Guest Editorial Introduction of the Special Issue on Edge Intelligence for Internet of Vehicles

EMPOWERED with advanced computation units, autonomous sensing platforms and various wireless access capabilities, connected and autonomous vehicles evolve over time and become tightly coupled and closely cooperative. Being one of the most active research fields in both academic and industry, the Internet of Vehicles (IoV) enables various types of vehicular applications, such as autonomous driving, precise fleet management, and real-time video analytics, which contribute significantly to bring us traffic efficiency, driving safety, and ride comfort. However, these powerful applications always require intensive computation and very large size caching services under ultra-low latency constraints, and thus pose significant challenges on resource-constrained vehicles.

To address the challenges, edge intelligence is emerging as a promising solution. Through pushing artificial intelligence (AI)-inspired computing, caching, and communication resources to the proximity of smart vehicles, appropriate edge service deployment and flexible resource scheduling are enabled for IoV systems. These abilities greatly help realize high-performance processing for mission-critical applications, real-time services to connected and autonomous vehicles as (e.g., HD maps, accidents alerts, and real-time information), low latency content delivery for interactive entertainments, and smart transmission for QoS-aware information. Despite these potentially promises brought by edge intelligence, many challenges as well need to be addressed in this new paradigm. For instance, high mobility leads to time-varying service relations among IoV entities, which renders more complexity and thus challenges to edge resource scheduling. Moreover, there exists essential and so far unexplored correlations between diverse types of edge resources deployed in different time and space dimensions with various capacities, which need to be extensively investigated and efficiently utilized in serving process management.

The objective of this Special Issue is to present the latest results, insights, and perspectives on the new area of edge intelligence-empowered IoV. The authors were successful in attracting 44 submissions. All of the submitted papers were rigorously evaluated according to the standard reviewing process of the IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS. Following a rigorous peer-review process, 12 papers were accepted in this Special Issue while the other three papers were transferred to regular issues.

The accepted papers cover a wide range of topics for enabling edge intelligence in IoV environments. The authors hope this Special Issue will shed light on edge intelligence technologies for IoV and open up many exciting and critical future research activities in the related fields.

The Guest Editors would like to thank all the authors for their contributions to the Special Issue and all reviewers for their voluntary services. Special thanks go to the Editor-in-Chief, Prof Azim Eskandarian, and all the members of the editorial team for their support during the editing process of this Special Issue.

Special Issue Short Summaries

The first six articles study content caching and task offloading issues toward edge intelligence for the IoV. The next two articles discuss edge intelligence in particular IoV applications. The last four articles discuss the privacy, security, and incentive mechanisms for edge intelligence for the IoV.

Edge Caching and Computation Management for Real-Time Internet of Vehicles: An Online and Distributed Approach

J. Zhao, X. Sun, Q. Li, and X. Ma

In this article, the authors investigate the joint edge caching and computation management mechanism for IoVs to realize delay-sensitive IoV services in a cost-efficient way. The authors first build an edge computation model with consideration of the time-varying channel conditions, dynamic network topology, and random service request arrivals. Then, aiming at minimizing the time-average service response delay, a novel online and distributed approach is proposed to jointly manage service caching, request scheduling and resource allocation. Theoretical analysis and computer simulations are conducted to show that their approach can achieve the close-to-optimal delay performance while satisfying the time-average cost budget constraints.

Edge Intelligence Empowered Urban Traffic Monitoring: A Network Tomography Perspective

S. Pan, P. Li, C. Yi, D. Zeng, Y.-C. Liang, and G. Hu

Efficient urban traffic monitoring is a key enabler for intelligent planning and management of modern cities. Network tomography can monitor the urban traffic with a comparably small number of traffic detectors like cameras, and has become an appealing technique for urban traffic management. However, existing studies on network tomography-based traffic monitoring focus primarily on developing estimators using the

Digital Object Identifier 10.1109/TITS.2021.3066837

given end-to-end travel time measurements, while the design of data collection for efficiently distributed collecting and processing the raw monitoring videos to such measurements is often neglected. The authors fill this gap by exploring the vision of edge intelligence for optimal urban traffic monitoring. The authors propose an edge intelligence-empowered urban traffic monitoring scheme to specifically deal with the challenges brought by the limited telecommunications resources. When the total number of monitoring videos that are successfully processed into the end-to-end travel time measurements are pre-bounded, the authors employ a Fisher Information Matrix (FIM) to help determine the best quota scheme for the monitoring videos that each traffic detector needs to generate. When the centralized processing of monitoring videos alone is insufficient, the authors make use of the computation capabilities from these edge devices, i.e., traffic detectors, and employ a multi-agent reinforcement learning approach to help them conduct intelligent computation offloading individually. Extensive simulations are used to demonstrate that the proposed scheme effectively reduces the estimation error of network tomography compared to baseline approaches with either uniform or random strategy.

Intelligent Edge Computing in Internet of Vehicles: A Joint Computation Offloading and Caching Solution

Z. Ning, K. Zhang, X. Wang, L. Guo, X. Hu, J. Huang, B. Hu, and R. Y. K. Kwok

This article considers an IoV scenario that exploits the resources of vehicles and road side units (RSUs) to execute various vehicular applications. Due to the increasing number of vehicles and the asymmetrical distribution of traffic flows, it is essential for the network operator to design intelligent offloading strategies to improve network performance and provide high-quality services for users. However, the lack of global information and the time-variety of IoVs make it challenging to perform effective offloading and caching decisions under long-term energy constraints of RSUs. To solve this problem, the authors push AI-inspired computing, caching, and communication resources to the proximity of smart vehicles, which jointly enable RSU peer offloading, vehicle-to-RSU offloading, and content caching in the IoV framework. A mix integer non-linear programming (MINLP) problem is formulated to minimize total network delay under long-term energy constraints for RSUs. The authors also propose an efficient online algorithm (i.e., OMEN) to orchestrate edge computing and caching resources by leveraging the Lyapunov optimization method and prove its near-optimal performance compared with the oracle method. Performance evaluations based on real-world traffic data in Hangzhou, China, are conducted to demonstrate their method for computation offloading and intelligent caching is practical, and achieves high-efficiency performance in large-scale vehicular networks.

Intelligent Task Offloading for Heterogeneous V2X Communications

K. Xiong, S. Leng, C. Huang, C. Yuen, and Y. Guan

The authors propose an intelligent task offloading framework in heterogeneous vehicular networks with three vehicle-to-everything (V2X) communication technologies, namely dedicated short-range communication (DSRC), cellular-based V2X (C-V2X) communication, and millimeter-wave (mmWave) communication. Based on stochastic network calculus, this article first derives the delay upper bounds of different offloading technologies with certain failure probabilities. Moreover, the authors propose a federated Q-learning method that optimally utilizes the available resources to minimize the communication/computing budgets and the offloading failure probabilities. The authors use computer simulations to show that their algorithm can significantly outperform the existing baselines in terms of resource cost and offloading failure probability.

Machine Learning-Based Workload Orchestrator for Vehicular Edge Computing

C. Sonmez, C. Tunca, A. Ozgovde, and C. Ersoy

Orchestrating the dynamic and heterogeneous resources in vehicular edge computing (VEC) systems is a challenging task. The vehicular workload orchestrator promises to offload the incoming tasks to the optimal computing unit to improve system performance. Since workload orchestration is an online problem, the formal optimization tools cannot solve this problem efficiently, since the inputs of the problem are very rapidly changing. In this study, the authors propose a two-stage machine learning-based vehicular edge orchestrator which takes into account not only the task completion success but also the service time. In the first stage, a classifier model predicts whether the results of the offloading options are successful or not for each target device. In the second stage, a regression model estimates the service time of the related options. Then, the target device which promises the lowest service time is selected. The authors conduct extensive simulations to evaluate the proposed approach by considering the characteristics of the vehicular applications, upload/download sizes, computational footprints of the tasks, multi-access network environments, and vehicle mobility.

QoE-Based Task Offloading With Deep Reinforcement Learning in Edge-Enabled Internet of Vehicles

X. He, H. Lu, M. Du, Y. Mao, and K. Wang

In the transportation industry, task offloading services of edge-enabled IoV are expected to provide vehicles with a better quality of experience (QoE). However, the various status of diverse edge servers and vehicles, as well as varying vehicular offloading modes, make the task offloading particularly challenging. To enhance the satisfaction of QoE, the authors first introduce a novel QoE model. The authors then propose PS-DDPG, an improved deep reinforcement learning (DRL) algorithm with the prioritized experience replay (PER) and the stochastic weight averaging (SWA) mechanisms based on deep deterministic policy gradients (DDPG) to seek an optimal offloading mode, saving energy consumption. Extensive experiments certify the better performance, i.e., stability and convergence, of PS-DDPG algorithm compared to existing work. Moreover, the experiments indicate that the QoE value can be improved by PS-DDPG.

DRLE: Decentralized Reinforcement Learning at the Edge for Traffic Light Control in the IoV

P. Zhou, X. Chen, Z. Liu, T. Braud, P. Hui, and J. Kangasharju

The IoV enables real-time data exchange among vehicles and RSUs and thus provides a promising solution to alleviate traffic jams in the urban area. Meanwhile, better traffic management via efficient traffic light control can benefit the IoV as well by enabling a better communication environment and decreasing the network load. In this article, the authors propose DRLE, a Decentralized Reinforcement Learning at the Edge for traffic light control in the IoV. DRLE exploits the ubiquity of the IoV to accelerate traffic data collection and interpretation towards better traffic light control and congestion alleviation. Operating within the coverage of the edge servers, DRLE aggregates data from neighboring edge servers for city-scale traffic light control. DRLE decomposes the highly complex problem of large area control into a decentralized multi-agent problem. The authors prove its global optima with concrete mathematical reasoning and demonstrate its superiority over several state-of-the-art algorithms via extensive evaluations.

Edge Learning for Surveillance Video Uploading Sharing in Public Transport Systems

L. Cui, D. Su, Y. Zhou, L. Zhang, Y. Wu, and S. Chen

Nowadays, surveillance cameras have been pervasively equipped with vehicles in public transport systems. For the sake of public security, it is crucial to upload recorded surveillance videos to remote servers timely for backup and necessary video analytics. However, the uploading of video content generated by tens of thousands of vehicles can be extremely bandwidth-consuming. In this work, the authors investigate the video uploading problem for moving buses by proposing to deploy dedicated access points (AP) at bus stops to facilitate video uploading. The authors propose a water filling placement (WFP) algorithm, aiming to balance the aggregated bandwidth allocated to each bus. A queuing model is established to analyze the uploading delay of video content. The authors further resort to machine learning models to factor the influence of bus routes into the queuing model. The authors demonstrate the effectiveness of their method by carrying out extensive experiments using bus traces collected in Shenzhen city of China.

A Cross-Layer Defense Scheme for Edge Intelligence-Enabled CBTC Systems Against MitM Attacks

Y. Li, L. Zhu, H. Wang, F. R. Yu, and S. Liu

While communication-based train control (CBTC) systems play a crucial role in the efficient and reliable operation of urban rail transits, the high penetration level of communication networks opens doors to Man-in-the-Middle (MitM) attacks. The limited computing capability of the on-board computers prevents the direct implementation of most existing intrusion detection and defense algorithms against the MitM attack. In this article, the authors introduce edge intelligence into CBTC to enhance the computing capability of the system. A cross-layer defense scheme with detection and defense stage is proposed. For the cross-layer detection stage, the authors propose a Long Short-Term Memory (LSTM) and Support Vector Machine (SVM)-based detection method to combine the detection probability calculated from the train control parameter sequence and operation log files. For the cross-layer defense stage, the authors construct a Bayesian game-based defense model to derive the optimal defense policy against MitM attacks.

A Decentralized Location Privacy-Preserving Spatial Crowdsourcing for Internet of Vehicles

J. Zhang, F. Yang, Z. Ma, Z. Wang, X. Liu, and J. Ma

With the rapid development of the IoV, vehicle-based spatial crowdsourcing (SC) applications have been applied to various fields. However, location privacy leakage is a serious issue in spatial crowdsourcing because workers who participate in a crowdsourcing task are required to upload their driving locations. In this article, the authors propose a decentralized location privacy-preserving SC for IoV, which allows vehicle users to securely participate in SC with ensuring the task's location policy privacy and providing multi-level privacy preservation for workers' locations. Specifically, The authors employ blockchain technology into SC, which can eliminate the control of vehicle user data by SC-server. In addition, any worker in the spatial crowdsourcing system can verify that whether The authors satisfy the task location policy and any requester in the spatial crowdsourcing system can verify the location proof to prevent workers from illegally obtaining rewards through forging their driving location. The authors use theoretical analysis and computer simulations based on a real-world data set to show their approach is able to satisfy security requirements and goals.

Social-Aware Incentive Mechanism for Vehicular Crowdsensing by Deep Reinforcement Learning

Y. Zhao and C. H. Liu

Vehicular crowdsensing (VCS) exploits both the crowd wisdom and sensing abilities offered by vehicle drivers' carried smart mobile devices and on-board sensors to accomplish challenging sensing tasks. The daily roadway commutes of vehicle drivers may form "virtual" mobile communities, namely, Vehicular Social Networks (VSNs). It offers an opportunity to include social network effect into incentive mechanism design where a driver can benefit from others' sensing strategy in one VSN. In this article, the authors consider a non-cooperative VCS campaign where multiple vehicles are incentivized by dynamically priced tasks and social network effect. In order to maximize the overall utility of vehicle drivers, The authors propose DRL-SIM, a social-aware incentive mechanism with deep reinforcement learning, to derive the optimal long-term sensing strategy for all vehicles. Numerical results are supplemented to show both the convergence and the advantage of DRL-SIM over existing baselines.

Joint Auction-Coalition Formation Framework for Communication-Efficient Federated Learning in UAV-Enabled Internet of Vehicles

J. S. Ng, W. Y. B. Lim, H.-N. Dai, Z. Xiong, J. Huang, D. Niyato, X.-S. Hua, C. Leung, and C. Miao

Due to the advanced capabilities of the IoV components such as vehicles, RSUs, and smart devices as well as the increasing amount of data generated, Federated Learning (FL) becomes a promising tool given that it enables privacy-preserving machine learning that can be implemented in the IoV. However, the performance of the FL suffers from the failure of communication links and missing nodes, especially when continuous exchanges of model parameters are required. In this article, the authors propose the use of Unmanned Aerial Vehicles (UAVs) as wireless relays to facilitate the communications between the IoV components and the FL server and thus improving the accuracy of the FL. The authors propose a joint auction-coalition formation framework of UAVs to support resource-constrained IoV components in completing the FL tasks. First, The authors design an auction scheme where each cell of workers submit its bids to all possible coalitions of UAVs based on their importance of the cells and the distance between the cells and the UAVs. Then, the authors use the merge-and-split algorithm to decide on the optimal coalitional structure that maximizes the total profit of the UAVs.

YAN ZHANG, *Guest Editor*
University of Oslo
0316 Oslo, Norway
e-mail: yanzhang@ieee.org

CELIMUGE WU, *Guest Editor*
The University of Electro-Communications
Tokyo 182-8585, Japan
e-mail: celimuge@uec.ac.jp

RODRIGO ROMAN, *Guest Editor*
University of Malaga
29071 Málaga, Spain
e-mail: roman@lcc.uma.es

HONG LIU, *Guest Editor*
East China Normal University
Shanghai 200062, China
e-mail: hliu@sei.ecnu.edu.cn

Yan Zhang (Fellow, IEEE) received the B.S. degree from Beihang University, the M.S. degree from the Nanjing University of Post and Telecommunications, and the Ph.D. degree from the School of Electrical and Electronics Engineering, Nanyang Technological University, Singapore. He is currently a Full Professor with the Department of Informatics, University of Oslo, Norway. His current research interests include 6G and the Internet of Things (e.g., transport and smart grid). He is also a member of the IEEE VTS Fellowship and Scholarship Committee. He is also a fellow of IET. He is also an Elected Fellow of the Academia Europaea (MAE), the Royal Norwegian Society of Sciences and Letters Academy (DKNVS), and the Norwegian Academy of Technological Sciences (NTVA). He received the Prestigious Award Clarivate Analytics (previously Thomson Reuters) as a "Highly Cited Researcher" in 2018. He also serves as the Chair for IEEE ComSoc Technical Committee on Green Communications and Computing (TCGCC). He is also serving as an Area Editor/Senior Editor/Editor for ten IEEE TRANSACTIONS/Magazines, including *IEEE Communications Magazine*, *IEEE Network Magazine*, IEEE COMMUNICATIONS SURVEYS AND TUTORIALS, IEEE TRANSACTIONS ON NETWORK SCIENCE AND ENGINEERING, IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS, IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, IEEE TRANSACTIONS ON GREEN COMMUNICATIONS AND NETWORKING, IEEE INTERNET OF THINGS JOURNAL, IEEE SYSTEMS JOURNAL, *IEEE Vehicular Technology Magazine*, and IEEE BLOCKCHAIN TECHNICAL BRIEFS. He is also the IEEE Communication Society Distinguished Lecturer and the IEEE Vehicular Technology Society (VTS) Distinguished Speaker. He was the IEEE VTS Distinguished Lecturer for two terms from 2016 to 2018 and from 2018 to 2020.

Celimuge Wu (Senior Member, IEEE) received the M.E. degree from the Beijing Institute of Technology, China, in 2006, and the Ph.D. degree from The University of Electro-Communications, Japan, in 2010. He is currently an Associate Professor with The University of Electro-Communications. His research interests include vehicular networks, edge computing, the Internet-of-Things, and intelligent transportation systems. He is also the Chair of the IEEE TCBD SIG on Big Data with Computational Intelligence and the IEEE TCGCC SIG on Green Internet of Vehicles. He also serves as an Associate Editor for IEEE TRANSACTIONS ON NETWORK SCIENCE AND ENGINEERING, IEEE TRANSACTIONS ON GREEN COMMUNICATIONS AND NETWORKING, IEEE ACCESS, and *Wireless Networks*. He has been a Guest Editor of IEEE TRANSACTIONS ON EMERGING TOPICS IN COMPUTATIONAL INTELLIGENCE, *IEEE Computational Intelligence Magazine*, and *ACM/Springer Mobile Networks & Applications (MONET)*.

Rodrigo Roman (Member, IEEE) received the M.Sc. degree in computer engineering and the Ph.D. degree in computer science from the University of Malaga, Spain, in 2003 and 2008, respectively. He is currently an Assistant Professor with the Department of Computer Science, University of Malaga. Pursuing to make security simple and usable, his research interests include the development of protection mechanisms for the Internet of Things and related paradigms, such as edge computing. He has published more than 25 articles in indexed JCR journals, with more than 5000 citations according to Google Scholar. Moreover, he has served as a Workshop Chair for several edge computing security workshops.

Hong Liu received the Ph.D. degree from Beihang University, China. She is currently an Associate Professor with East China Normal University, and the Shanghai Institute of Intelligent Science and Technology, Tongji University. She also works as the CTO with Shanghai Trusted Industrial Control Platform Company Ltd., China. Her research interests include the security and privacy issues in vehicular edge computing, and industrial Internet of Things. She has published more than 30 SCI articles, and Google Scholar citations are 2800 times, including one IEEE Best Paper Award, one IEEE Popular Article, and two ESI "Highly Cited Papers," and also serves as the program committee (PC) member and a workshop chair for several international conferences.