Integrating Licensed and Unlicensed Spectrum in Internet-of-Vehicles with Mobile Edge Computing

Celimuge Wu, *Senior Member, IEEE,* Xianfu Chen, *Member, IEEE,* Tsutomu Yoshinaga, *Member, IEEE,* Yusheng Ji, *Senior Member, IEEE,* Yan Zhang, *Senior Member, IEEE*

***Abstract*—In order to satisfy the application requirements in Internet-of-Vehicles scenarios, it is important to efficiently utilize different wireless spectrums while considering the dynamic features of network environments. In this article, we propose a context-aware communication approach to efficiently integrate different licensed and unlicensed spectrums leveraging the edge computing technologies. In addition, a joint *Aggregation, Caching & Decentralization* scheme is proposed to efficiently combine route aggregation, data caching, and decentralized computing approaches to compensate for the limited wireless resources. *Asynchronous multi-hop broadcast* and *Asynchronous multi-hop unicast* scheme are introduced to improve the routing performance in multi-hop broadcast and multi-hop unicast communications, respectively. We conduct computer simulations to evaluate the effects of the proposed scheme by comparing with other baseline approaches.**

***Index Terms*—Licensed and unlicensed spectrum, Internet-of-Vehicles, dynamic edge, asynchronous multi-hop broadcast, asynchronous multi-hop unicast.**

I. Introduction

Vehicle-to-everything (V2X) communications are important for realizing enhanced intelligent transport systems, autonomous driving, etc. Vehicle mobility, highly dense distribution of vehicles, complex road conditions make the V2X communications particularly challenging. Current Internet-of-Vehicles (IoV) applications mainly use Sub-6 GHz cellular communications in providing connections to vehicles on the road. However, cellular communications are not sufficient to provide a high quality-of-service (QoS) due to the limited resources and radio interferences [1]. As the vehicle density increases, it becomes more difficult to provide all the services through infrastructure-based wireless communications (including cellular networks, and wireless access point-based communications) due to the cost of deploying and maintaining the infrastructures. Thus, 3GPP intends to fully leverage unlicensed bands for cellular V2X services, such as by placing cellular V2X and 802.11p in different channels of the ITS band. Multi-hop decentralized communications in unlicensed bands can provide a low cost and efficient solution for emerging IoV due to the flexibility and expandability. However, the limited wireless resources and the changes of environment pose new challenges on the design of an efficient end-to-end multi-hop transmission scheme [2, 3].

IEEE 802.11p is designed as a standard for decentralized vehicle-to-vehicle (V2V) communications. There have been lots of work discussing an efficient use of IEEE 802.11p in vehicular networks [4–6]. These studies employ different types of technologies in the design of packet forwarding algorithms including position-based approach, cooperative forwarding, opportunistic forwarding, and so on. Operating in ITS band of 5.9 GHz, although IEEE 802.11p can provide bit rate of 27 Mbps, it is still far from being sufficient, especially in a highly dense vehicular environment. By using unlicensed 60 GHz spectrum, millimeter wave (mmWave) communication [7] is able to provide up to 2.5 Gbps, which could be a possible solution to achieve larger throughput. However, some critical challenges exist in deploying mmWave in vehicular networks. First, a line-of-sight communication path is required between the transmitter and receiver. Second, a directional antenna or beamforming technology is needed to overcome pathloss, which determines that the mmWave communications only support unicast applications. Therefore, it is important to efficiently integrate these three communication technologies. Some existing studies [8, 9] discussed about an efficient integration of these technologies. However, the vehicular network environment is extraordinarily complex, and the best solution is dependent on the context information including available resources (communication, computing and storage resources), communication types, and application requirements. When the communication resource is scarce, computing and storage resources can be used to compensate for the communication limitation. For example, by caching contents at mobile-edge nodes, the communication overhead can be significantly reduced.

Celimuge Wu and Tsutomu Yoshinaga are with the University of Electro-Communications, Tokyo, Japan. Emails: {celimuge, yoshinaga}@uec.ac.jp

Xianfu Chen is with the VTT Technical Research Centre of Finland, Finland. Email: xianfu.chen@vtt.fi

Yusheng Ji is with the National Institute of Informatics and SOKENDAI (Graduate University for Advanced Studies), Tokyo, Japan. Email: kei@nii.ac.jp

Yan Zhang is with University of Oslo, Norway. Email: yanzhang@ieee.org.

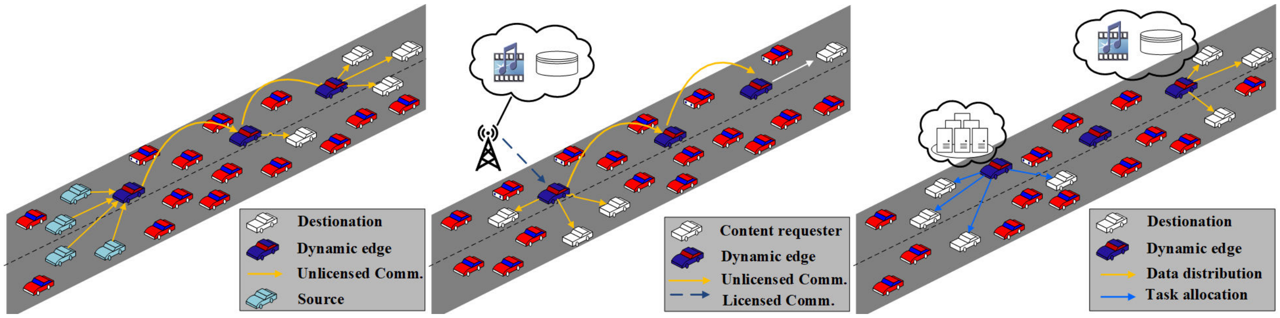

Fig. 1. Aggregation, Caching & Decentralization scheme (left: Aggregation, middle: Caching, right: Decentralization).

According to the communication types and application requirements, the networking problem in vehicular networks can be classified into two categories, namely, broadcast data delivery and unicast data delivery. Existing approaches fail to fully address the context information in the route selection and packet forwarding.

Mobile edge computing (MEC) is an approach that conducts computing tasks and data caching near the end users. Although there have been many studies [10, 11] explaining the advantages of MEC in performance improvement, most studies mainly consider conducting edge computing on the base stations, and the edge node formation problem in a decentralized vehicular network is not seriously discussed. In order to deal with the dynamic feature of vehicular networks, the edge node selection algorithm should be able to address the context information.

In this paper, we propose a context-aware vehicle edge-based communication approach, where different licensed and unlicensed spectrums are integrated efficiently through edge nodes, and different edge nodes are used for different contexts in order to optimize the whole network performance. We propose a joint *Aggregation, Caching & Decentralization* scheme to handle the resource limitations (Fig.1). *Aggregation* employs a route aggregation technology to improve the wireless resource utilization efficiency, which is a promising way to solve the resource limitations incurred from highly dense distribution of vehicles. *Caching* is used to shorten the delay and reduce the wireless resource usage by caching contents at edge nodes. *Decentralization* denotes a distributed way of storing data and executing computation tasks, which improves the performance by fully utilizing the local resources. In order to take into account different types of networking requirements, we also propose *Asynchronous multi-hop broadcast* and *Asynchronous multi-hop unicast* schemes for broadcast applications and unicast applications, respectively. These two schemes use different types of communications in data delivery, resulting in more efficient use of different spectrums. Realistic computer simulations are conducted to show the advantage of the proposed approaches over the baselines, and several open research problems are discussed.

The remainder of this article is organized as follows. We describe our solutions for the efficient use of different spectrums in Section II. Simulation results are presented in Section III. Finally, we point out future research directions and then draw our conclusions in sections IV and V, respectively[1].

II. Dynamic Edge-based Context-aware Integration of Different Spectrums

Major challenges in vehicular networking come from dynamic vehicular environment due to the vehicle mobility, varying vehicle density, and resource limitations. Therefore, it is important to consider these characteristics in the design of a communication protocol. Here, we first propose a context-aware dynamic edge concept that selects different edge nodes based on the context information. Two different classes of context information, specifically resource limitations and networking requirements are mainly addressed in the paper. We then propose a joint *Aggregation, Caching & Decentralization* approach to handle the resource limitations, and obtain *Asynchronous multi-hop broadcast* and *Asynchronous multi-hop unicast* schemes to support broadcast communications and unicast communications, respectively.

A. Context-aware hierarchical dynamic edge

Here, *Dynamic* means that the edges should be different for different contexts, and the edges should be updated with the environmental change. We propose a hierarchical dynamic edge architecture that creates multi-tier edge clusters by integrating licensed Sub-6 GHz band, large-throughput short-range unlicensed commutations (such as mmWave), and low-throughput long-range unlicensed communications (IEEE 802.11p). As shown in Fig. 2, short-range communications are used to provide a high-throughput connection between end users and Tier-2 edges. Long range unlicensed communications are used to guarantee the connectivity between different edges. Finally, licensed Sub-6 GHz communications are used to connect Tier-1 edges directly to the cellular base stations. Based on the exchange of

[1]We use the words “vehicle” and “node” interchangeably in the rest of this paper.

hello messages, these edges are created dynamically according to the context information, namely, node density and propagation condition [12]. The vehicle mobility, the link quality between vehicles, and vehicle distributions are considered in the edge node selection. Edge nodes are responsible for forwarding data packets, and our aim is to facilitate the use of edge nodes in the route selection in order to improve the packet forwarding performance. The *hierarchical* feature of this edge architecture ensures that the proposed approach could deal with a high-density condition by utilizing different types of wireless spectrums.

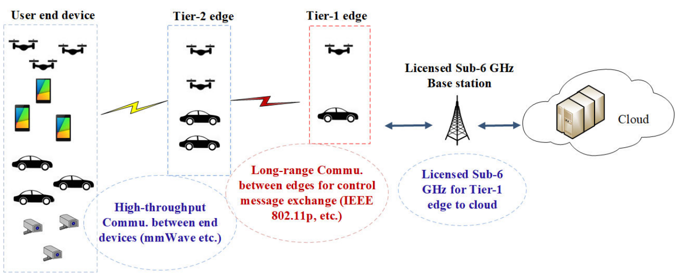

Fig. 2. Hierarchical dynamic edge.

B. The context information for route selection

Two classes of contexts are addressed in the paper. The first class of context is the resource limitations due to the high mobility, high network density, etc. The communication protocols should optimize packet forwarding process according to the available resources. The overall quality of a computer system is determined by the joint effect of communications, computing, and storage resources. In many scenarios, the communication resource is the main bottleneck. Therefore, a full utilization of computing and storage resources would be a way to solve the communication resource limitation problem. For example, it is possible to improve the communication performance by conducting efficient caching and computing near the end users, which is also the main functionality of mobile edge computing.

The second class of context is the application requirements on the networking. Specifically, some applications such as vehicular safety applications require broadcast type data delivery while some applications require unicast type data delivery. Broadcast communications and unicast communications require totally different types of networking protocols. Therefore, these requirements should be considered in the design of communication protocols.

C. Joint Aggregation, Caching & Decentralization scheme

As show in Fig.1, a joint *Aggregation, Caching & Decentralization* scheme is designed to provide a better communication performance by efficiently utilizing the available computing and storage resources. Here, *Aggregation* denotes route aggregation instead of data aggregation. The data aggregation mainly denotes the aggregation of data from different sources that have similar information. The difference between data aggregation and route aggregation is that the latter one does not change the data and therefore is independent of specific applications. In the route aggregation, multiple routes are aggregated at edge nodes in order to reduce the number of transmission nodes in the network without changing the data delivered. This scheme is specifically designed for data delivery scenarios in vehicular networks where the movement of vehicles is restricted by roads resulting in a higher chance of conducting route aggregation. *Caching* is the approach of conducting caching at edge nodes, which is particularly efficient for one-to-many data delivery scenarios such as video data downloading. *Decentralization* means decentralized storage and computing. In particular, the decentralized storage can store the data in a distributed network, and the decentralized computing is useful for executing some jobs that require high computational capabilities and short response delay.

The main purpose of *Aggregation* is to improve the wireless resource utilization efficiency by reducing the MAC layer contention time. *Aggregation* does not reduce the volume of data transmitted in the network, but it is efficient when multiple traffic flows coexist in the network. *Caching* is used to reduce the volume of data transmitted in the network by caching some data at some vehicles. *Decentralization* is an approach to redistribute the data and computing tasks in the network, which can improve the communication efficiency by integrating with other two approaches. All these three schemes or any two of these can be combined together to achieve a better utilization of wireless resources. *Aggregation* and *Caching* scheme can be integrated in to the routing protocol, and *Decentralization* scheme can be integrated with resource scheduling protocols.

D. Asynchronous multi-hop broadcast

In broadcast communications, it is particularly difficult to check the reception status of intended receivers as there is no acknowledgment for a broadcast frame at the MAC layer. Therefore, an upper layer acknowledgment approach is required to confirm a successful delivery. However, requesting acknowledgments from all the receivers could possibly cause a traffic congestion due to limited wireless resources. We propose a *Asynchronous multi-hop broadcast* approach that uses two different types of communications for the broadcasting procedure. More specifically, as shown in Fig.3, the broadcast capability of IEEE 802.11p signal is used to send broadcast packets and the large bandwidth of mmWave is used to send acknowledgement packets. By using explicit acknowledgments, each sender node is able to ensure the successful delivery of packets. As data packets and acknowledgement packets can be delivered concurrently using different spectrums, this approach is beneficial for vehicular safety applications that require a short delay with high reliability.

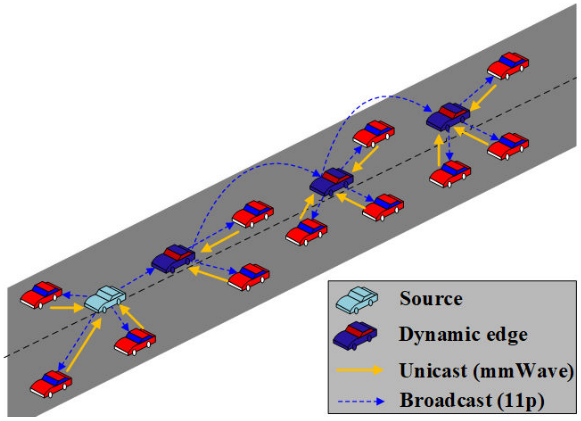

Fig. 3. Asynchronous multi-hop broadcast.

E. Asynchronous multi-hop unicast

As shown in Fig.4, *Asynchronous multi-hop unicast* involves different types of communications in different hops. In order to achieve a smooth end-to-end data delivery, a virtual data delivery approach based on a hop-by-hop custody transfer approach is derived. Different from the conventional custody transfer used in delay tolerant networks, in the *Asynchronous multi-hop unicast*, all the data delivery procedure is controlled and observed by edge nodes based on session information that is maintained by the communications between edge nodes using IEEE 802.11p. Each session is described by a tuple of {Session ID, Source IP, Destination IP} where the session ID field is generated based on the traffic flow identifier. Each edge node is responsible for finding the best next edge node for the destination node of each session, and forwards this session information to the next edge node using IEEE 802.11p. By exchanging the session information between edge nodes, end-to-end data delivery could be possible without synchronous multi-hop communications.

The data forwarding is achieved by whether mmWave or IEEE 802.11p depending on the network environment. In the route selection, we use a fuzzy constraint Q-learning approach as in [13]. In the evaluation of each direct wireless link, the available bandwidth, vehicle mobility, and link quality between vehicles are accounted for by using a fuzzy logic. The number of hops is considered by discounting the reward with the increase in the number of hops. In addition to this, the overhead of beam alignment in mmWave should be used to discount the reward when a mmWave link is used. Therefore, we propose a specific discount factor. The value of this factor should be a system specific parameter that varies with the system hardware. In order to simply this, we use a simplified version of *Asynchronous multi-hop unicast* where only the last one hop uses the mmWave communications. This simplified version is easy to be combined with the route aggregation approach proposed in Subsection II-C as the routes from different sources are aggregated at edge nodes except the last hops.

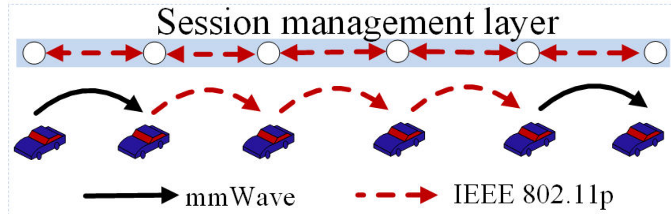

Fig. 4. Asynchronous multi-hop unicast.

III. Performance analysis

The network simulator ns-2.34 was used for conducting simulations. We evaluated the proposed approach in V2V data delivery for two different types of communications, namely broadcast transmissions and unicast transmissions. The performance of vehicle-to-cloud communications depends on the available cellular resources, which can be found in [14]. The same freeway topology and street topology as in [13] were used. The Nakagami propagation model was integrated to simulate a realistic vehicular communication channel [13]. There were two different types of communications available for vehicles, namely, IEEE 802.11p and mmWave.

A. Broadcast applications

A freeway with two lanes in each direction was used to evaluate the performance in broadcast applications. The number of source nodes was set to 2 (the two nodes were neighbors) in order to simulate a condition of two collided vehicles sending data messages at the same time. The proposed protocol was compared with "EMPR" [15], "Weighted p-persistence" [15], and "Edge with aggregation". Here, "Edge with aggregation" denotes the edge-based forwarding with route aggregation, which is actually the proposed protocol without using mmWave.

Fig. 5 is the performance comparison for various numbers of vehicles. We can observe that the conventional sender-based approach ("EMPR") and probabilistic approach ("Weighted p-persistence") are not able to provide a high data dissemination ratio. This is due to the lossy wireless channel and the difficulty in checking the reception status of the receivers. Although "Edge with aggregation" can achieve a better performance by using efficient edge nodes for the data forwarding, it is still insufficient to achieve a high data dissemination ratio. With the asynchronous multi-hop broadcast approach, the proposed protocol can efficiently utilize mmWave communications to check the reception status of broadcast packets, resulting in a high dissemination ratio. The low end-to-end delay shown in Fig. 5 (b) can be explained by two reasons. First, the use of mmWave can efficiently reduce the MAC layer contention in IEEE 802.11p. Second, by using different spectrums, the proposed asynchronous multi-hop broadcast conducts the data transmission and acknowledgment packet transmission concurrently, which is particulary effective in terms of fast data delivery.

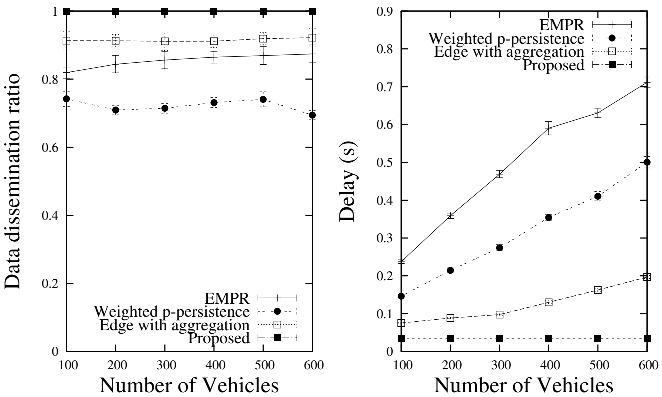

Fig. 5. Performance for multi-hop broadcast communications (left: data dissemination ratio, right: end-to-end delay).

B. Unicast applications

We used a 2500 m × 2500 m square area of New York City as shown in [13] to evaluate the protocol performance for unicast communications. The proposed approach was compared with "Without edge" approach. "Without edge" is a typical approach without using edge computing, and AODV-L [13] is used in the route selection of "Without edge". There were 30 CBR flows with 36kbps data rate for each. The maximum allowable velocity of the vehicles was 12 m/s. Fig. 6 shows the performance for unicast communications in terms of packet delivery ratio and end-to-end delay for various numbers of vehicles. As shown in the figure, the proposed protocol can provide the highest packet delivery ratio by using the asynchronous multi-hop unicast approach. Especially in terms of delay, while the other protocols show a drastic increase of end-to-end delay as the node density increases, the proposed protocol achieves a stable end-to-end delay due to the efficient utilization of mmWave communication resources.

IV. Future research directions

The dynamic features of vehicular networks, the limited wireless resources, and the variety of wireless spectrums open up many interesting research topics including:

- **Data driven approaches for learning the best edge placement policy–** There is a need to disseminate and collect information from/to the large number of vehicles. Due to the limited wireless resources and large node density, it is difficult to provide a satisfactory throughput with the traditional networking

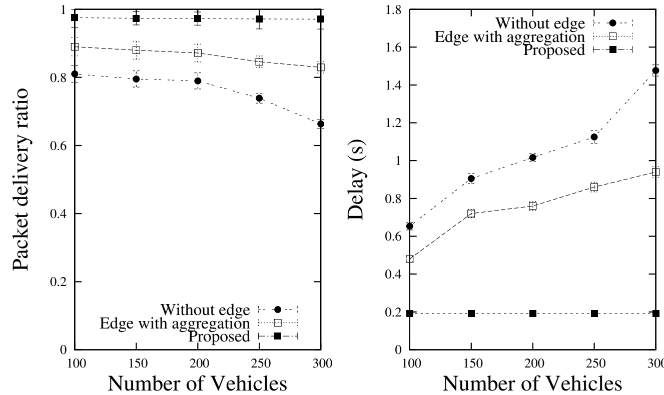

Fig. 6. Performance for multi-hop unicast communications (left: packet delivery ratio, right: end-to-end delay).

technologies. Therefore, designing a dynamic edge mechanism that turns on/off some edges (access points or the edge functionality of user devices) according to the number of devices, traffic distribution, QoS requirement, and device capacities would continually be an important topic. However, due to various traffic patterns, node distributions, device types, and QoS requirements, the optimization of data forwarding is difficult to achieve using simple mathematical models. In recent years, data driven approaches are attracting increasing interests due to its capability of finding a good solution for a complex system. This would create new opportunities for a study on data driven approaches in learning the best edge placement policy.
- **Deep reinforcement learning based approach for handling complexity–** Reinforcement learning-based approaches are able to find the best action without labeled, classified or categorized data. However, well-used reinforcement learning approaches, such as Q-learning, require a clear structure to store the states and actions, which is insufficient for representing the complex network environment and user requirements. Since deep neural networks are able to store complex information, a combination of reinforcement learning and deep neural networks would be an interesting way to allocate the licensed and unlicensed spectrums automatically based on the past experiences and the feedbacks from environments.
- **Adapting quickly with the environment change–** The use of different spectrums in vehicular networks poses various challenges as the spectrum resources change over the road, time and other factors. Therefore, it is crucial to design an approach that is capable of adapting to these changes. Reinforcement learning can be used to learn the best action. However, due to the movement of vehicles, it is challenging to converge to the best action before the environment changes, especially for vehicles that newly join the network. Transfer learning could

be away to speed up the learning. How to transfer learned information between vehicles by using different spectrums would be an interesting and important topic.

- **Privacy issues and edge-computing based solutions–** Efficient utilization of different spectrums could significantly improve system performance. However, privacy issues would be a major concern as the owners of different networks could be different. This is a sensitive issue that could directly affect the deployment of a good system. While some IoV applications require collecting a large amount of vehicular data, it is simply unproductive to transmit in real-time all sensed data, for processing and analysis in the cloud. Hence the concept of edge computing could be a way to solve the privacy issues. Some data could be pre-processed and potentially used in real-time within different edges (belonging to different communities) whereas other data are stored or even archived (taking into consideration legal aspects) for much later use in a more centralized (e.g. regional) cloud infrastructure. An interesting topic would be to investigate the privacy aspect involved in managing such distributed data among different communities and regions based on edge computing technologies while utilizing both licensed and unlicensed spectrums.
- **Intermediate layer for handling route changes–** An efficient use of different spectrums in a multi-hop data delivery could possibly incur frequent changes of routes. This could affect the upper layer protocols, resulting in performance degradation. For example, the change of routes could directly reduce the transmission rate of a TCP connection. Therefore, it is important to design an intermediate layer protocol that exists between the network layer and the transport layer to conceal the change of data forwarding path from the transport layer.

V. Conclusions

In the paradigm of an efficient use of licensed and unlicensed spectrums in vehicular networks, this article discussed the importance of utilizing the context information with edge computing in highly mobile and resource limited networks. We first introduced a context-aware vehicle edge-based communication approach to integrate different licensed and unlicensed spectrums where different edge nodes are selected for different contexts in order to optimize the whole network performance. Then we proposed a joint *Aggregation, Caching & Decentralization* scheme to handle the communication resource limitations by utilizing local computing and storage resources. *Asynchronous multi-hop broadcast* and *Asynchronous multi-hop unicast* scheme were further put forward to enhance multi-hop data delivery with different spectrums. Simulation results explain that the proposed approaches achieve much better performance than other baselines. Finally, we pointed out some important research topics for the next step research.

Acknowledgment

This research was supported in part by the open collaborative research program at National Institute of Informatics (NII) Japan (FY2018), the Telecommunications Advanced Foundation, JSPS KAKENHI Grant Numbers 16H02817, 18KK0279 and 16K00121, and JST-Mirai Program Grant Number JPMJMI17B3, Japan.

References

[1] H. Chen and J. Wu, “A Novel Interference Suppression Method in Wireless Relay Networks,” in *Proc. IEEE SAM*, pp.60–64, 2018.
[2] M. Khalil *et al.*, “Unlocking 5G Spectrum Potential for Intelligent IoT: Opportunities, Challenges, and Solutions,” *IEEE Commun. Magazine*, vol.56, no.10, Oct. 2018, pp.92–93.
[3] K. A. Yau *et al.*, “Cognition-inspired 5G cellular networks: a review and the road ahead,” *IEEE Access*, vol.6, July 2018, pp.35072–35090.
[4] J. Wu *et al.*, “MBR: A Map-Based Relaying Algorithm For Reliable Data Transmission Through Intersection in VANETs,” *IEEE Trans. Intell. Transp. Syst.*, 2018, Early Access, DOI:10.1109/TITS.2018.2877993.
[5] E. Ahmed and H. Gharavi, “Cooperative Vehicular Networking: A Survey,” *IEEE Trans. Intell. Transp. Syst.*, vol.19, no.3, Mar. 2018, pp.996–1014.
[6] N. Li *et al.*, “Probability Prediction-Based Reliable and Efficient Opportunistic Routing Algorithm for VANETs,” *IEEE/ACM Trans. Netw.*, vol.26, no.4, Mar. 2018, pp.1933–1947.
[7] D. Zhang *et al.*, “Capacity Analysis of Non-Orthogonal Multiple Access with mmWave Massive MIMO Systems,” *IEEE J. Sel. Areas Commun.*, vol.35, no.7, Apr. 2017, pp.1606–1618.
[8] H. Wymeersch *et al.*, “5G mmWave Positioning for Vehicular Networks,” *IEEE Wirel. Commun.*, vol.24, no.6, Dec. 2017, pp.80–86.
[9] A. Bazzi *et al.*, “On the Performance of IEEE 802.11p and LTE-V2V for the Cooperative Awareness of Connected Vehicles,” *IEEE Trans. Veh. Technol.*, vol.66, no.11, Nov. 2017, pp.10419–10432.
[10] F. Giust *et al.*, “Multi-Access Edge Computing: The Driver Behind the Wheel of 5G-Connected Cars,” *IEEE Commun. Standards Magazine*, vol.2, no.3, Sep. 2018, pp.66–73.
[11] Z. Zhou *et al.*, “BEGIN: Big Data Enabled Energy-Efficient Vehicular Edge Computing,” *IEEE Commun. Magazine*, 2018, Early Access, DOI:10.1109/MCOM.2018.1700910.
[12] Q. Hu *et al.*, “Vehicular Multi-access Edge Computing with licensed Sub-6 GHz, IEEE 802.11p and mmWave,” *IEEE Access*, vol.6, Dec. 2017, pp.1995–2004.
[13] C. Wu *et al.*, “Flexible, Portable, and Practicable Solution for Routing in VANETs: A Fuzzy Constraint Q-Learning Approach,” *IEEE Trans. Veh. Technol.*, vol.62, no.9, Nov. 2013, pp.4251–4263.
[14] C. Wu *et al.*, “Cluster-Based Content Distribution Integrating LTE and IEEE 802.11p with Fuzzy Logic and Q-Learning,” *IEEE Comput. Intell. Mag.*, vol.13, no.1, Feb. 2018, pp.41–50.
[15] C. Wu *et al.*, “VANET Broadcast Protocol Based on Fuzzy Logic and Lightweight Retransmission Mechanism,” IEICE Trans. Commun., vol.E95-B, no.2, Feb. 2012, pp.415–425.

Celimuge Wu [M’10-SM’18] (celimuge@uec.ac.jp) received his ME degree from the Beijing Institute of Technology, China, in 2006, and his PhD degree from The University of Electro-Communications, Japan, in 2010. He is currently an associate professor with the Graduate School of Informatics and Engineering, The University of Electro-Communications. His current research interests include vehicular networks, sensor networks, intelligent transport systems, IoT, 5G, and mobile cloud computing.

Xianfu Chen [M'13] (xianfu.chen@vtt.fi) received his Ph.D. degree in Signal and Information Processing, from the Department of Information Science and Electronic Engineering at Zhejiang University, Hangzhou, China, in March 2012. He is currently a Senior Scientist with the VTT Technical Research Centre of Finland, Oulu, Finland. His research interests cover various aspects of wireless communications and networking, with emphasis on software-defined networking, green communications, centralized and decentralized resource allocation, dynamic spectrum access, and the application of artificial intelligence to wireless communications.

Tsutomu Yoshinaga [M'99] (yoshinaga@uec.ac.jp) received BE, ME, and DE degrees from Utsunomiya University in 1986, 1988, and 1997, respectively. Since August 2000, he has been with the Graduate School of Information Systems, The University of ElectroCommunications, where he is now a professor. His research interests include computer architecture, interconnection networks, and network computing. He is a fellow of IEICE, and a member of ACM, IEEE, and IPSJ.

Yusheng Ji [M'94-SM'18] (kei@nii.ac.jp) received B.E., M.E., and D.E. degrees in electrical engineering from the University of Tokyo. She joined the National Center for Science Information Systems, Japan, in 1990. Currently, she is a Professor at the National Institute of Informatics (NII) and SOKENDAI (the Graduate University for Advanced Studies). Her research interests include network architecture, resource management, and quality of service provisioning in wired and wireless communication networks.

Yan Zhang [M'05-SM'10] (yanzhang@ifi.uio.no) is a full professor at the University of Oslo. He is an Editor of several IEEE publications, including IEEE Communications Magazine, IEEE Network, IEEE Transactions on Green Communications and Networking, IEEE Communications Surveys & Tutorials, and IEEE Internet of Things. His current research interests include next generation wireless networks leading to 5G and cyber physical systems. He is an IEEE VTS Distinguished Lecturer and a Fellow of IET. He received the award "Highly Cited Researcher" (Web of Science top 1% most cited worldwide) according to Clarivate Analytics.