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Parallel Vehicular Networks: A CPSS-based Approach via Multi-modal Big Data in IoV

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***Abstract*—Vehicular networks have received great attention as one of the crucial supportive techniques for intelligent transportation systems (ITS). However, the introduction of dynamic and complex human behaviors into vehicular networks makes it a cyber-social-physical system (CPSS). Thus, ACP-based (Artificial systems, Computational experiments, Parallel execution) parallel vehicular networks (PVN) are proposed in this paper. The framework of PVN is then designed and presented, its characteristics and applications are demonstrated, and its related research challenges are discussed. PVN uses software-defined artificial vehicular networks for modeling and representation, computational experiments for analysis and evaluation, and parallel execution for control and management. Thus, more reliable and efficient traffic status and ultra-high data rate communications are obtained among vehicles and infrastructures, which is expected to achieve the descriptive intelligence, predictive intelligence, and prescription intelligence for vehicular networks. The proposed PVN offers a competitive solution for achieving a smooth, safe and efficient cooperation among connected vehicles in future intelligent transportation systems.**

***Index Terms*—CPSS, Parallel System, Internet of Vehicles, Social Networks**

I. Introduction

The development of wireless communications and network technologies in the last few decades has brought the research interests of essential network architectures [1]–[3]. Besides, an increasing amount of wireless intelligent mobile devices, e.g., vehicular intelligent devices, have led to tremendous increasing network workload. Therefore, it is important to make efficient use of limited computing and communication resources to increase the capability of supporting mobile applications. Nowadays, wireless networks gradually evolve into systems of wirelessly interconnected computational elements embedded in physical societies [4], [5], with applications in cellular mobile networks, vehicular networks, smart cities, smart grids, remote e-health systems and so on.

As one application of intelligent networks, the vision of intelligent transportation systems (ITS) and vehicular ad hoc networks (VANETs) is now very close to reality [6], [7]. Vehicles will be equipped with intelligent vehicular devices, which allow short-ranged wireless communication and hence facilitate vehicle-to-anything (V2X) communications. Road(side) infrastructure will further assist vehicular long-ranged communication for transmitting multi-modal traffic information to the core networks, and support intelligent network applications [8]. VANETs in ITS enables traffic information exchange, for example, information about traffic status, weather conditions, congestion and accident areas, road conditions, even live video streaming and file sharing, etc.

However, flooding the network by multi-modal data may exhaust network resources, causing severe contention and collisions, and VANET failure [9]. Recent rapid advances of social networking applications in vehicular networks have been a major drive force for the emergence of vehicular social networks [10]–[16]. Based on the social interactions among vehicles and human that communicate for services and exchange traffic information, social networks emerge as a new paradigm to design networking solutions by exploiting the social properties of vehicular networks, particularly onboard vehicular devices or mobile devices. For the social aspect in vehicular communications, many new parameters must be taken into account, including interaction frequency among users (e.g., vehicles, passengers, drivers, road and users), historical data of user behaviors, user habits, etc.

On one side, the explosion of big data and social media sites is increasingly impacting the users involved in traffic from drivers, passengers and pedestrians, with the pervasive use of vehicular devices and other smart mobile devices. On the other side, the data provides us massive social signals to manage and guide traffic in computational ways. Therefore, the vehicular network system is one typical complex system because of its multi-displinary, unpredictable, and dynamic features. The application of cyber-physical-social systems (CPSS)-based parallel approach [17]–[20] in complex vehicular network systems, named as Parallel Vehicular Networks (PVN), will be able to significantly improve physical vehicular network (VN) operating status and social network efficiency, and thus could satisfy the changing network demands for traffic systems.

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CPSS-based parallel system means a complex system that is composed of a actual physical system and its corresponding virtual or artificial systems. The artificial system is software-defined and might consist of one or more systems. The main theory for studying CPSS-based parallel system is the ACP approach [21]–[25], i.e., Artificial systems, Computational experiments, and Parallel execution. Based on the computational experiments and parallel execution between the actual system and the artificial system, the PVN system compares and analyzes the behaviors of physical and virtual systems, completes prediction and evaluation for traffic status, provides suggestions for efficient network management and control, and derives optimized solutions. Comparing to the traditional vehicular networks, CPSS-based PVN integrates an additional dimension-human and social characteristics to achiever more effective network design and operation. It is hard to precisely model a human-in-loop system because of the unpredictability of human. Therefore, based on the parallel execution of the proposed PVN, the artificial system could be continuously optimized and improved. Besides, by jointly analyzing the physical and artificial data, the results of computational experiments are more valuable for the optimization of vehicular networks. For the future research works, there are several challengeable directions, such as the modelling of artificial vehicular networks, data fusion of physical and artificial multi-modal data, and security and privacy of vehicular networks.

This paper is organized as follows. In Section II, the background and the related works of the proposed PVN are introduced. Section III introduces the PVN framework and the corresponding key components. The characteristics of PVN system are demonstrated in Section IV. Section V and VI give the main applications and several typical challenges, respectively. Finally, conclusions are provided in Section VII.

II. BACKGROUND

With governmental support and economic growth, ITS is becoming a reality, which enables remote management and data services for moving vehicles. In our vision, vehicular networks interconnect vehicles, things, people and society as shown in Fig. 1, with the following challenges.

- Increase storage capacity: Expand data storage to handle 10 petabyte (PB)-level data from millions of commercial vehicles while enhancing storage performance and flexibility to address future data demands.
- Improve multi-modal big data analysis: Collect, process, store, and analyze collected data in a real-time way, and support real-time access from a large number of users.
- Provide blueprints for Internet of Vehicles (IoV): Enable a safe, stable, and complete information service solution for IoV and dynamically expand platform performance to meet increasing and changing user demands.

As demonstrated in [26], multi-modal data means that information about the same phenomenon can be acquired from different types of perceptions, at different conditions, in multiple experiments or subjects. In vehicular networks, multi-modal data, including vehicle, vision, voice, and physiological information, are collected by relevant sensor systems installed

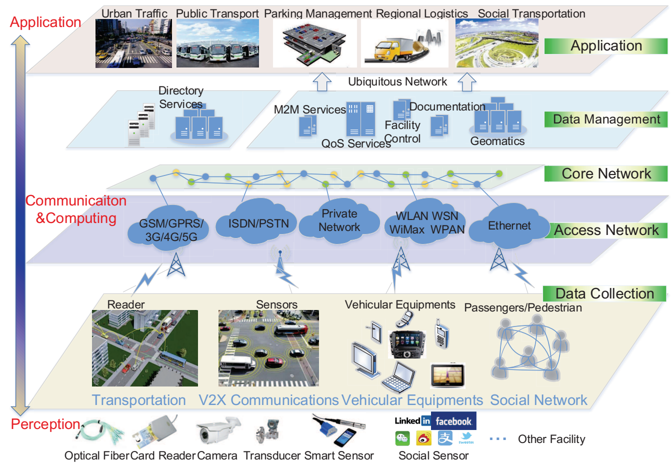

Fig. 1. Interconnecting vehicles, things, people and society

in the driving environment [27], [28]. These data could be used for object detection, recognition, and mapping based on the fusion of stereo camera frames, point cloud Velodyne LIDAR scans, and vehicle-to-vehicle (V2V) basic safety messages (BSMs) exchanges using vehicular networks. Therefore, a safer and more stable service could be provided to intelligent transportation systems and autonomous vehicles.

A. Traditional Internet of Vehicles

With the rapid development of communication and computation technologies, IoV has attracted a large number of companies and researchers because of its huge commercial interest and research value. IoV is the convergence of Internet of Things (IoT) and the mobile Internet. It is comprised of human-driven or automated intelligent vehicles, and is integrated with intelligent perception and V2X communication equipment (Fig. 2). Therefore, IoV is a cross-disciplinary technology that encompasses communications, networks, controls, cyber-security and social sciences.

Current IoV research focuses on traffic safety and efficiency, low latency information transmission, high reliability, zero handover execution time, etc. IoV technology generally refers to dynamic mobile communication systems that communicate between vehicles and public networks using V2X interactions, including V2V (vehicle-to-vehicle), V2R (vehicle-to-road), V2I (vehicle-to-infrastructure), V2H (vehicle-to-human) and V2S (vehicle-to-sensor) communications. These interactions complete information sharing and aggregation from vehicles, road(side) infrastructure and surrounding intelligent equipment. Furthermore, the characteristics of IoV is integrating process, computation, share, and secure for the release of related information through information platforms. Based on the analysis of vehicular data, the IoV system is able to effectively supervise and guide vehicles, and provide abundant multi-modal and mobile Internet application services.

B. Social Transportation Network

Currently, the rapid development of online social networks has stressed moving vehicles' social relationships, which conversely has led to more data traffic because of the effect

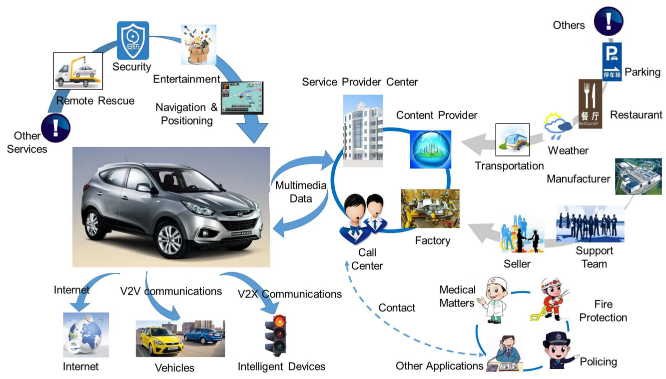

Fig. 2. Internet of vehicles.

of vehicular networks. Vehicular communications could be thought as the social network for vehicles because the drivers, passengers and pedestrians can share data with others. For example, there are commonly traffic jam or accidents in some specific areas, such as intersections, high-speed road in/out intersections, taxi loading/unloading areas, etc. Besides, traffic condition is generally changing according to weather conditions. Thus, social features and human behavior have significant impacts on transportation networks.

The social IoV concept is an example of the social IoT, which is a network of intelligence objects with social interactions. It is commonly described as social interactions among vehicles that communicate autonomously for services and information exchange. The main part is the vehicle equipped with advanced technological devices, while the vehicles may also use the online social network service to share information with others. The vehicular network collects real-time data, and provides the ability to share information among vehicles/pedestrians in different locations. This would combine the multi-modal data from vehicular networks and social networks.

C. Network State of the Art

Cloud Radio Access Network (C-RAN), proposed by the China Mobile Research Institute, stands for centralized, collaborative, Cloud RAN [29], is a new type of RAN architecture to help operators address the existing challenges in current IoT. C-RAN system centralizes different baseband processing resources to form a single resource pool to manage them dynamically on demand. It has several advantages over the traditional base station architecture, such as increased resource utilization efficiency, lower energy consumption, and decreased interference.

Most academic and industrial organizations have utilized cloud computing and have exploited its benefits. However, cloud architectures usually are not able to handle the demand of data communications with computing ultra-low latency requirements in IoT or IoV. For this reason, fog computing was proposed to meet the changing requirements. Fog computing brings computing closer to the end user, instead of forcing all processing to backend clouds and forcing all data communication through backbone network. Fog computing supports emerging IoT applications that demand real-time and predictable latency.

A new class of computing approach, mist computing, is also under investigation. Mist computing consists of very edge including sensors and actuator controllers. It brings elastic computing, storage, and communication directly onto the things, which allows arbitrary computations to be provisioned, deployed, managed, and monitored.

IoT is a heterogeneous system in terms of platforms, resources, and connectivity. Thus, the main challenge for the current network is to establish infrastructures that virtualizes computing, storage, and communication with maximal efficiency. Consequently, parallel approach [30] would be one of the essential and important way to achieve this goal.

D. Related Works

With the rapid development of automotive telematics, it is expected for vehicles to be connected through vehicular networks and to exchange massive information with their surrounding environment [9], [31]. Recent technology advances have dramatically enhanced the functionality of social and mobile networks in various aspects such as sensing, computing, communication, and control. To fully exploit the potential benefits of vehicular social networks [14], a great deal of research have been conducted to make them towards more efficient, reliable, and robust systems of coordinated components working.

Vehicular social networks were proposed in [32], which connect physically nearby vehicles and make all the vehicles to make full use of their proximity to build a virtual social networks. A novel architecture, called VeShare, was propsoed in [33] to support highly dynamic and time-sensitive social behaviors in vehicle networks by separating the control and data planes of a vehicular network. A novel perspective on vehicular communications and social vehicle swarms was studied and analyzed based on a socially aware Internet of Vehicles with the assistance of an agent-based model intended to reveal hidden patterns behind superficial data.

How to combine both the physical and social information for realizing rapid content dissemination in vehicular networks has been attracted much more attentions [26], [34]–[36]. For example, the factor of social relationship in the deployment of content caching was considered in [37], where a stochastic geometry theory was applied to derive an analytical expression of downloading performance for caching networks. A social vehicle route selection method was introduced in [38] to reduce traffic congestion and achieve the purpose of traffic flow control. DynaMIT, represented in [39], generated consistent anticipatory information about the future state of the transportation network based on current real-time data. In [40], a privacy-preserving scheme, MixGroup, was proposed to be capable of efficiently exploiting the sparse meeting opportunities for pseudonym changing. A weighted and undirected graph model for vehicular sensing networks was established [41] and its time-invariant complex characteristics was verified relying on a real-world taxi GPS dataset. A driver state estimation algorithm in [27] was to use multimodal vehicular

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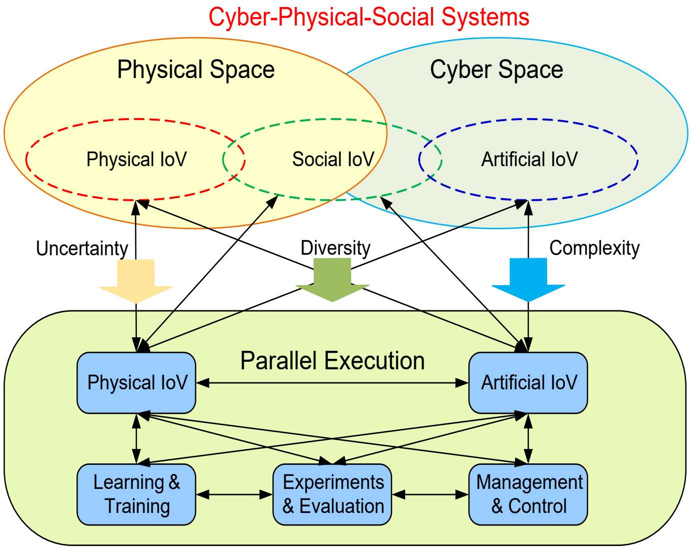

Fig. 3. The framework of parallel vehicular networks.

and physiological sensor data for more promising driver state estimation.

For the applications, a novel social network architecture for rail traffic transportation system was proposed [42], including the social network service management center, a dedicated social network for internal information exchanges among the drivers, the dispatchers, and the train control center, the social network service for the information exchanges among the train marshals, crews, and passengers. This framework attempted to exploit social networks in an active manner in the field of rail traffic transportation systems to make the system safer, more secure, reliable, comfortable, and humane. For parked vehicles around the street, they can form vehicular social communities with the moving vehicles passing along the road, where the storage capacity can be increased by using the contents in parked vehicles. The detailed process of content delivery in VSNs including interest sending, content distribution, and content replacement was demonstrated in [43].

III. System Architecture

As illustrated in [20], CPSS enables the pervasive intelligent space to interact smartly with people and things anywhere and anytime. This is built upon the foundation of pervasive computing, communication, and control. Therefore, based on CPSS system and the ACP approach, the framework of CPSS-based PVN is proposed as shown in Fig. 3. PVN becomes an intelligent system when they are capable to observe and prescribe what is happening within the system, construct system models, communicate with internally and externally, act based on the system decisions, and predict and guide the future system status by data analysis. There are three main components in the proposed PVN, which are artificial software-defined VN, computational experiments, and parallel execution.

A. The ACP Approach

Two essential characteristics are essential to complex systems. The first is inseparability, i.e., with limited resources, it is impossible to determine or explain the global behaviors of the complex system via independent analysis of its components; instead, a complex system is viewed as a complete determination about how its components behave. The second characteristic is unpredictability, meaning that the global behaviors of a complex system cannot be explained or determined in advance at a large scope with limited resources.

Many systems involving human and social behaviors display those two characteristics, which leads to three deductions.

- We must take a holistic approach in modeling complex systems. Artificial systems would be one of the most effective tools in representing such complex systems in a holistic fashion.
- There are no fixed once-and-for-all solutions for the problems in complex systems. Any effective and satisfiable solution should be adaptive and able to learn from its changing environment and previous experience. Computational experiments are essential in developing and supporting such solutions.
- Generally, there are no optimal solutions for complex systems. Parallel execution provides an effective mechanism to implement various solutions, as well as evaluate, validate, and improve system performance.

The ACP aproach consists of Artificial societies, Computational experiments and Parallel execution [21]–[23].

Artificial Systems: Many benefits could be derived from the characteristics of artificial systems on modeling complex systems. For instance, artificial systems address the interactivity, interrelationship and integration among several complex systems; Artificial systems in real, simulated or mixed environments are capable of generating complex interactions and behavior patterns. With these two characteristics, especially the latter one, the features of real complex systems could be utilized by artificial systems to support various flexible, controllable and accurate computational experiments. Furthermore, different behaviors and impact elements could be quantitatively analyzed, evaluated and predicted.

Computational Experiments: The main purpose of computational experiments is to generate artificial objects and to proactively create their diverse behaviors based on the interactions of artificial objects in a bottom-up way. Simultaneously, various factors influence on these diverse behaviors are jointly considered to analyze the behavior of the overall system. Moreover, various algorithms of conventional experimental analysis can be directly utilized for computational experiments in the proposed PVN system.

Parallel Execution: Parallel execution means the real-time interaction between actual system and artificial system. The goal is to make full use of the potential of artificial systems from offline to online, from static to dynamic, and from passive to proactive. Then, the artificial systems would be able to play equivalent roles as actual systems. Various parallel systems are designed according to practical requirements and the developing progress of artificial systems. Conventionally, it

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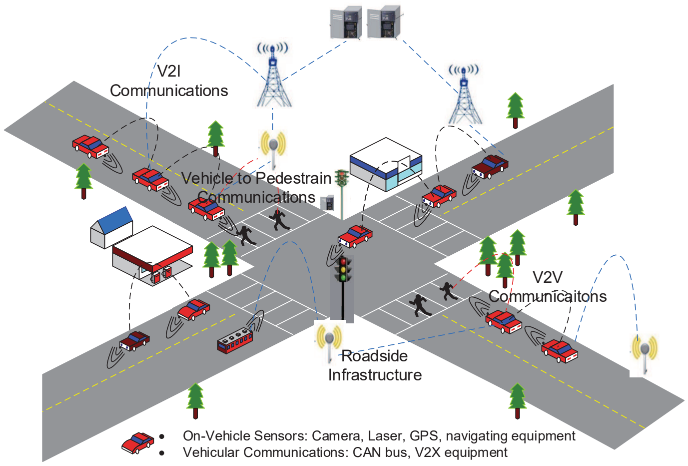

Fig. 4. The artificial software-defined VN system.

is infeasible to derive an optimal solution for complex systems; however, parallel execution provides an effective approach to implementing various solutions for evaluating, validating, and improving the performance of complex systems.

B. Artificial Software-Defined Vehicular Network

As shown in Fig. 4, corresponding to the physical VN, there could be one or several artificial VN systems to model the physical system. Thus, a variety of computational experiments could be implemented in the artificial software-defined VN for network deployment, resource allocation, guidance or prediction for the actual VN system. An artificial software-defined VN embraces vehicle models, road(side) infrastructure models, information transmission network models, pedestrian models, social network models, etc. These artificial systems could operate by themselves in the Cyberspace, and their operating status and results could be the reference for real network system deployment.

Next, an example for modeling a specific vehicular network is given here. Assuming there are N vehicles denoted by $n_1, n_1, \ldots, n_N$ moving within a region. Two vehicles can share the information only when they meet and have social relation. This artificial network could be modeled by an unweighted and undirected graph $G(V, E)$, where V denotes the set of nodes (vehicles), and E represents the set of edges (social ties). $P(k)$ is defined to be the probability of a node having k friends, where k denotes the degree of the node. Assuming $P(k)$ is the power-low distribution [44], it can be derived by

$$P(k) = \begin{cases} 0, & k < m \\ C(m,\gamma)k^{-\gamma}, & m \le k < N \end{cases}, \qquad (1)$$

where m is the smallest degree of the network, γ is the skewness of the degree distribution, and $C(m,\gamma)$ is the normalization constant. Different m and γ describe different VN scenes. For example, social ties are stronger in crowded areas, thus the social graph has a larger m and a smaller γ.

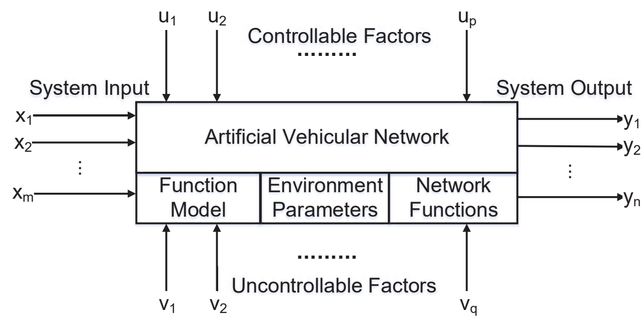

Fig. 5. The process of Computational Experiments.

C. Computational Experiments

The second component of the proposed PVN is computational experiments. As known, the sensors of the physical VN includes electronic police, monitoring devices, social network sensors etc., whose tasks are data collection, data uploading, vehicles networking, social networking, and so on. All these modules constitute a multi-modal data vehicular network system. By the analysis on these multi-modal big data, the cyber source could be effectively allocated. For instance, individual recommendation, traffic status prediction, recommended trajectory, and so on. Here, for the individual recommendation, collaborative filtering recommendation algorithm and the key rules recommendation algorithms could be used for specific scenarios. While for the traffic status prediction, there are many kinds of algorithms, for example, neural network, Calman filtering, nonparametric regression model, and so on. It is worthy to mention that the multi-modal big data for computational experiments are derived not only from physical VN system but also from artificial VN system.

Generally, the main purpose of computational experiments is to analyze performance of both systems and processes. These systems and processes are composed of agents, objects, approaches and other resources. Once an input is given, the corresponding output could be derived. During computational experiments, there are some controllable factors and uncontrollable factors. It is necessary to confirm which factors are more important for system performance. Further, another key problem is how to make the system response close to the ideal status. Fig. 5 shows the general process of computational experiments, where $x_i, i = 1, 2, \ldots, m$ denotes the system input, $y_j, j = 1, 2, \ldots, n$ denotes the system output, $u_k, k = 1, 2, \ldots, p$ means the controllable factors, and $v_l, l = 1, 2, \ldots, q$ represents the uncontrollable factors.

1) Quality of Experience: In computational experiments, quality of experience (QoE) would be the measure of vehicles' satisfactory when multi-modal services are provided. Assuming the cloud processing rate of r, a QoE model can be defined as $Q(r) = h(r)$, where $h(r)$ could be defined according to different scenarios. For example, in the logarithmic form of multimedia tasks, $Q(r)$ is defined as

$$Q(r) = h(r) = \begin{cases} q_{max}, & r < r_{max} \\ \alpha \log_2(\beta r), & r_{min} \le r \le r_{max} \\ q_{min}, & r \le r_{min} \end{cases}, \qquad (2)$$

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where α and β are positive constant parameters, and can be set up for various applications. q_{max} denotes the maximum QoE when the highest processing rate r_{max} is achieved; while q_{min} denotes the minimum QoE when the lowest processing rate r_{min} is achieved. Because QoE function is continuous, therefore, r_{min} can be derived by

$$r_{min} = \frac{2^{\frac{q_{min}}{\alpha}}}{\beta}, \tag{3}$$

and r_{max} is obtained by

$$r_{max} = \frac{2^{\frac{q_{max}}{\alpha}}}{\beta}. \tag{4}$$

2) Utility Functions: To quantify the utility of each vehicle, both the price of resource and the processing rate based on the obtained resources are jointly considered. Assuming the allocated resource follows logarithmic function [15], the payoff for a vehicle can be defined as

$$s(r) = \epsilon \log(1 + f(r)), \tag{5}$$

where ϵ is the payoff parameter, and $f(r)$ is the function of the obtained cloud resource from the connected broker. The utility function of a vehicle in region j is defined as

$$U_{i,j}(r_i) = s_{i,j}(r_i) - C_{i,j}(r_i), \tag{6}$$

which aims to achieve maximized payoff with the least cost. Here, $s_{i,j}(r_i)$ represents the payoff of a vehicle in region j which connects broker i. $C_{i,j}(r_i)$ denotes the cost for buying the cloud resource from broker i. The payoff $s_{i,j}(r_i)$ can be derived by

$$s_{i,j}(r_i) = \epsilon_{i,j} \log\left(1 + Q_{i,j}\left(\frac{r_i}{n_i}\right)\right), \tag{7}$$

where $Q_{i,j}\left(\frac{r_i}{n_i}\right)$ is the QoE of a vehicle in region j which connects broker i, and n_i is the number of vehicles which connects broker i. Assuming that the vehicles share the identical amount of resource when connecting broker i, the QoE can be defined as

$$Q_{i,j} = \alpha_{i,j} \log_2\left(\beta_{i,j}\frac{r_i}{n_i}\right), \tag{8}$$

where $\alpha_{i,j}$ and $\beta_{i,j}$ are two constants which can be set up according to different applications.

The cost $C_{i,j}(r_i)$ can be defined to be the price of resource p_i, which is given as

$$C_{i,j}(r_i) = p_i. \tag{9}$$

Therefore, the utility function of a vehicle in region j which connects to broker i is derived by

$$U_{i,j}(r_i) = \epsilon_{i,j} \log\left(1 + \alpha_{i,j}\log_2\left(\beta_{i,j}\frac{r_i}{n_i}\right)\right) - p_i. \tag{10}$$

As known, the goal of each vehicle is to achieve an optimal QoE with the lowest cost. Therefore, the problem becomes

$$\max_{r_i} U_{i,j}(r_i), \tag{11}$$

with $r_i \geq 0$ and $\log_2\left(\beta_{i,j}\frac{r_i}{n_i}\right) > 0$.

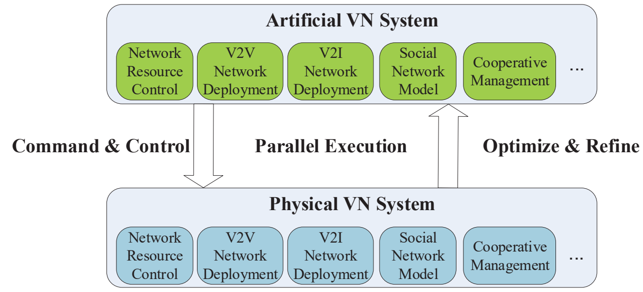

Fig. 6. The framework of parallel execution.

D. Parallel Execution

Fig. 6 demonstrates the concept of parallel execution between actual and artificial VN system. On one hand, various experimental or computational results of artificial VN system would provide guidance and prediction for actual VN systems to achieve global optimization. On the other hand, the multi-modal big data from actual VN system would also feedback to artificial VN system for its amendment and adjustment. To further improve the operating status of actual system and artificial system, different parallel execution approaches can be developed for different requirements, such as network resource control, V2V/V2I network deployment, social network model, cooperative management, etc.

- Overall parallel execution: The artificial VN system and actual VN system are indivisible, and we can use the artificial VN system to predict and control the actual VN system. The constructed artificial VN system model should contain all the parts of the actual VN system, while the integrity of artificial VN system is consistent with actual VN system.
- Partial parallel execution: The artificial VN system and actual VN system are partly connected as needed. The distinguishing components of the artificial VN system are dynamically simultaneous with the partial components of actual VN system.
- Mixed parallel execution: The artificial VN system and actual VN system are overall or partly connected in some parts, respectively. Some modules in artificial system could be amended, and the global property could also simultaneously be adjusted via the interactions between actual and artificial VN systems.

One complex system may be made up of several complex subsystems. Therefore, most of the parallel systems for complex systems are constructed in mixed parallel execution mode.

E. Operation Processes

There are normally more than one artificial VN systems used in PVN management and control. Different artificial VN systems can be created, respectively, for the purposes of historical network situations, normal and average performance, optimal and ideal operations, or worst-case scenarios for emergency management. Through interaction and parallel operations between an actual VN system and its corresponding multiple artificial VN systems, the effectiveness of different

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network strategies under various conditions can be evaluated and analyzed, and useful information can be obtained timely and combined to generate decisions for management and control of the actual VN system.

1) Training and Learning: Operator training systems for VN systems could be developed for learning and training mode operations for network operators and administrators. The use of operator training system was partially inspired by applications and success of operator training simulation in many other advanced and complex industrial operations. Task requirements and procedures for both regular network operations and emergency situations are incorporated into operator training system to make its functionality more useful and closer to reality. Sessions here can be generated manually by artificial operators or automatically by agent programs. Artificial sessions are also used to collect behavioral data from trainees and learners. Using agent-based behavioral modeling, automatic sessions can be employed when conducting accelerated testing and evaluation on the reliability and effectiveness of network operational procedures and regulations.

2) Testing and Evaluation: Dynamic network allocation based on complex adaptive systems could be constructed to design, conduct, evaluate, and verify computational experiments for network systems. Besides, it detects existing and emerging network patterns, and supports the use of advanced network information systems, advanced network management systems, and other network system modules. Dynamic network allocation system facilitates the estimation and predication of network conditions, performance evaluation of different network control and management measures and information dissemination strategies, and decision support to dissemination operators and individual client. Using artificial VN system, it possible to study rule-based computational modeling of the social and behavioral aspects of network activities.

3) Control and Management: Agent-based distributed and adaptive platforms for VN systems could be built to provide supporting and operating environments to design, construct, manage, and maintain autonomous agent for various network tasks and functions. Those agents are deployed to network control centers, base station controllers, sensing devices, and information systems via communication networks to make decisions and collect information. Generally, an agent can autonomously identify its tasks, and actively improve its performance. Network task agents can be deployed at different operating centers and information sites. To ensure a coherent control and communication mechanism among those agents, their objectives and activities must be integrated and coordinated. A hierarchical intelligent control architecture consisting of organization, coordination, and execution levels has been used to facilitate the activities and operations of network agents. The more detailed discussion of agent-based control and management is referred to [30].

IV. Characteristics

In the proposed PVN, all the users, including vehicles, human, communication devices, road(side) infrastructure, control center, etc., coexist and cooperate for improving traffic and network status as shown in Fig. 7. The proposed PVN guides network deployment, obtains social relationship, and provides specific data services for users in VNs by jointly analyzing social activities. Therefore, there are four major characteristics as follows.

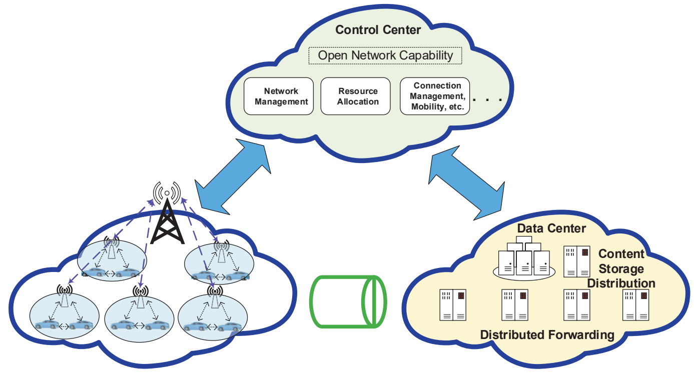

Fig. 7. Cooperative VN system.

A. Mobility

The first characteristic of the proposed PVN is mobility. There are many impact factors on the mobility of PVN, such as drivers' preference, specific location and time, neighbor's status, etc. Some locations might be the communication hotspots, e.g., shopping malls, theaters, restaurants, schools, etc. Similarly, the mobility in PVN is time-varying, and traffic congestions tend to happen at some particular period, such as rush hours, school time, etc. Based on the proposed PVN, traffic status and network requirements could be analyzed and predicted based on the multi-modal big data from both the actual VN and the corresponding artificial VN.

Vehicle mobility patterns are determined by driver behaviors, which are very sophisticated and can not be captured well by simple mobility models. The existing empirical studies reported that the inter-contact time of human beings generally follows some power low distribution. However, the computation of delivery delay is extremely difficult by following power low distribution. Thus, a random variable following exponential distribution with rate γ is commonly assumed.

B. Sociality

The second feature of the proposed PVN is the social relationships in actual VN. The construction of actual VN is dynamic because of its mobility. When the vehicles/pedestrians depart from the current VN, the social relationship is no longer active. Therefore, individuals in actual VN are more likely to have common interests rather than family members or friends. Similar to the actual VN, the artificial VNs in cyberspace also hold social relationship and mobility. Social features and human behavior play an important role on PVN. Each user in this network could share data with other neighbors based on their communications needs. For example, the information about traffic congestion or accidents could be transmitted to online network, and then be broadcasted to the potential users for their interests.

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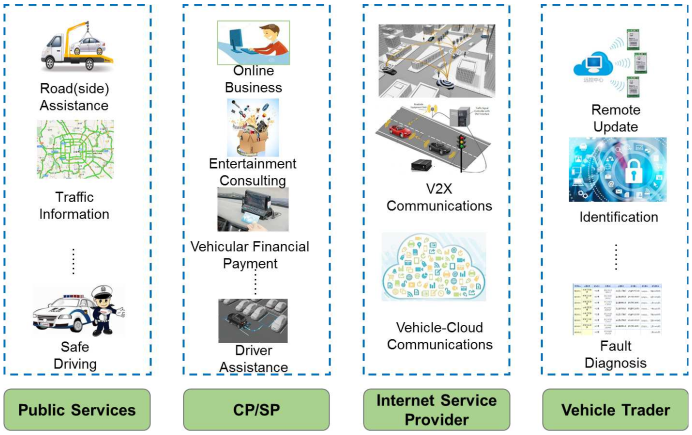

Fig. 8. The information services of PVN

C. Information Service

Another important feature in the proposed PVN is information transmission services. As shown in Fig. 8, the PVN provides services for public services, content provider/service provider, Internet service provider, and vehicle trader. In particular, road(side) assistance, traffic information transmission, and safe driving will be significantly improved based on the proposed PVN system. Network deployment for V2X communications is optimized for improved reliability, ultra-low latency, and efficiency. Furthermore, remote updating, safe identification, and fault diagnosis are also to be derived by the proposed PVN system.

D. Prediction&Prescription

The most important features of the proposed PVN are prediction and prescription. Accurate and prompt vehicular network status and traffic flow information is imperative for individual drivers, passengers, pedestrians, business sector and government departments. Therefore, prediction and prescription for the transportation status have the potential to generate optimized travel decision and improved network deployment strategy. Thus, it is possible to alleviate traffic congestion/accidents, improve traffic efficiency, and reduce carbon emissions. However, prediction and prescription of traffic and network heavily depend on the real-time and historical traffic multi-modal data collected from actual and artificial VNs. The data resources include radars, cameras, vehicular devices, infrastructure equipment, mobile devices, social media, etc. In the proposed PVN, a variety of data processing algorithms are used for the multi-modal big data analysis, such as deep learning, machine learning, statistical analysis, and so on.

E. Vehicular Communication Supporting Techniques

In order to obtain the aforementioned advantages of the PVN, supporting vehicular communications techniques must be ultra-reliable, ultra-low latency, high data rate, and large-scale for the multi-modal traffic data transmission. Thus, many academia and researchers focus on the R&D of the vehicular communications. Currently, there are three main standards for V2X communications, that is, dedicated short range communications (DSRC), LTE-V, and cellular V2X (C-V2X).

DSRC, specifically designed for automotive use and supported by National Highway Traffic Safety Administration (NHSTA), is one-way or two-way wireless communication for short-range to medium-range. NHSTA predicts that the security application of V2X communications can eliminate or reduce up to 80% non-damaged fault, including collision in intersections or when changing lanes. DSRC is proposed based on 802.11p standard, which defines the enhancements compared to the standard of IEEE 802.11 (Wi-Fi based) to support wireless access for vehicles.

LTE-V, promoted by the Enterprises in China (including Datang, HUAWEI, etc.), is an intelligent transportation and vehicular networking application, which is an evolution of 4G technology based on LTE system. LTE-V includes two main working modes, LTE-V-Cell and LTE-V-Direct. Generally, LTE-V-Cell uses existing cellular networks to support large bandwidth, large coverage of communication and to meet the requirements of Telematics; While LTE-V-Direct is independent of cellular network to implement direct and reliable communications between vehicles and the surroundings while meeting the safety requirements.

C-V2X technology leverages the commercial cellular network, that is a technology involving the use of developing cellular standards for a wide range of vehicle connectivity use cases and applications. It could complement other vehicle sensor technologies and extend a vehicle ability to “see” higher level of predictability for enhanced traffic safety.

The above three standards have their own advantages and disadvantages. Moreover, it is expected that VN will be significantly enhanced when 5G and its corresponding highly reliable, low-latency mission critical services are available for V2X applications. The proposed PVN make full use of the existing and future communication technologies to achieve improved network experience and traffic status.

V. Applications

The emergence of vehicular applications has been triggered by recent improvements in communication technologies and increasing traffic density. The applications and wireless technologies have resulted in better decision making and traffic management. The main applications of the proposed PVN mainly focus on the benefits for terminals, Internet, platform, and services as shown in Fig. 9. This could be considered as two main categories, safety-based and entertainment-based applications. The first one is focused on enhancing the traffic safety to reduce the probabilities of traffic accidents and congestion. These data include the information of vehicles' position, speed, direction, etc. The second category focuses on multi-modal services for human according to different interests. The final goal is vehicle behavior analysis, network resource allocation, and traffic efficiency improvements.

A. Network Improvement

The explosive growth of network traffic, users, and various intelligent terminal equipments brings many kinds of communication services for IoV. Various services have different

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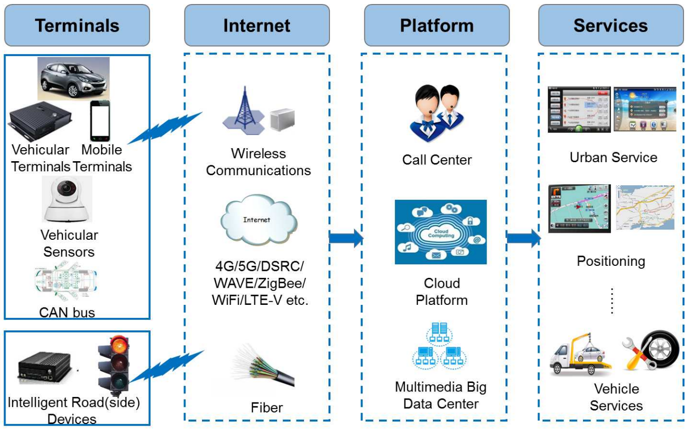

Fig. 9. The applications of PVN

requirements for data size, delay, reliability, safety, and others. These rich application demands also greatly increase the complexity of network system design and management. How to effectively guarantee the quality of user experience and satisfaction is a currently significant task, which needs further investigation and comprehensive discussion. The proposed PVN is expected to deal with the following issues.

- Achieve maximum efficiency of network business capacity: The essence of network business rate and final user experience is to maximize the efficiency of service capacity. Different wireless networks, business, management strategies, and user distributions will greatly affect the efficiency of the service capacity.
- Realize the transplantation, interconnection and intercommunication between multiple communication networks in the future, and to utilize their complementary advantages: The merge of various communication networks (such as cellular networks, mobile satellite networks, Wi-Fi, Bluetooth, etc.) will be able to support larger amount of data communication, seamless network coverage, network load balance, higher reliability, better user experience, and lower equipment cost.
- Effectively utilize the coordination of cloud control center and network edge processing for different network user service requirements: Due to different network needs, such as network coverage, data rate, reliability, spectrum resources, transmission delay and so on, optimizing network operation state is becoming the goal of next generation network system, which would be implemented via mutual adjustment, parameter optimization, traffic load control and the whole network management.

B. Traffic Safety&Efficiency

In vehicular networks, social aspects and features of the passengers, drivers and pedestrians have emerged the development of the PVN in this paper. As known, mobile interaction is provided between the users on the road (drivers, passengers, pedestrians), so that the traffic safety could be improved based on efficient communications. Moreover, when two vehicles have a common interest, they can not only communicate with each other, but also make contact based on social metrics. More specifically, in the topology, users can be characterized and classified based on their social behaviors, relationship, daily activities, routes, etc. Depending on social groups, vehicles can collect and elaborate useful data based on its different needs.

Multi-modal big data in PVN, enabled by the rapid popularization of ITS, are often collected continuously from actual and artificial VN systems. These data are with huge size and rich information, and the seemingly disorganized data could considerably be analyzed to achieve optimized solutions for the improvements of traffic safety and efficiency. In addition, proactive traffic and network management is possible to be obtained due to the real-time multi-modal big data processing and parallel execution of the PVN.

For the aforementioned problems, crowdsourcing could address many challenges and solve many complex tasks via harnessing the power of individuals. This phenomenon is also especially impressive in PVN. The individual multi-modal data from actual and artificial VNs and the capabilities of mobile devices and software-defined equipment are combined to obtain more effective solutions for physical VN system. The information is contributed by naturalized data and virtual data from drivers, passengers and pedestrians through mobile devices, and then used to derive a optimized solution for a complex task in vehicular crowdsourcing applications.

VI. Challenges

Next generation ITS development requires the overcoming of challenges such as comprehensive traffic status information access, timely detection of road conditions and vehicle operating status, and intelligent release of information based on relevant factors such as vehicle/road conditions; thereby, it can provide vehicles and travelers with more effective traffic information. This helps transportation to be more eco-friendly and efficient. Based on the proposed PVN, it is possible to achieve the goal of future ITS system. However, there are several main challenges needed to be addressed in the future. Several challenges are highlighted below.

A. Modeling of Artificial VN

In the proposed PVN, one of the most important technique is the modelling of artificial VN system, i.e., software-defined VN, which includes software-defined physical sensors, software-defined social sensors, network model, transportation model, artificial human, and so on. One common modelling method is called agent-based method. Artificial VN explores the emerged characteristics caused by the interaction between agent and agent, agent and environment, environment and environment, and demonstrates different states and development characteristics of artificial VN system. The artificial system is generally designed or modelled to be much more similar to the actual system, thus it could operate by itself and provide guidance and prediction for the physical VN. Furthermore, the software-defined system would be updated and optimized periodically during the parallel execution of the actual system and the artificial system.

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B. Multi-modal Big Data Treatment

Nowadays, a large volume of data is being generated, transmitted, processed and analyzed every day. Many multi-modal information is on the fly in the mobile vehicular networks. The network services wish to push the data to their users, while people wish to produce and share the information/infotainment with their family or friends. From the social perspective, people always are grouped into communities, and their behaviors are regular. These social properties are beneficial for improving the efficiency of data treatment. Consequently, there is an increasingly crucial demand for the algorithms on multi-modal big data treatment in the proposed PVN framework.

C. Security&Privacy

When designing and deploying a communications network, especially for a large-scale trustworthy actual VN, security and privacy would be the most important factors to be considered. The requirements for security and privacy could vary according to different network applications. For instance, for traffic safety applications (e.g., hazard warning, collision reminding, etc.), information integrity and reliability are of paramount importance (unlike confidentiality). While for traffic efficiency applications, both the integrity and the verifiability is crucial to help users to prevent being misled. On the other hand, the availability of the service is important for infotainment applications. The system deployment would be decided by the different requirements for VNs.

VII. Conclusions

In this paper, the architecture of CPSS-based parallel vehicular networks was proposed, which could provide guidance and suggestion for optimized network deployment and efficient resource allocation, and obtain accurate prediction and prescription for the forthcoming traffic status. These helpful solutions are derived by the analysis of multi-modal big data from both actual and software-defined artificial VN systems. Along with the system framework, the main characteristics of PVN were demonstrated and discussed, followed by the main applications. Finally, a few research challenges were highlighted. We believe that the proposed PVN would attract great attention in the near future, which are likely pave the way for fast and sustainable improvements of intelligent transportation system, vehicular communication networks and social networks.

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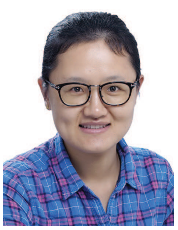

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