors in EKF. Simulation results indicate that, compared with traditional methods, the proposed method effectively improves the system performance.

The fifth article, "Interference-Free Pilot Design and Channel Estimation Using ZCZ Sequences for MIMO-OFDM-Based C-V2X Communications," is authored by Haibin Chen *et al*. The authors investigate the pilot design and channel estimation problem in MIMO-OFDM-based C-V2X systems with severe co-channel interference due to spectrum reusing among different V2X communication links. By using zero-correlation zone (ZCZ) sequences, the authors provide an interference-free pilot design scheme and a corresponding time-domain (TD) correlation-based channel estimation (TD-CCE) method, based on which, the co-channel pilot interference of the designed pilot symbols can be effectively eliminated. Simulation results indicate that the accuracy of channel estimation can be effectively improved by the proposed scheme, whose performance is close to that of the

non-interference situation.

Finally, we give some brief introductions to the other accepted articles that focus on MAC design and applications. More recently, there have been ever-increasing number of works contributing to vehicular networking and applications. Hence, we select a total of six articles regarding this area.

On the vehicular networking side, the sixth article, "A Multi-hop Moving Zone (MMZ) Clustering Scheme Based on Cellular-V2X," is authored by Zahid Khan *et al*. The authors propose a Multi-hop Moving Zone (MMZ) clustering scheme by combining IEEE 802.11p with 3GPP 5G cellular technology. In MMZ, vehicles are clustered up-to three hops using V2V communications based on IEEE 802.11p aiming to reduce excessive cellular hand-off cost. The cluster heads (CHs) are selected by C-V2X based on multiple metrics including relative speed, distance and link life time. The main goal of MMZ is to form stable clusters achieving high packet delivery and low latency. Simulation results demonstrate that, 5G wide range technology significantly improves the stability of MMZ in term of CH duration and change rate. The average data packet delivery ratio and end-to-end latency are also improved as compared with existing clustering schemes.

On the scheduling side, the seventh article, "Vehicular Beacon Broadcast Scheduling based on Age of Information (AoI)," is authored by Yuanzhi Ni *et al*. The authors investigate the beacon broadcast scheduling problem considering the Age of Information (AoI). The authors first propose an algorithm to minimize the expected sum of AoI considering the limited communication resource and vehicle mobility. Then the performance of the proposed algorithm is analyzed. With the proposed algorithm, the optimal solution can be obtained under certain conditions.

On the routing side, the eighth article, "A Greedy Traffic Light and Queue Aware Routing Protocol for Urban VANETs," is authored by Yangyang Xia *et al*. Routing is a challenging problem in vehicular networks due to the fast-changing network typology caused by high mobility at both ends of transmission. An efficient routing protocol plays a vital role to achieve good network performance. The authors propose a greedy traffic light and queue aware routing protocol (GTLQR) which jointly considers the street connectivity, channel quality, relative distance, and queuing delay to alleviate the packet loss caused by vehicle clustering at the intersection and balance the traffic load among vehicles. Simulation evaluations indicate that the proposed protocol outperforms related existing schemes in terms of packet delivery ratio and end-to-end delay.

On the content distribution side, the ninth article, "Proactive Content Delivery for Vehicles over Cellular Networks: The Fundamental Benefits of Computing and Caching," is authored by Jiping Jiao *et al*. The emergence of self-driving technologies implies that a future autonomous connected vehicle demands personalized multimedia contents with very high quality. The surge of vehicular content demand brings significant challenges for 5G communication network. To address the challenge of massive content delivery, the authors propose a novel theoretical framework to characterize the tradeoff among computing, caching, and communication (3C) resources required by the mobile edge network to fulfill the task of content delivery. Analytical and numerical results are obtained to characterize the 3C resource tradeoff curve. These results reveal key insights into the fundamental benefits of computing and caching in vehicular mobile content delivery networks.

Last but not least, the editors would like to thank all of the authors for their submissions to this Special Issue. We are also grateful to the anonymous reviewers for their timely responses and their valuable comments to improve the quality of the articles. We hope that this Special Issue will further stimulate research interests in the significant research area of 5G-enabled vehicular communications and networking.

Biographies

Xiang Cheng, [IEEE SM'13] received the Ph.D. degree from Heriot-Watt University and the University of Edinburgh, Edinburgh, U.K., in 2009, where he received the Postgraduate Research Thesis Prize. He is currently a Professor at Peking University. His general research interests are in areas of channel modeling and mobile communications, subject on which he has published more than 160 journal and conference papers, 3 books and 6 patents. Dr. Cheng was the recipient of the IEEE Asia Pacific (AP) Outstanding Young Researcher Award in 2015, the co-recipient for the 2016 IEEE JSAC Best Paper Award: Leonard G. Abraham Prize, the NSFC Outstanding Young Investigator Award, the Second-Rank Award in Natural Science, Ministry of Education in China, and received the Best Paper Awards at IEEE ITST'12, ICCC'13, ITSC'14, ICC'16, and ICNC'17. He has served as Symposium Leading-Chair, Co-Chair, and a Member of the Technical Program Committee for several international conferences. He is now an Associate Editor for IEEE Transactions on Intelligent Transportation Systems.

Rongqing Zhang, [IEEE M'15] received the B.S. and Ph.D. degrees from Peking University, Beijing, China, in 2009 and 2014, respectively. Since 2014, he has been a post-doctoral research fellow at

Colorado State University, CO, USA. He has published two book chapters and more than 70 papers in refereed journals and conference proceedings. His current research interests include physical layer security, vehicular communications and networking, and electric vehicles. Dr. Zhang was the recipient of the Academic Award for Excellent Doctoral Students, Ministry of Education of China, the co-recipient of the First-Class Natural Science Award, Ministry of Education of China, and received the Best Paper Awards at IEEE ITST 2012 and ICC 2016. He was also awarded as International Presidential Fellow of Colorado State University in 2017. Currently, he serves as the Associate Editor of Complexity.

Shanzhi Chen, [IEEE SM'04] received the Bachelor and Ph.D. degree from Xidian University, and Beijing University of Posts and Telecommunications (BUPT), China, in1991 and 1997, respectively. He joined Datang Telecom Technology & Industry Group and CATT in 1994, and has served as EVP R&D since 2008, and the director of State Key Laboratory of Wireless Mobile Communications, where he conducted research and standardization on 4G TD-LTE and 5G. He has authored and co-authored four books (among them the textbook Mobility Management: Principle, Technology and Applications, Springer Press), 17 book chapters, approximately 100 journal papers, 50 conference papers, and more than 50 patents in these areas. He has contributed to the design, standardization, and development of 4G TD-LTE and 5G mobile communication systems. Dr. Chen's achievements have won multiple top awards by China central government and honors, especially, the Grand Prize of National Award for Scientific and Technological Progress, China, 2016 (This Grand Prize is the highest category and in some years, it leaves with no winners due to its high standard). He is the Area Editor of IEEE Internet of Things Journal, the Editor of IEEE Network, and the guest editor for IEEE Wireless Communications, IEEE Communications Magazine and IEEE TVT, and served as TPC Chair and Member of many international conferences. His current research interests include 5G mobile communications, network architectures, Vehicular communication Networks, Internet of Things (IoT).

Jia Li, received her B.S. degree in electronics and information systems from Peking University, Beijing, China, in 1996, the M.S.E. degree, and the Ph.D. degree both in electrical engineering from the University of Michigan, Ann Arbor, MI, in 1997 and 2002, respectively. She has been a faculty member in the School of Engineering and Computer Science at Oakland University since 2002. Her research interests are in the areas of statistical learning and signal processing with applications in radar, sensor fusion, communications and biomedical imaging. Dr. Li has authored/co-authored over 70 referred publications, including one book. Her past and current researches are sponsored by NSF, NIH, General Motors, Fiat Chrysler, and National Research Council. Dr. Li serves as a member of technical committees of several international conferences and workshops, and a regular reviewer of a number of international journals. She is a senior member of IEEE.

Liuqing Yang, [IEEE F'15] received the Ph.D. degree from the University of Minnesota, Minneapolis, MN, USA, in 2004. Her main research interests include communications and signal processing. Dr. Yang has been actively serving the technical community, including the organization of many IEEE international conferences, and on the editorial boards of a number of journals, including the IEEE Transactions on Communications, the IEEE Transactions on Wireless Communications, the IEEE Transactions on Intelligent Transportation Systems, and the IEEE Transactions on Signal Processing. She received the Office of Naval Research Young Investigator Program Award in 2007, the National Science Foundation Career Award in 2009, the IEEE GLOBECOM Outstanding Service Award in 2010, the George T. Abell Outstanding Mid-Career Faculty Award and the Art Corey Outstanding International Contributions Award at CSU in 2012 and 2016 respectively, and Best Paper Awards at IEEE ICUWB'06, ICCC'13, ITSC'14, GLOBECOM'14, ICC'16, and WCSP'16.

Hongwei Zhang, [IEEE SM'13/ACM M'07] is an associate professor of electrical and computer engineering at Iowa State University, U.S.A. His primary research interests lie in the modeling, algorithmic, and systems issues in trustworthy wireless networking for real-time cyber-physical-human systems such as those in mixed-reality, agriculture, connected and automated vehicles, smart grid, and industrial automation. He is a recipient of the NSF CAREER Award. (URL: http://www.ece.iastate.edu/~hongwei).