Vehicle-Mounted Base Station for Connected and Autonomous Vehicles: Opportunities and Challenges

Changle Li, Quyuan Luo, Guoqiang Mao, Min Sheng, and Jiandong Li

Abstract

The crown jewel of intelligent transportation is achieving autonomous driving that can ultimately become accident- and congestion-free through CAVs and the associated traffic management systems. Recently, this vision has sparked huge research interest, such as IoV, LTE-V2X, and 5G. However, the huge amount of traffic data generated by CAVs poses challenges for the current networks and even the upcoming 5G communication networks.In this article, we first analyze the communication requirements of CAVs and present the progress of vehicular communication networks, and on that basis propose the novel concept of VMBS and a VMBS-CCNA for CAVs. The VMBS plays multiple roles of a user node and edge computing node for external communication networks, and a base station and information caching node for CAVs, thus achieving the fusion of communication and computing for CAVs. To this end, we present both the VMBS-enabled wireless communication and computing for CAVs, and the VMBS-assisted wireless communication for other wireless devices. Several research challenges and some open research issues are highlighted and discussed. Finally, simulation results reveal that the proposed VMBS-CCNA can bring a significant improvement in terms of throughput, delay, and average number of links.

Introduction

With the development of the automotive industry and increasing car ownership, traffic congestion is becoming more and more serious, and people suffer from increasingly heavy traffic congestion, especially on public holidays or during rush hours. Moreover, traffic accidents also cause serious personal casualties and financial loss. Autonomous driving technology is a promising solution to reduce traffic congestion and traffic accidents, as well as to optimize the road usage and to reduce fuel consumption [1]. It is envisioned that humans will be banned from driving within 25 years, and the ultimate goal of autonomous driving is achieving level 5 autonomy, namely, *full automation*. In the foreseeable future, it will no longer be necessary for drivers to sit in the cab and control the vehicle; instead, they can entertain or work during the trip.

For autonomous vehicles, it is essential to utilize vehicular wireless communications to exchange information with each other and with the roadside infrastructure to become communicating autonomous vehicles (CAVs), enabling autonomous vehicles to make better decisions and plan ahead for enhancing the overall performance of both vehicles and the transportation system [2]. CAVs may generate and consume a large amount of data from:
- Uploading the data generated by various vehicular sensors
- Generation, update, and dissemination of high-precision dynamic 3D maps
- Real-time video transmission
- Providing high-speed Internet access for passengers

According to [3], it is predicted that each CAV may generate and consume 40 TB data every eight hours. Although most of the data is processed and stored locally and just a small portion of data need to be exchanged through communication networks, based on a conservative estimation that about 10 percent of these generated and consumed data may be exchanged through communication networks, there are still 512 GB data per hour (i.e., the data rate is over 1 Gb/s) requiring to be transmitted.

There are a number of wireless communication standards and architectures that have been developed and implemented in vehicular communication systems [4, 5]. Among the existing standards and architectures, none of them is able to satisfy the hunger of CAVs for bandwidth as the throughput of those techniques in a highly mobile environment is limited to the megabit per second level. For example, the data rate of dedicated short-range communication (DSRC) for intelligent transportation systems (ITS) is about 3–27 Mb/s, and the data rate of the present fourth generation (4G) system is about 75 Mb/s for upstream and 300 Mb/s for downstream. Moreover, 5G, the most promising communication system for autonomous driving and a hot research topic in academia and telecommunication companies, may only support 0.1–1 Gb/s user experienced data rate and 20 Gb/s peak data rate at the network level according to the IMT-2020 (5G) Promotion Group [6]. Accordingly, the data rate is becoming a bottleneck for the current networks and even upcoming 5G communication networks to support the

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large-scale deployment of CAVs, not to mention the fact that a 5G communication network should reserve capabilities to support three other major application scenarios defined by the Third Generation Partnership Project (3GPP), namely enhanced mobile broadband (eMBB), massive machine type communication (mMTC), and ultra-reliable low-latency communications (URLLC). More importantly, if all the data generated by CAVs is sent to the cloud for processing, on one hand, the response time would be too long, which is not sufficient to support vehicles to make timely decisions; on the other hand, the bandwidth and reliability of the current networks and upcoming 5G communication networks would be strained in their capabilities of supporting a large number of CAVs in one area.

Motivated by the work in [7], where the authors considered the unmanned aerial vehicle (UAV) as an aerial mobile base station and proposed a new hybrid network architecture, and the work in [8], where an edge computing paradigm was proposed and computing should happen in proximity of data sources, we propose a vehicular moible base station (VMBS)-CCNA for CAVs. Through VMBS, the fusion of communication and computing for CAVs can be achieved. In the remaining sections, we elaborate the proposed VMBS-CCNA and the advantages of VMBS. Furthermore, some challenges and open research issues for VMBS-CCNA are presented. Finally, we demonstrate the benefits of our proposed VMBS-CCNA via simulations. The conclusion section concludes the article.

Communication and Computing Network Architecture for CAVs

Since the huge amount of data generated by CAVs pose challenges for the current networks and even the upcoming 5G communication networks, the evolution of vehicular communication network architecture needs to strive to meet the requirements of CAVs. More importantly, CAVs need ultra-low processing latency for data, rather than sending all the data to the cloud for processing; therefore, CAVs need to process part of the data locally. That is, some portion of computing needs to be conducted at the data source. For the purpose of satisfying the bandwidth, delay, and computation requirements of processing and transmitting data for CAVs, we propose the novel concept of *VMBS*, and Fig. 1 illustrates our proposed VMBS-based communication and computing network architecture for CAVs, where each CAV is equipped with a VMBS that can serve as a communication node and an edge computing node, which also reflects the current trend of integration of communication and computing [9]. The VMBSs are characterized by miniaturization, low transmitting power, good controllability, and intelligentized and flexible networking, and are easy to integrate into CAVs. In the following, we elaborate the communication and computing network architecture and the corresponding advantages of VMBS.

Perception Layer

In the perception layer of the proposed architecture, six major parts are included:

- The vehicular information terminal, consisting of an onboard module, is used for vehicular data collection.

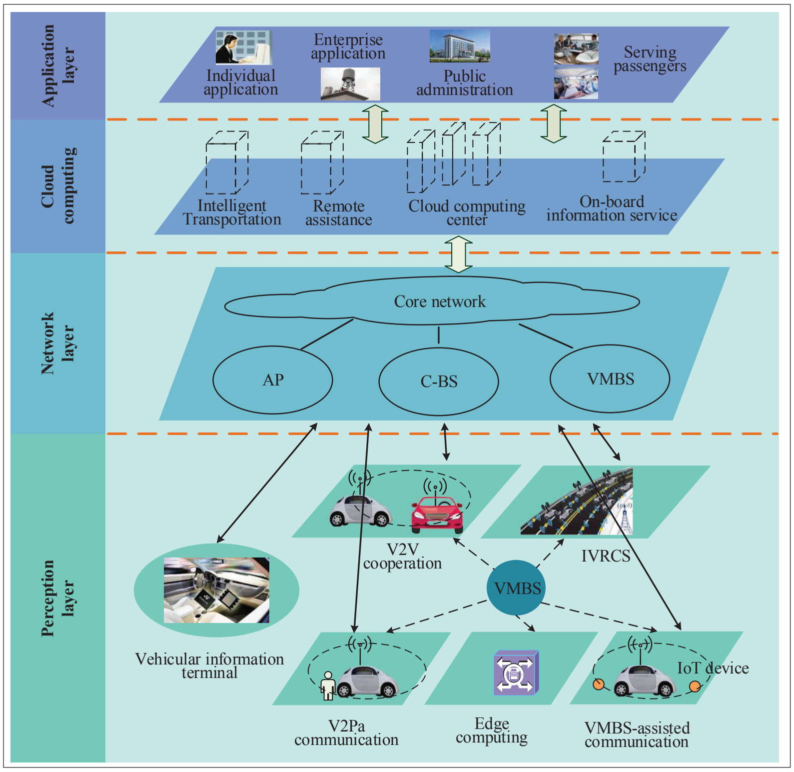

FIGURE 1. Communication and computing network architecture for CAVs.

- Vehicle-to-vehicle cooperation, achieved by the communication between VMBSs, plays the role of improving network throughput and sharing traffic information for enhancing traffic safety.
- The intelligent vehicle-road cooperative system (IVRCS) can achieve immediate and accurate environmental perception of CAVs through the assistance of a road. Accurate environmental perception is the basis and prerequisite for the realization of safe, efficient, and energy-saving driving of CAVs. However, the environmental perception of CAVs currently mainly relies on onboard sensor equipment, which is limited by visual distance. It is impossible to achieve the goal of global perception beyond visual distance and the goal of immediate and accurate detection of the states of road and traffic signal facility by the intelligence of CAVs. With the development of smart road, along which a large number of low-cost wireless beacons are deployed, it is imminent to use the smart road to assist vehicle perception and thus achieve the goal of immediate and accurate detection of the states of roads and traffic signal facility by means of vehicle-road collaboration. Through IVRCS, the states of road and traffic signal facility can be detected immediately and accurately, and then the information is broadcast to passing vehicles after being processed, which contributes to improving traffic efficiency and enhancing traffic safety.
- V2Pa communication, achieved by the communication between VMBS and passengers, can greatly improve data transmission rate and reduce network latency, which satisfies the requirement of passengers for high-speed Internet access and is used for in-car office and in-car entertainment.

The VMBSs on CAVs can act not only as a communication node for uploading and downloading data but also a computing node for data processing, which achieves the integration of communication and computing. Furthermore, in addition to the advantages in communication and computing aspects, the VMBS has other advantages.

- VMBS-assisted communication refers to the VMBS assisting other wireless communications, which is elaborated in the next section.
- Edge computing [8], performed by VMBS, accomplishes the local computing and processing of a huge amount of data. If all the data needs to be sent to the cloud for processing, the response time would be too long; not to mention that current network bandwidth and reliability would be challenged for its ability to support a large number of vehicles in one area. In this case, the data needs to be processed at the edge for shorter response time, more efficient processing. and less network pressure. Hence, the VMBS can serves as an edge computing device. Furthermore, the data generated by CAVs are processed and analyzed by VMBS or roadside server, and then transmitted to other CAVs in the adjacent area at a very low delay.

Different from the traditional architecture, one CAV plays multiple roles in our proposed architecture, such as a network user and a service provider. As a user, it transmits and receives information from roadside units (RSUs) or base stations, and as a service provider, it can provide high-speed Internet access for passengers, execute data computing and processing as a computing node, and assist other wireless communications, as discussed later. In order to realize autonomous driving, it is of vital importance to keep CAVs informed of real-time traffic data and have the capability of reliable identification of other vehicles' behaviors. Hence, the communication between CAVs for information exchange is crucial. In the following, we elaborate several of those different communication methods.

V2I Communication: V2I communication mainly includes three types: vehicle-to-RSU (V2R) for the transmission of huge amounts of data, vehicle-to-road-facility (V2RF) for local communication, and vehicle-to-base-station (V2BS) for global communication.

Vehicle-to-RSU: The V2R communication is expected to be the main communication method for CAVs. Huge amounts of data generated or collected from CAVs are uploaded to RSUs, or RSUs provide local traffic information and infotainment for CAVs through V2R communication link.

Vehicle-to-Road-Facility: V2RF communication refers to the communication between CAVs and road facilities (e.g., between CAVs and traffic lights or speed limit signs [1]). The V2RF communication serves as an auxiliary communication method in the local area. Event-driven and periodic messages can be disseminated through this communication method. The main purpose of V2RF communication is broadcasting warning messages about traffic light signals to neighboring vehicles, and speed limit notifications to specific road sections for the sake of avoiding traffic accidents. More importantly, in some areas such as intersections with obstacles or high buildings, the V2RF link can be used as a relay link to improve the communication reliability.

Vehicle-to-Base-Station: The V2BS communication refers to the communication between CAVs and base stations, and serves as an auxiliary communication method for V2R and is mainly supported by cellular networks. Due to the wide coverage of cellular base stations, more traffic information can be obtained through V2BS communications, such as accident reports. Based on the information obtained through V2BS communications, a global view of the traffic network can be obtained by the service center, which provides useful guidance for CAVs such as optimal navigation paths [1].

V2V Communication: Except for V2I communication, CAVs can communicate with each other to share information through V2V communication. For example, a potential approach named platooning using V2V communication is proposed to solve traffic jams on highways, which also enhances on-road safety [10]. V2V communication can contribute to enhancing traffic safety, avoiding vehicle collisions, and reducing traffic congestion.

V2Pa Communication: V2Pa communication in our proposed architecture refers to vehicle-to-passengers, which differs from V2P (vehicle-to-pedestrian) defined by 3GPP. Passengers in CAVs can access the Internet through VMBS with a high data rate. Furthermore, V2Pa communication can provide passengers with multimedia services such as in-car entertainment and in-car office.

Network Layer

In the network layer, apart from the traditional WiFi-based (i.e., access point, AP) and cellular-based (i.e., cellular base station, C-BS), there is a newly added access technology, namely VMBS. RSUs are deployed along the roadside and connected to the core network through wired or wireless links.

Cloud Computing and Application Layer

Cloud computing takes on the role of supporting information service, mainly including intelligent transportation, remote assistance, cloud computing center, and onboard information service. Since VMBS can act as not only a computing node, but also a communication node, if some delay-tolerant and popular data or contents are put on the cloud for data processing through data transportation by VMBS, less computing pressure is pushed to CAVs and more computing capability is reserved for real-time computing tasks. Furthermore, VMBSs on CAVs are striving to upload the collected data to the cloud computing center for the purpose of assisting the collection and analysis of big data. The network for CAVs is a cloud architecture enabled vehicle running information platform, the ecological chain of which includes intelligent transportation systems (ITS), logistics, passenger and freight, car rental, vehicle management, insurance, emergency rescue, mobile internetworking, and so on. It is the aggregation of multi-source and mass information. Therefore, cloud computing functions including virtualization, security authentication, real-time interaction, mass storage, and so on are needed for the network for CAVs. In the application layer, apart from traditional applications such as individual applications, enterprise applications, and public administration, there is a newly added application, that is, passenger services. The application of VMBS serving passengers can achieve the functions of dynamic caching, resource sharing, and high-speed Internet access services (e.g., in-car office and entertainment), which greatly improve the travel experience of passengers.

Advantages of VMBS

The VMBSs on CAVs can act as not only a communication node for uploading and downloading data but also a computing node for data processing, which achieves the integration of communication and computing. Furthermore, in addition to the advantages in communication and computing aspects, the VMBS has other advantages, discussed below.

Real-Time Connection with Infrastructure: Due to high mobility, the traditional CAV antennas cannot be adaptively adjusted, resulting in severe signal attenuation. Once the VMBSs are installed on CAVs, the beamforming of multi-antennas of VMBS can be adaptively adjusted to the direction of the strongest signal for the sake of maintaining high-data-rate communication and real-time connection between VMBS and infrastructure (e.g., base stations or RSUs).

Massive MIMO Technology: Through VMBS, massive multiple-input multiple-output (MIMO) technology can be achieved onboard. Massive MIMO can increase the transmission capability and capacity due to the aggressive spatial multiplexing. In addition, massive MIMO has many other advantages such as reducing latency on the air interface, simplifying the multiple access layer, and increasing the robustness against both unintended man-made interference and intentional jamming. All those advantages from massive MIMO would greatly benefit CAVs.

Dynamic Caching: With the urgent requirement of users for contents (mainly delay-tolerant and popular), storing and caching content in a data center server or cloud would cause serious delay for content retrieval. Therefore, storing and caching content at the network edge or a location closest to users has been a trend for vehicular networks. The VMBSs would help achieve dynamic caching, which would reduce the backhaul latency and cost for content retrieval and increase the delivery probability of contents to users.

Resource Sharing: The VMBS equipment on each CAV and the mobility of VMBSs accelerate resource sharing from the perspective of the network, such as popular content or information exchange between CAVs. Furthermore, with the density of VMBSs as APs increases, access opportunities and bandwidth increase greatly from the perspective of the user, which benefits from the resource sharing among VMBSs.

VMBS-Assisted Wireless Communication

Apart from meeting the requirements of CAVs for wireless communication, VMBSs can also be leveraged for other typical use cases, namely VMBS-assisted wireless communication scenarios, which are discussed in the following and illustrated in Fig. 2:

- VMBS-assisted offloading, where CAVs with VMBSs serve as relaying and are utilized for assisting the existing communication infrastructure. For example, in an extremely crowded scenario, where the existing base station is overloaded, VMBS-assisted offloading plays an important role for guaranteeing uninterrupted communication, as illustrated in Fig 2a.

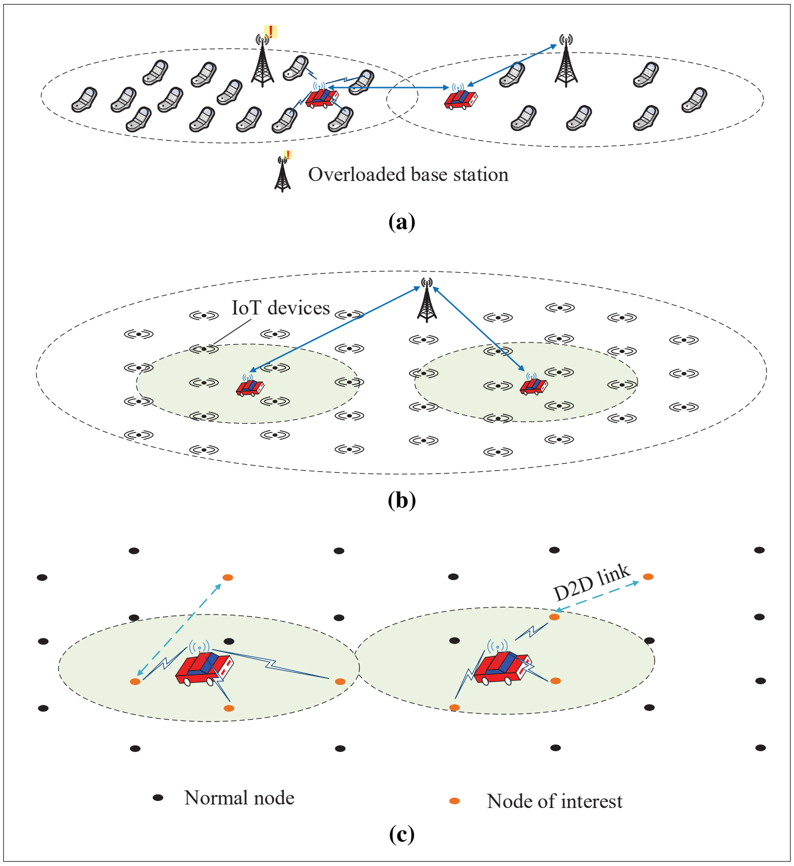

FIGURE 2. Three typical use cases of VMBS-assisted wireless communications: a) VMBS-assisted offloading; b) VMBS-assisted data collection; c) VMBS-assisted information dissemination.

- VMBS-assisted data collection, where CAVs with VMBSs are leveraged to collect delay-tolerant data generated by a massive number of distributed wireless devices, also known as Internet of Things (IoT) devices, or collect data about the road environment for the purpose of uploading various road environment data to RSUs that allows RSUs to distribute processed data to more passing CAVs.
- VMBS-assisted information dissemination, where some nodes (e.g., various wireless devices), termed nodes of interest, have downloading requests for a common file. Information dissemination can be achieved by repeatedly transmitting the same file as CAVs with VMBSs passing over different nodes of interest. After each node successfully receives just a portion of the file due to the limited wireless connectivity with the VMBS, a device-to-device (D2D)-enhanced information dissemination scheme is leveraged until all the nodes of interest receive the whole file [11].

Performance Evaluation

Simulations have been conducted in order to establish the performance of the proposed VMBS-CCNA. We consider a 1000 m × 4 m (just one lane) road segment, where two RSUs are deployed along the side of the road segment with a separation distance of $2R$, where R refers to the RSU's communication range. We assume that the communication range of an RSU is 250 m, and the whole segment is within the cover-

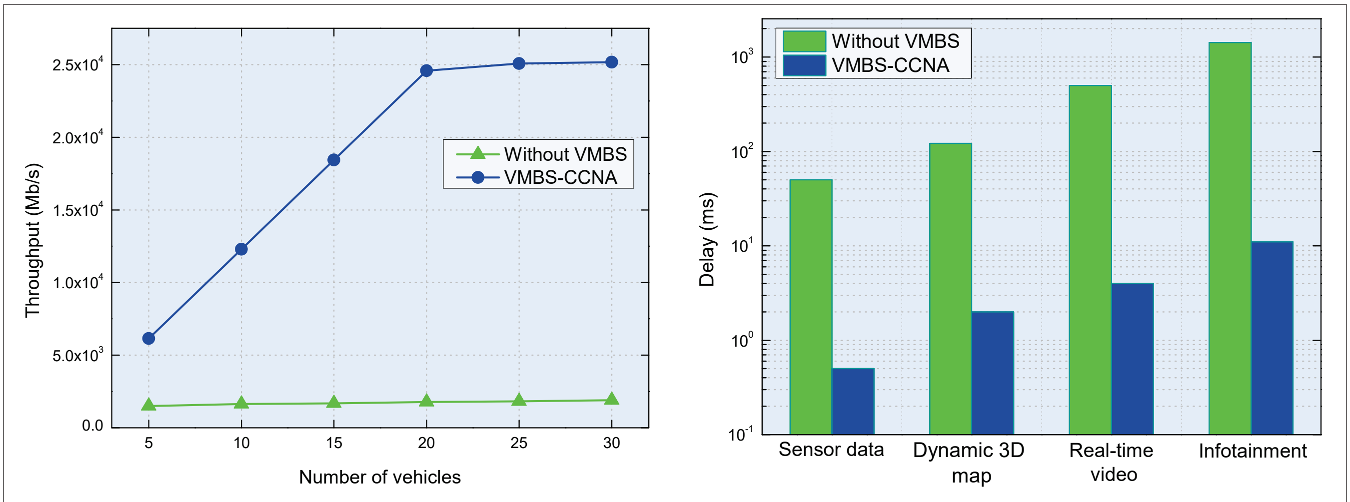

FIGURE 3. a) Throughput for different number of vehicles; b) delay for four different data types: sensor data, dynamic 3D map, real-time video, and infotainment.

age area of two RSUs and one base station. We assume that the vehicles run at a constant speed of 10 m/s from the start to the end of the road segment; the average vehicle-following distance is 10 m. For the scenario where vehicles are without VMBSs, we adopt IEEE 802.11p as the V2V communication standard, with the maximum data transmission rate of 27 Mb/s, 802.11n as the V2R communication standard, with a maximum data transmission rate of 600 Mb/s. For the cellular base station, we adopt the 4G standard, with a maximum uplink data transmission rate of 75 Mb/s and a maximum downlink data transmission rate of 300 Mb/s, respectively. For our proposed VMBS-CCNA, we assume that the maximum data transmission rate of VMBSs is 1.2 Gb/s, and the communication range of VMBSs is 100 m. We assume that for every 20 m × 20 m area, there is one roadside IoT device to collect and upload the information about IoT.

We first conduct simulations to compare the throughput of our proposed VMBS-CCNA with its counterpart without VMBS. Figure 3a illustrates the effect of the number of vehicles on throughput, and we can see from Fig. 3a that increasing the number of vehicles contributes little to the throughput for the scheme where vehicles are without VMBSs, while our proposed VMBS-CCNA benefits much from the increased number of vehicles. This is due to the fact that VMBSs can communicate with RSUs or other vehicles at a higher data rate than traditional V2V or V2I communications. The throughput of VMBS-CCNA tends to be stable when the number of vehicles is up to 20 on account of the limit of the number of vehicles with which one RSU can communicate simultaneously. Figure 3b illustrates the simulation result of delay for different data types. Obviously, the magnitude of delay of VMBS-CCNA for four data types is in milliseconds, while the delay of the scheme without VMBSs varies from tens of milliseconds to thousands of milliseconds. For one thing, this is due to the adoption of VMBS in our proposed VMBS-CCNA that increases the data transmission rate; for another, this is due to the deployment of edge computing that processes and shares traffic data and information in a more timely manner compared to the traditional remote cloud computing based architecture, which results in serious delay.

In addition, we define that one link is established between two connected nodes (V2V, V2R, vehicle-to-IoT-device, vehicle-to-base-station, etc.). The impact of the number of vehicles on the average number of wireless links is illustrated in Fig. 4. The comparison is between our proposed VMBS-CCNA and that without VMBSs. In Fig. 4, VMBS-CCNA always performs better than the scheme without VMBS, which demonstrates the value of VMBS for other wireless communications, such as collecting information from IoT devices.

Challenges and Open Research Issues

In our proposed VMBS-CCNA, the installation of VMBS on CAVs contributes to the densification of a wireless network, where VMBSs transmit data for CAVs and provide high-speed Internet access for passengers in CAVs. The VMBS brings a lot of benefits and contributes to the development of autonomous driving, which also introduces new open research issues and challenges at the same time. In the following, we elaborate.

Challenges

High-Data-Rate Wireless Transmission Techniques: Once a VMBS is mounted on a CAV, huge amounts of data are expected to be exchanged between CAVs and RSUs, which requires that the data rate should be at the gigabit-per-second level. Furthermore, information or messages of different types have different requirements for quality of service (QoS), for example, safety-related messages need QoS requirements of low latency and high reliability, and non-safety-related multimedia applications need high data rate. However, it is very challenging to satisfy all the QoS requirements just relying on the transmission techniques of either the present LTE network or the upcoming 5G network, which stimulates the evolution of new transmission techniques such as millimeter-wave (mmWave) and terahertz-wave (THz-wave) technologies in our proposed architecture for autonomous driving. MmWave is expected to provide higher data rate at the multi-gigabit-per-second level [2]. THz-wave, the electromagnetic spectrum of which is located between infrared lightwave and mmWave, is envisioned to achieve data rates of 10 Gb/s or higher [12].

Interference Management: The installation of VMBSs on CAVs will result in dense networks (DensNets), which increases the network capacity and also brings severe interference to the wireless communication network. The interference emerges as an old acquaintance with new significance. In order to obtain more access opportunities in DensNets, resource multiplexing is often adopted, which results in both an increase in and more complex interference. In what follows, we elaborate the detailed problems that will be faced:

- More interference sources will exist in the DensNets environment, where more scattering and reflecting paths exist for signals, which in turn result in more complex interference.
- The purpose of increasing radio resource utility is contradictory to reducing interference, which motivates us to find a better trade-off between them.
- The mobility of VMBS makes the interference mitigation techniques more challenging, which motivates the development of new interference mitigation techniques.
- Traditional parameters are no longer suitable for measuring and evaluating the interference. More appropriate parameters should be adopted to better reflect the relationship between system performance and the results of interference management.

Open Research Issues

Apart from the challenges mentioned above, there are also some open research issues based on our proposed VMBS-CCNA for CAVs, discussed as follows.

Environment Sensing Technology: Due to intricate vehicular scenarios and obstacles, sensing error or blind zones would happen for a single vehicle. How to increase the sensing robustness and sensing range of a single vehicle is crucial to CAVs. On one hand, improving the sensing capability of a single vehicle may be an alternative; on the other hand, leveraging multi-vehicle cooperative sensing technology can greatly improve the sensing capability.

Data Processing and Fusion: For each CAV, huge amounts of data are generated. Since some data may be redundant and may also be locally meaningful only, it is vital to analyze such data to produce useful information for autonomous driving and to save wireless radio resources. Various sensors may generate complex multi-source heterogeneous sensing data, so it is crucial to integrate multiple data sources to produce more consistent, accurate, and useful information than that provided by any individual data source.

Hybrid Computing Architecture: In our proposed VMBS-CCNA for CAVs, ECUs are co-located with the RSUs, and several ECUs form an edge cloud for data processing and switching. Many computation-intensive applications in autonomous driving, such as artificial intelligence, machine learning, and computer vision, are envisioned to work seamlessly with real-time responses, whereas the traditional methods of offloading computation to the remote cloud will lead to heavy usage of backhaul and severe delay (e.g., hundreds of milliseconds) that is unacceptable for autonomous driving [13]. Thus, it is of great significance to leverage edge cloud to process and store data in close proximity to CAVs, and combine edge cloud with remote cloud for constructing a hybrid computing architecture to enhance computing ability and hence improve the transportation efficiency.

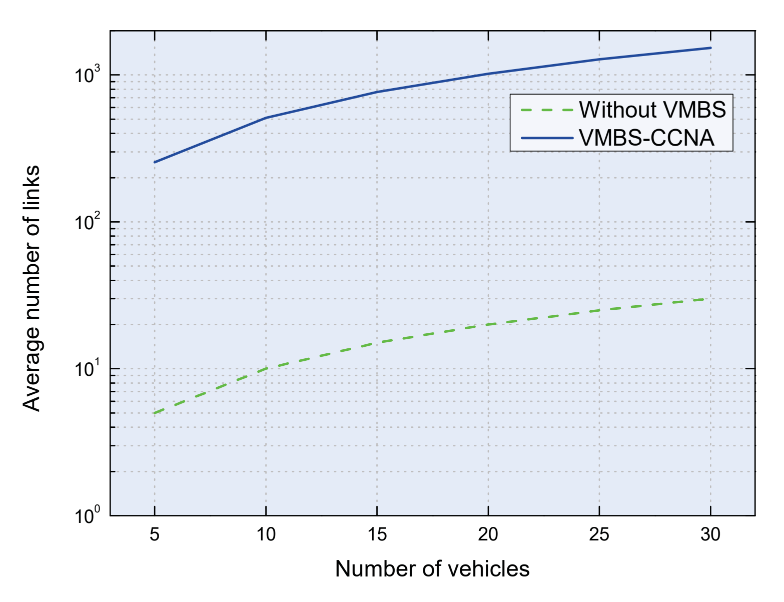

FIGURE 4. Average number of links for different number of vehicles.

Joint Allocation of Communication and Computing Resources: A VMBS acts under multiple rules, such as a communication node, a computing node, and a caching node; thus, if the resource allocation issues of communication and computing are considered separately, a waste of communication or computing resource of VMBS will occur. For example, warning information, which is the result of a sensing and a computing task, can be shared between CAVs through V2V communication once a CAV has finished the computing process, rather than repeating the computing process at adjacent CAVs. Moreover, various emerging CAV applications and services are restricted by the limited computation capacity; hence, if computation-intensive and rich-media tasks of vehicles could be offloaded to edge or cloud, it would be able to overcome the limitation of insufficient computation capability of CAVs and also result in relatively long transmission latency when tasks are offloaded to edge or cloud through wireless communications. Therefore, it is vital to determine whether a task should be executed locally through computing resource of VMBS or at the roadside or a cloud server through communication resource of VMBS. As a result, the joint allocation issue of communication and computing resources is becoming a hot research topic [14, 15].

Conclusion

In this article, we first present the requirements of CAVs for wireless communication and explain why current networks and upcoming 5G communication networks will be insufficient for future CAVs. We then propose the novel concept of VMBS and a communication and computing network architecture for CAVs, where three main

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communication methods and three VMBS-assisted wireless communication scenarios are discussed. In addition, the performance of the proposed VMBS-CCNA is evaluated. In the end, we discuss several open issues and challenges that are worth deep study and addressing. It is expected that the opportunities and challenges of designing and building VMBSs for CAVs will help researchers to better study autonomous driving in the future.

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