Vehicular Fog Computing: A Viewpoint of Vehicles as the Infrastructures

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***Abstract*—With the emergence of ever-growing advanced vehicular applications, the challenges to meet the demands from both communication and computation are increasingly prominent. Without powerful communication and computational support, various vehicular applications and services will still stay in the concept phase and cannot be put into practice in the daily life. Thus, solving this problem is of great importance. The existing solutions, such as cellular networks, roadside units (RSUs), and mobile cloud computing, are far from perfect because they highly depend on and bear the cost of additional infrastructure deployment. Given tremendous number of vehicles in urban areas, putting these underutilized vehicular resources into use offers great opportunity and value. Therefore, we conceive the idea of utilizing vehicles as the infrastructures for communication and computation, named vehicular fog computing (VFC), which is an architecture that utilizes a collaborative multitude of end-user clients or near-user edge devices to carry out communication and computation, based on better utilization of individual communication and computational resources of each vehicle. By aggregating abundant resources of individual vehicles, the quality of services and applications can be enhanced greatly. In particular, by discussing four types of scenarios of moving and parked vehicles as the communication and computational infrastructures, we carry on a quantitative analysis of the capacities of VFC. We unveil an interesting relationship among the communication capability, connectivity, and mobility of vehicles, and we also find out the characteristics about the pattern of parking behavior, which benefits from the understanding of utilizing the vehicular resources. Finally, we discuss the challenges and open problems in implementing the proposed VFC system as the infrastructures. Our study provides insights for this novel promising paradigm, as well as research topics about vehicular information infrastructures.**

***Index Terms*—Cloud computing, infrastructures, vehicular fog computing (VFC), vehicular network.**

I. INTRODUCTION

URBAN vehicular networks are recognized as a significant component of the future intelligent transportation systems [1], and they support various mobile services ranging from the content-sharing applications (e.g., advertisements and entertainments) to the information-spreading services (e.g., emergency operations for natural disaster and terrorist attack) [2]. These urban vehicular networks ensure driving safety, traffic efficiency, and great convenience by exchanging valuable information. During the last decade, with the emergence of more advanced equipments and technologies, such as cellular networks and cloud computing, vehicular networks and associated applications have been developed dramatically. As a consequence of this trend, a significant issue also appears, namely, the sharp increases in the demand of both data communication and computational capability. New applications, such as augmented reality (AR) techniques [3], self-driving, etc., all deal with complex data processing and storing operations, which require higher level of data communication, computation, and storage. This poses great challenges to the existing conventional vehicular networks, particularly in terms of communication and computational capacities. To meet this ever-increasing demand in communication and computational capacity, using vehicular clouds as data centers and augmented processing resources is an appealing idea. For instance, the parked vehicular clouds at a company parking lot can be utilized to handle the computational tasks or they can be employed to collaborate with each other to transmitting messages and sharing communication resources.

To solve the communication and computational capacity problem, some existing methods were proposed, including third- (3G) and fourth-generation (4G) cellular networks [4], roadside units (RSUs) [5], and mobile cloud computing [6]. However, they are not sufficient for the following reasons. Cellular networks provide an augment in communication but quite limited, and they are controlled primarily by network operators, which is not efficient and effective from the application aspect [4]. RSUs enlarge the network communication capacity but are really expensive and are difficult to be fully deployed along roads, particularly on a large scale, such as over a whole city [5]. Mobile cloud computing can bring rich computational resources to mobile users but is costly and time consuming when uploading real-time information because mobile cloud computing uses the client–server communication model [7].

Manuscript received April 1, 2015; revised July 21, 2015 and November 11, 2015; accepted January 25, 2016. Date of publication February 23, 2016; date of current version June 16, 2016. This work was supported in part by the National Basic Research Program of China (973 Program) under Grant 2013CB329001 and in part by the National Nature Science Foundation of China under Grant 61301080, Grant 91338203, Grant 91338102, and Grant 61321061. The review of this paper was coordinated by the Editors of CVS.

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Digital Object Identifier 10.1109/TVT.2016.2532863

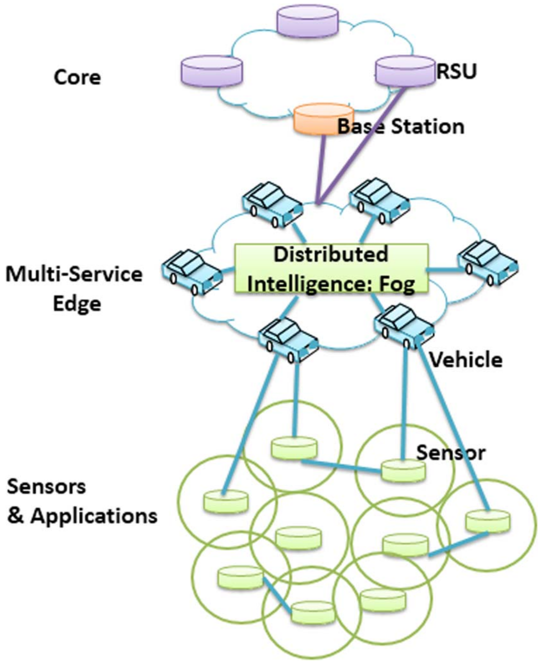


Fig. 1. VFC multitier architecture.

Mobile cloud computing also requires a high quality of network connections with remote infrastructures [8]. Therefore, it remains a great challenge for researchers and engineers to find out how to deal with communication and computational demands more efficiently and conveniently.

Nowadays, the global number of vehicles has increased rapidly and reached a staggering number of one billion in 2010 [9]. As a direct consequence, heavy traffic with slow-moving vehicles occurs frequently, and numbers of parked vehicles are quite huge, particularly in many urban areas. This situation is usually regarded as a nightmare scenario, but we can view it from a new perspective and consider these parked and slow-moving vehicles as huge underutilized resources. Thus, we eventually come up with the novel idea of vehicular fog computing (VFC), which employs vehicles as the infrastructures to make the best utilization of these vehicular communication and computational resources. Specifically, VFC is an architecture that utilizes a collaborative multitude of end-user clients or near-user edge devices to carry out a substantial amount of communication and computation [10], [11]. Apart from the cloud characteristics, such as providing data, computing, storage, and application services to end users, VFC distinguishes itself from other existing techniques with its proximity to end users, dense geographical distribution, and support for mobility [12]. Therefore, VFC exploits the best of the features of slow-moving and parked vehicles, such as clustering distribution in locations, to enable them to collaborate with nearby vehicles. The specific fog computing multitier architecture modified and adopted by the VFC is illustrated in Fig. 1. In this way, this proposed vehicular system can meet the demands for considerable communication and computational capacity, and it works better compared to the conventional systems. It is also worth emphasizing that the multitier architecture of VFC depicted in Fig. 1 is fundamentally different from that of the original fog computing paradigm [10]–[14]. Specifically, in the fog computing architecture, vehicles and mobile devices are end users, and between these edge users and the cloud, there exists the fog server layer. By contrast, in the VFC architecture, vehicles and mobile devices themselves are parts of the "fog" as well.

The idea of considering vehicles as the infrastructures is technically practical. For instance, the existing work [15], [16] view parked vehicles as infrastructures, which developed the concept of parked vehicle assistance to enable parked vehicles to join vehicular networks as static nodes. Wireless devices and rechargeable batteries also help in this process, enabling parked vehicles to easily communicate with one another and with nearby moving cars. Due to the characteristics, such as large number, long-time staying, and specific locations, these parked vehicles are a very ideal choice to serve as static backbones and service infrastructures. Both communication and computational capacity in urban areas can be greatly enhanced when these vehicles as infrastructures collaborate together and form a type of new hybrid networks.

As an extending paradigm of fog computing, the VFC has a lot of common features with fog computing, such as the geodistribution and low-latency communication. Fog computing is a network between the underlying networks and the clouds. It extends the traditional cloud computing paradigm to the edge of the network, enabling creation of refined and better applications or services [11]. In contrast to the cloud, which is more centralized, fog computing targets the services and applications with widely distributed deployments. Since the fog is localized, it provides low-latency communication and more context awareness [17], [20]. The fog suits applications with low-latency communication, video streaming, gaming, AR, etc. With the concept of fog computing, researchers have studied some useful and interesting applications based on it. For example, Aazam *et al.* [17] have discussed the architecture of fog computing and Smart-Gateway-based communication for Cloud of Things. Another work [18] points out that fog computing brings cloud resources close to the underlying devices and Internet of Things, which makes it ideal for latency-sensitive services. They present the idea of utilizing the services of fog for offloading and preprocessing purposes to provide a quick way of notifying the relevant emergency-dealing department. In [19], a system called Fog Micro Datacenter, where the fog plays a vital role in managing resources, performing data filtration, preprocessing, and security measures, is also proposed.

It is worth noticing that key characteristics of the VFC are different from those of the vehicular cloud computing (VCC). Some researchers have conducted some studies about VCC and presented their own perspectives. For example, Olariu *et al.* [21], [22] have developed the VCC to a new concept "Autonomous Vehicular Clouds" with key features dynamically pooling to serve users and having autonomy in service sharing. They coined this concept to refer to a group of largely autonomous vehicles whose corporate computing, sensing, communication, and physical resources can be coordinated and dynamically allocated to authorized users. Then, they also described several application scenarios, specifically, such as data cloud in a parking lot, data center at the mall, and dynamically

TABLE I
DIFFERENCES BETWEEN VCC AND VFC

Features	**VCC**	**VFC**
Decision Making	Remote	Local
Geo-distribution	No	Yes
Communication	Bandwidth Constrained	Real-Time Load-Balancing
Computation Capacity	Medium	Large
Deployment Cost	High	Low

synchronizing traffsic lights. In addition, Whaiduzzaman *et al.* [23] also conducted a survey on VCC, and they emphasized the idea that, as for VCC, the vast number of vehicles on streets, roadways, and parking lots will be treated as plentiful and underutilized computational resources, which can be used to provide public services. However, our research is quite different from theirs. Although we both mentioned the features such as using underutilized infrastructures, our VFC concept highlights the new features as, instead of sending the information to the remote server, utilizing near-located vehicle resources and letting them collaborate with each other. Because we do not need to send information to remote servers, this brings significantly less time delay and less deployment cost. The geodistribution, local decision making, and real-time load-balancing features are of great novelty and can definitely distinguish our proposed concept from others.

The specific differences are compared in Table I. On one hand, the VCC is bandwidth constrained, latency sensitive, and more expensive to deploy, whereas the VFC is based on geo-distribution and has real-time load balancing and local decision mechanism. What is more important, as aforementioned, VFC depends more on the collaboration of near-located vehicles, instead of sending the information to remote servers. This greatly reduces the deployment costs and time delay. On the other hand, VFC can cope with emergency situations better and more robustly than VCC. For instance, the VCC will suffer a great hit if the links to the cloud or remote controller are broken or power outage occurs, but the VFC can still run correctly with the help of power supply within vehicles. In addition, due to the resource utilization of geo-related vehicles, the VFC has more computation capacity and less communication delay compared with the VCC.

In this work, we present an overview of potential capability and open problems for the novel VFC paradigm that utilizes vehicles as infrastructures. Specifically, we consider all the four scenarios, namely, employing *moving* and *parked* vehicles as infrastructures for *communication* and *computation*, respectively. On one hand, moving and parked vehicles as communication infrastructures can support larger flow capacity because of the improvement in packet delivery delaying and the enhanced connections between vehicles. We can employ predictable moving patterns among the vehicles to achieve better communication. On the other hand, moving and parked vehicles as computational infrastructures can make the best utilization of computational resources of each vehicle. For example, congested vehicles can form a vehicular mobile cloudlet, consisting of a group of nearby vehicles connected by wireless vehicle-to-vehicle communication. Thus, our proposed VFC system can exploit tremendous computational potentialities by aggregating the resources of individual vehicles as a whole. The key contributions of this paper are summarized as follows.

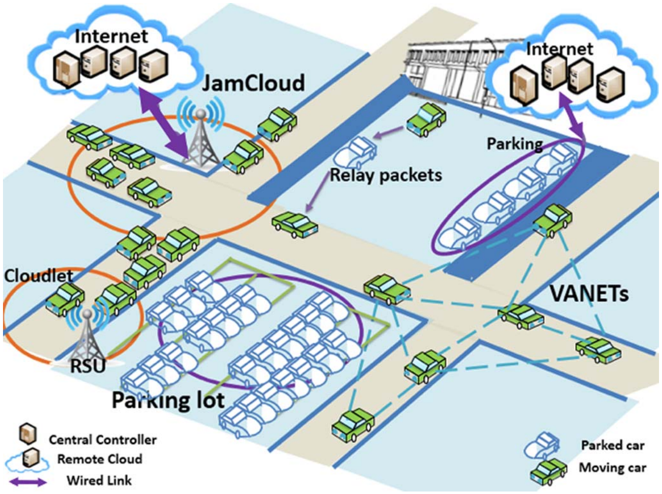


Fig. 2. System overview of four types of scenarios for VFC.

- We propose a novel system of VFC that employs vehicles as infrastructures for communication and computation to enlarge the available resources and to enhance the achievable capacities. To our best knowledge, we are the first to consider and investigate this intriguing and important problem.
- We analyze all the four scenarios of utilizing moving and parked vehicles as infrastructures for communication and computation, respectively. Moreover, we quantitatively characterize the communication and computational capacities with a specific case study supported by real vehicular mobility environment.
- We discuss the challenges in realizing VFC and point out open problems that need to be investigated further. This provides fundamental insights and valuable guidelines for future works in this field.

The remainder of this paper is organized as follows. In Section II, we describe our VFC paradigm and four types of application scenarios regarding employing moving and parked vehicles as infrastructures. In Section III, based on real-world vehicular mobility traces, we provide a quantitative analysis of potential capabilities for all the four types of application scenarios. Section IV points out the challenges and open problems, which are worth further studying. Finally, we conclude our work in Section V.

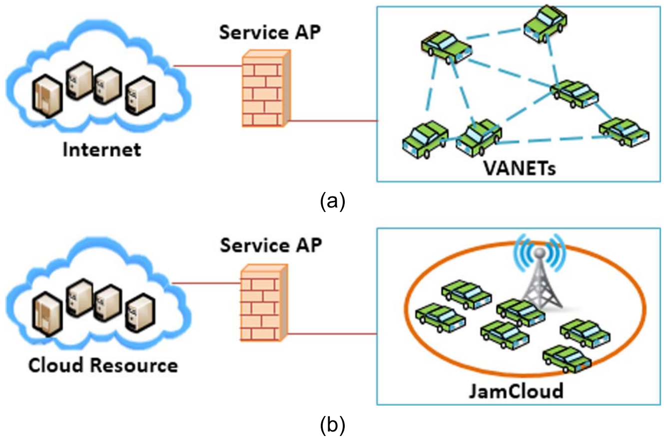
II. SYSTEM OVERVIEW AND APPLICATION SCENARIOS

Fig. 2 illustrates the system overview and scenarios of VFC with moving and parked vehicles' service and applications. There exist four types of scenarios, as described in the following. The first two cases involve employing moving vehicles as infrastructures for communication and computation, respectively. In urban areas, moving vehicles are not at a high speed. On the contrary, most vehicles are slowly moving when entering into downtown, particularly in certain time periods. We investigate the connectivity among moving vehicles in urban areas and unsurprisingly find that nearby moving vehicles can communicate well with each other. Thus, moving vehicles in urban areas can be utilized as communication infrastructures. Moving vehicles become very good computational infrastructures once they are connected to each other, forming a powerful cloudlet capable of offering high computational capacity. The other two scenarios consider parked vehicles as infrastructures to enlarge communication and computational capacities. The number of parked vehicles in urban areas is tremendous, together with moving vehicles, representing two significant states of vehicles. Apart from rush hours, during a long period of daytime and over nighttime, most vehicles are parked along roads or in parking lots. Parked vehicles along roads can play a vital role in relaying packets, whereas those in a parking lot can make up a large computation cloud. In this way, both communication and computational capabilities of the area can be greatly enhanced. We now discuss these four application scenarios in more detail.

A. Moving Vehicles as Infrastructures

1) Communication: Vehicular networks generally contain two types of nodes: vehicles and RSUs. Vehicular communication was developed as a part of the intelligent transport system, which seeks to achieve safety and productivity through intelligent transportation by integrating various information. Communications in an intelligent transport system are achieved with the combination of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. In V2I communication, the energy consumption of roadside infrastructure wireless nodes, e.g., RSUs, is one of the most important constraints that must be taken into consideration in working toward high reliability and long lifetime of the network [24]. As for V2V communication, direct exchange of information happens between vehicles, and the main problem is whether the distance between two vehicles is smaller than the communication range to build up a successful connection. It can be seen that network connectivity is one of the most important issues for enabling information transmission, particularly for V2V communication.

Therefore, we turn to the VFC, which utilizes moving vehicles as communication infrastructures, for help with the solution for this communication problem and to bring better network connectivity. VFC takes the advantages of multihop characteristic and moving features of vehicles to carry the information from one place to another place, which is illustrated in Fig. 3(a). Moving vehicles become good message carriers and can continuously transmit information by building up new connections. Due to the desired characteristics of VFC, such as geodistribution and local decision making, moving vehicles in close geographic locations can collaborate and connect with each other. Specifically, when some vehicles play the role of communication hubs, they connect the near-located vehicles together, therefore connecting with more mobile access points. Because of these communication hubs, the fog is formed, and instead of sending information to cloud servers, tasks are completed by utilizing computational and communication resources locally, which involves both local decision making and geodistribution features. All these bring less delay, lower cost, and higher efficiency. To sum up, VFC does a better job in communications compared to the VCC, because the former can deploy tasks with less time delay and less cost utilizing georelated vehicles, whereas the latter needs a lot of information transmission between the mobile access points and remote servers.



(a)

(b)

Fig. 3. Moving vehicles as infrastructures.

To characterize moving vehicles and employ them as infrastructures, we first need to know vehicular speed distribution in the space and time domains. With this knowledge, we can explore the relationship between connectivity and mobility of vehicular networks. This helps us to obtain a comprehensive understanding of the communication circumstances in urban areas and, therefore, to accurately assess the potentials of using moving vehicles as infrastructures.

2) Computation: Moving vehicles, particularly slow-moving vehicles, are important components for computational infrastructures in VFC. For example, a cloud can be formed by vehicles, which are equipped with embedded computers, jammed around an intersection of city roads, where an RSU may also be deployed to connect to the remote clouds. The schematic of such a system is illustrated in Fig. 3(b), where the RSU connects with the remote cloud computing centers by wired Internet. In such a VFC system, with the help of local mobile cloudlets, offloading or loading computation can be achieved through V2V communications. Congested vehicles can also exchange information through V2I communications with RSUs, whereas RSUs communicate with remote cloud computing centers through Internet. Thus, the whole system becomes a hybrid cloud, which aggregates computation resources from both mobile cloudlets and remote clouds and then reallocates them to vehicles to satisfy the computation demands of individual vehicles. It is worth emphasizing that mobile cloudlets may also carry out computational tasks for remote clouds. This is particularly attractive, as it turns otherwise wasted energy due to congestion into valuable and useful computational power.

B. Parked Vehicles as Infrastructures

1) Communication: In any large urban areas, the number of parked vehicles is huge. Furthermore, parked vehicles are widely geodistributed in street parking, outside parking (mainly off-street parking on the ground), and interior parking (garages

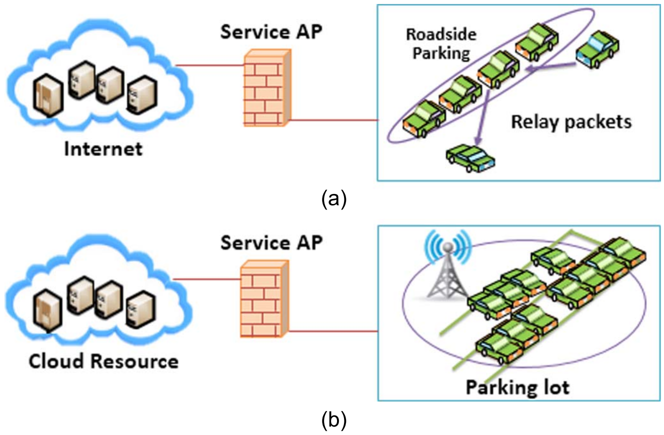


Fig. 4. Parked vehicles as infrastructures.

or underground parking lots). Unlike moving vehicles, these parked vehicles have relatively unchanged locations over certain long periods of time. Thus, they cannot help to carry the information from place to place directly in the space domain. However, parked vehicles as communication infrastructures have their own unique features. With wireless device and rechargeable (vehicle) battery, parked vehicles can easily communicate with one another and nearby moving vehicles. These parked vehicles can serve as static backbones and service infrastructures to improve connectivity.

As shown in Fig. 4(a), parked vehicles on roadsides can serve as communication infrastructures by carrying and forwarding packets to other vehicles. Relaying packets greatly improves the opportunistic style connectivity, which will benefit the content-sharing application significantly. Due to the characteristics of large number, long-time staying, wide geodistribution, and specific locations, parked vehicles are able to become abundant, credible, and convenient communication nodes in urban areas. This can compensate for the disadvantages of moving vehicles, which have relatively unbalanced distribution and rapid-changing positions. Intuitively, the number of parked vehicles and the distribution of parking time will influence the achievable capability and other key features of using parked vehicles as communication infrastructures.

2) Computation: As aforementioned, numerous parked vehicles are widely geodistributed, with large numbers in street parking, outside parking, and interior parking. When these parked vehicles join together under suitable communication conditions, they can collaborate with each other to achieve large computing tasks. Thus, these parked vehicles become abundant computation infrastructures, providing a great deal of computation resources. This scenario is illustrated in Fig. 4(b). According to the literature, meeting huge computation demands is challenging because individual vehicles have limited computing resources [25]. This computation capacity problem can be perfectly solved by VFC, as VFC can provide powerful computation resources and achieve computing tasks in less time, as well as at higher efficiency. For instance, when the parked vehicles in a company parking lot join VFC, these vehicles form a small data center and, therefore, can deal with various complex tasks, which require large computation capability.

There exist very limited works on the topic of using parked vehicles as infrastructures. We anticipate that more realistic scenarios and practical approaches will be proposed to promote this application in the future. In this paper, we assess the potential computational capacity of utilizing parked vehicles as infrastructures and provide a primary quantitative analysis on the advantages of this application.

III. CAPABILITY ANALYSIS

A. *Data Sets and Preprocessing*

To investigate vehicular mobility and connectivity in urban scenarios, we conduct our study on two real-world large-scale urban vehicular traces, i.e., Shanghai and Beijing.

The Shanghai trace [26] was collected by the Shanghai Grid project [27], in which mobility trace data from over 4000 taxis were collected during the whole month of February 2007 in Shanghai. In this trace, reports were sent back to the data center by General Packet Radio Service (GPRS). Specifically, the frequency of reports was either every 1 min when a taxi had passengers on board or every 15 s when it was vacant. The information reported included the taxi's ID, the longitude and latitude coordinates of the taxi's location, the speed, and other factors such as heading angle, as well as the status of the taxi. In our study, we preprocess the data set in the following way. To analyze the vehicular mobility and connectivity, we need to know the exact location of every taxi in a large number of time points. Therefore, it is important to sample appropriate timepoints with a fixed frequency to obtain the real-time topology. Since GPS reports were collocated in discrete time at the time interval of 15 s or 1 min, we sample the data every 10 min. Thus, every 10 min, a new real-time topology is obtained, and in this way, we collect 144 topologies in 24 h. After empirical data processing, we found that it is an acceptable sampling frequency because most of the sampled topologies have no significant change in just 10 min.

The Beijing trace [28] is the largest urban city vehicular data trace available. In collecting the Beijing trace, we used the mobility track logs obtained from 27 000 participating Beijing taxis carrying GPS receivers during May 2010. Specifically, we utilized the GPS devices to collect the taxis' locations and time stamps and GPRS modules to report the records every 15 s for moving taxis. The specific information contained in such a report includes the taxi's ID, the longitude and latitude coordinates of the taxi's location, time stamps, instant speed, and heading. Similarly, the data set is appropriately preprocessed before the analysis.

B. *Moving Vehicles*

1) Communication: The communication capacity is of great significance in vehicular networks because information exchanges cannot happen without reliable communications. Among various variables that impact capacity, the connection is one of the most important metrics. The amount of connection between vehicles fundamentally represents how good are the network communication conditions between vehicles. Thus, we focus on the connectivity to investigate the capability of utilizing moving vehicles as communication infrastructures. Since it is important to study how the mobility of a vehicular network impacts its connectivity, as measured by the topology metric known as component size, we first unveil the fundamental relationship between mobility and connectivity of large-scale urban vehicular networks by analyzing the Shanghai trace.

We consider the establishment of communication links based on a simple unit disc model by defining the unit disc communication range R to judge whether a successful link is established. In this work, we set the communication range to $R = 600$ m. To depict the key characteristics of large-scale vehicular networks, we offer the following definitions.

Definition 1 (Component and Component Size): Consider a topology obtained in a certain time-point t. We have a graph $G(N, E)$ consisting of its node set N and edge set E at t. If we associate the nodes $\{n_i\}$ with each other, as long as there exist paths represented by the edges between them, then a subgraph at t, which is denoted by $C(t)$, can be obtained, which defines a component.

The component $C(t)$ represents the network within which each vehicle can reach any other vehicles at time t by multihop connections. The size of the component is the number of nodes belonging to it, i.e.,

$$S(t) = \|C(t)\| .$$

In the sequel, we will drop the time index t to simplify notations, and we simply denote the component by C and the component size by S, which are two key metrics in our study.

Definition 2 (Vehicular Speed): For $n_i \in N$, let the vehicular speed of n_i be v_{n_i}.

The vehicular speed v simply describes the mobility of individual vehicle.

Definition 3 (Component Speed): The component speed V is defined as the average value of all the vehicle speeds in the same component, which represents the mobility of the component. With S representing the size of component C, the component speed V is given by

$$V = \frac{1}{S} \sum_{n_i \in C} v_{n_i}.$$

Remarks: In the network topology terminology, the vehicular speed refers to the movement of a node per unit time, showing the individual motion from a node level. By contrast, the component speed reflects the mobility at the component level, which is a more macroscopic metric than vehicular speed. Given all the vehicles in the same component, the component speed provides us with the mobility of the network instead of an individual vehicle. We emphasize this because the component speed gives us more mobility information from a network perspective.

With these definitions of metrics, we calculate the cumulative distribution function (CDF) and the complementary CDF (CCDF) for both the vehicular speed and component speed based on Shanghai trace data. We observe that the CDFs of the vehicular speed and component speed are both exponential distributions, whereas the CCDFs of the vehicular speed and component speed both exhibit a similar exponential decay. Moreover, over 80% of the vehicles have vehicular speeds smaller than 40 m/s, and around 40% of the vehicle speeds are smaller than 10 m/s. Similarly, over 80% of the component speeds are smaller than 45 m/s, and around 40% of them are smaller than 10 m/s. Thus, both the vehicular speed and component speed exhibit the same distribution with very similar parameter values. Furthermore, the speeds of moving vehicles are not very high, and therefore, it is practical to consider these vehicles as communication infrastructures.

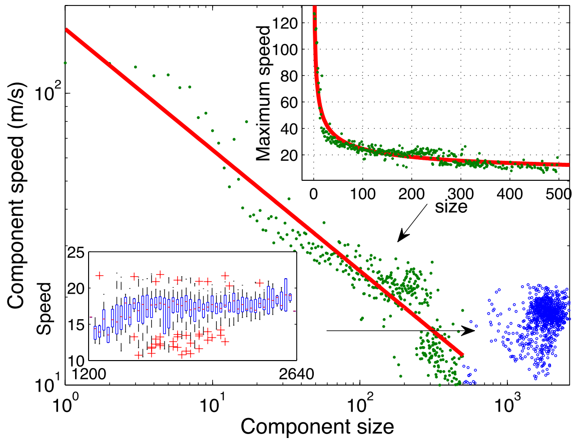


Fig. 5. Scatterplots based on the Shanghai trace representing the component speed versus component size, where with a log–log scale, the green spots correspond to the maximum component speeds for the component sizes up to 500, the red curve is a power-law fitting, and blue spots correspond to the maximum component speeds for the component sizes larger than 500. The top-right subplot shows the power-law fitting in the red curve, where the green spots correspond to the green spots in the main plot. The bottom-left boxplot represents the blue spots of the main plot in an alternative way to reveal more details.

For the purpose of revealing the relationship between mobility and connectivity, we conduct an empirical analysis of the component speed and component size. We draw a scatterplot in Fig. 5 to explore this relationship. As for the component size ranging up to 500, the scatterplots of the maximum component speed versus the component size are presented in the main plot and the top-right subplot in Fig. 5. With a log–log scale, we can appreciate a power-law decaying relationship from the fact that most plots are on or near the straight red line with a fixed slope. Thus, for the component speed larger than 20 m/s, the component speed clearly exhibits a power-law decaying relationship with the corresponding component size. Moreover, blue spots in the main scatterplot correspond to the case of the component size larger than 500. We draw the bottom-left boxplot to have a close look into this case. In this bottom-left boxplot, every blue strip represents the component speed distribution with an x-axis of 30, i.e., with a width 30 in component size, while the length of a blue strip in the y-axis indicates the interquartile range of the component speed, reflecting the variability of the component speed. Additionally, each black dashed line represents the corresponding maximum and minimum values, whereas the red plus symbols indicate extreme outliers. This boxplot in Fig. 5 for the component sizes between 1200 and 2640 clearly indicates a uniform distribution when the component speeds are smaller than 20 m/s. Therefore, we observe a dichotomy in the relationship of the component speed versus the component size, which is partitioned by a certain threshold component speed A. In this case, $A \approx 20$ m/s. A more detailed analysis of this dichotomy relationship can be found in [29].

Because the communication capacity and the connectivity both reflect the underlying information-transferring capability, we can infer that the communication capacity exhibits similar dynamic changing trends with the connectivity. More specifically, on one hand, when the component speed is larger than a certain threshold speed A, the power-law fitting model reflects the true relationship between the component size and corresponding maximum component speed. As stated previously, the component speed describes the mobility, whereas the component size depicts the connectivity of network. This power-law relationship indicates that, for the component speed larger than A, the mobility destroys the connectivity with a power-law decay. The faster a vehicle moves, the fewer vehicles it can successfully connect with, leading to a smaller component size and, hence, poorer communication capacity. On the other hand, when the component speed is smaller than A, this relationship changes into a uniform distribution, which implies that the component speed may correspond to any component size, ranging from the minimum size to the maximum size. In other words, the mobility when lower than a threshold has no apparent impact on the connectivity of the network, i.e., the communication capacity.

Based on the aforementioned analysis, we can make evaluations and predictions for connectivity and, hence, communication capacity, according to mobility metrics such as vehicular speeds or component speeds. This provides us a better understanding of the communication characteristics in vehicular networks and offers relevant guidelines for us to design associated vehicular applications. Basically, once we know the influencing factors of connectivity from a higher level, i.e., communication capacity, we can design more efficient and practical methods to improve it.

2) Computation: Computation is an important key aspect for VFC, and therefore, we carry out a case analysis to investigate computational capability. In this case, we employ the Beijing trace. This is because it is well known that the traffic loads in Beijing are huge and vehicles are always congested at the intersections within the Fifth Ring Road, which is ideal for investigating the potential of utilizing slow-moving or congested vehicles as computational infrastructures. More specifically, we choose ten intersections with high traffic jams and study the computation capacity of the vehicles in these selected regions.

To analyze the computation capacity, we first focus on the variables, such as resident number of vehicles, patterns of staying time, and incoming and outgoing processes, which all affect the capacity of a vehicular mobile cloudlet. These variables, which can be acquired according to vehicular trace information, help us to find an appropriate mobility model and, hence, understand computation capacity. Hence, we employ a statistical approach to analyze the Beijing trace, which involves 27 000 taxis carrying GPS receivers, over the duration of 16 days in May 2009. Specifically, we consider the mobility patterns of vehicles and study the incoming and outgoing processes, which also bring us statistics on the staying time and resident number of vehicles. Then, we propose a general mathematical mobility model to describe the whole process for a cloudlet. Finally, we predict the computation capacity of a vehicular mobile cloudlet, by comparing the results obtained from both the real trace and our model.

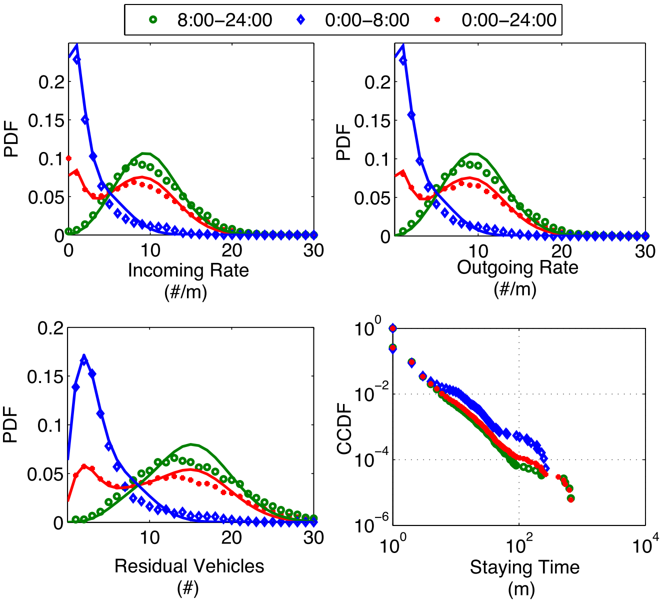


Fig. 6. Distributions of incoming and outgoing numbers of vehicles per minute, as well as resident numbers of vehicles and staying time in the selected regions, where the points are the empirical results obtained from the trace, whereas the solid curves are the theoretical results calculated by our proposed model.

Since computation capacity can be deduced from vehicular mobility, we propose a mathematical model to characterize mobility. Consider a JamCloud [30] that includes N cloudlets, which is denoted by $\mathcal{N} = \{A_1, A_2, \ldots, A_N\}$. We begin by building a mathematical mobility model to describe the process related to a cloudlet A_n. Based on the fitted Poisson distribution for the incoming number of vehicles per minute, we assume that the incoming process is a periodic nonhomogeneous Poisson process with a time-variant parameter $\lambda_n(t)$ and a period T of one day. We also assume that there exists a time-variant outgoing rate $\mu_n(t)$ with the same period T. Therefore, the whole process is modeled as a periodic nonhomogeneous immigration-death process, which is denoted by $\{X_n(t)\}$. The resident number of vehicles is modeled as the population, whereas the staying time is modeled as the lifetime of this process. Then, the distributions of the resident number of vehicles and the outgoing number of vehicles per minute are both Poisson with mean $E_n(t)$ and $E_n(t)\mu_n(t)$, respectively, where

$$E_n(t) = E_n(t+T) = \int_{-\infty}^{t} \lambda_n(s) \exp\left(-\int_{s}^{t} \mu_n(r)dr\right) ds \tag{1}$$

which matches the fitting models described previously.

As clearly shown in Fig. 6, the probability density functions (PDFs) of the incoming and outgoing and the resident numbers

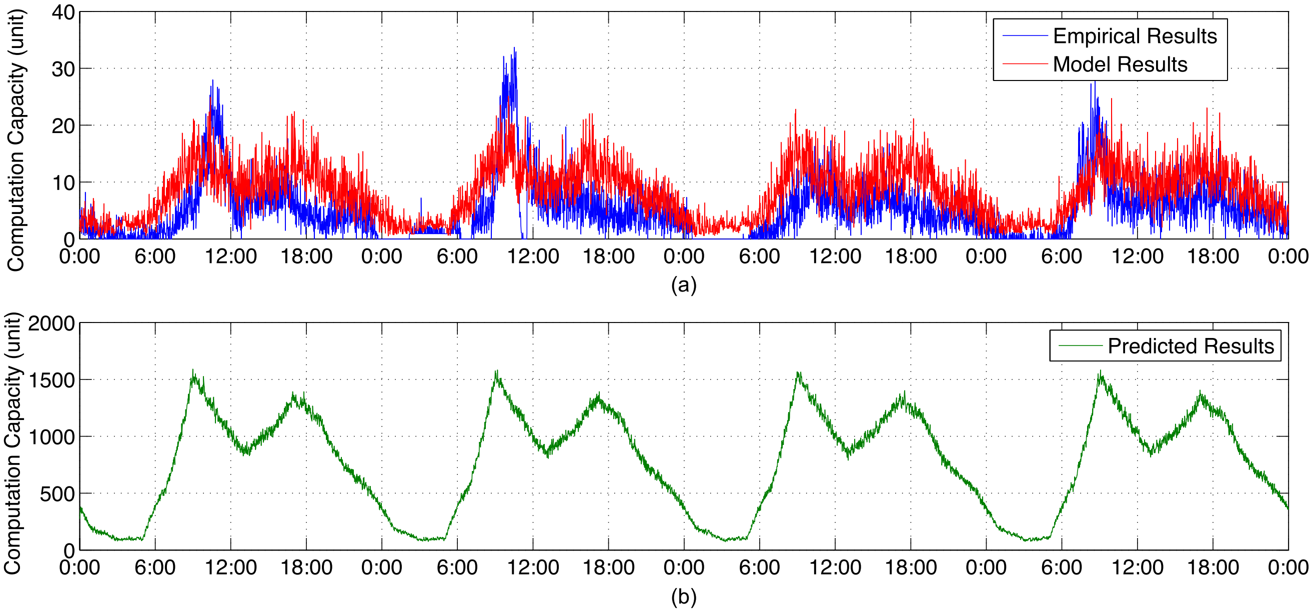


Fig. 7. Computing capacity validation and prediction. (a) Comparing of empirical results obtained from the trace with theoretical results calculated by our proposed model. (b) Predicted results calculated by the proposed model.

of vehicles (taxis) are time variant. By observing the arrival and departure time intervals in many short time periods, we find that these three variables follow exponential distributions approximately. Thus, we can use Poisson distributions to fit the numbers of incoming, outgoing, and resident vehicles. The computation capacity indicates the computation potentials or, more specifically, the computation resources available in a certain region. In this paper, the computation capacity is defined as the cumulative sum of individual vehicles' staying times in a certain area, assuming that every vehicle has similar computation capability. By understanding the specific dynamic changes of computation resources in the whole region, we can achieve better utilization of the available computation capacity.

We simulate and predict the computing capacity of a mobile cloudlet based on the real trace and the proposed model, under the assumption that individual vehicle computing capacity follows a normal distribution [30]. We first validate the proposed mobility model via a persuasive approach, in which we randomly choose 50% of the taxis in the trace to train the parameters in the model and compare the results obtained by the model and real trace. Then, we train the parameters of the model again by using all the taxi data in the trace, and we predict the computation capacity of a cloudlet with different vehicular traffics. To train the model's parameters, we choose one of the selected intersection regions, and the results obtained are shown in Fig. 7.

Specifically, Fig. 7(a) shows the results for the four days, from May 1 to May 4, based on the real trace and the proposed model, with the model parameters estimated from 50% of the taxis data. We observe that the computing capacities of both the empirical statistics and the predictive model exhibit strong periodicity. More importantly, the empirical results obtained directly from the real trace are very close to those obtained based on the proposed model. Thus, the computation capacity for the 100% taxis of the trace is well predicted by the model whose parameters are estimated from 50% of the taxis data. This validates our proposed model.

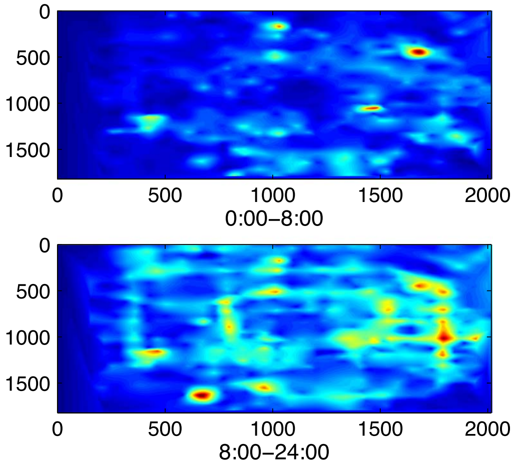


Fig. 8. Overview of computation capacity distribution for moving vehicles in central Beijing, depicting the computation capacity in nighttime (00:00–08:00) and in daytime (08:00–24:00). The color bar indicating computing capacity is as given in Fig. 9.

Thus, we can use our proposed model with some confidence to predict the computation capacity for various vehicular traffic conditions, and Fig. 7(b) presents the prediction of the computing capacity of the cloudlet under the condition that the total number of vehicles on the road in Beijing is 3 million, according to the government census [31]. The result in Fig. 7(b) indicates the huge potential of computing capacity for such a cloudlet.

Then, we further analyze the predicted computation capacity distributed in the spatial domain within the 4-km^2 square area of Beijing City Center, and the related results are shown in Figs. 8 and 9. As shown in Fig. 8, the computation capacity in daytime is larger than that of nighttime, which is, of course,

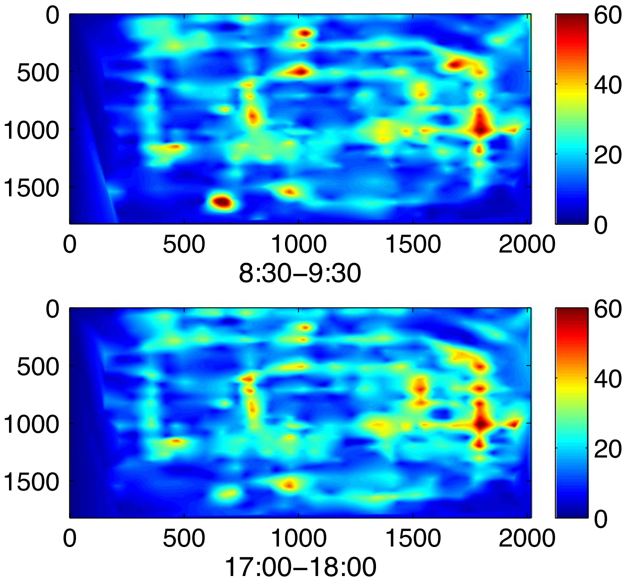


Fig. 9. Overview of computation capacity distribution for moving vehicles in central Beijing, depicting the computation capacity in A.M. rush hours (08:30–09:30) and in P.M. rush hours (17:00–18:00).

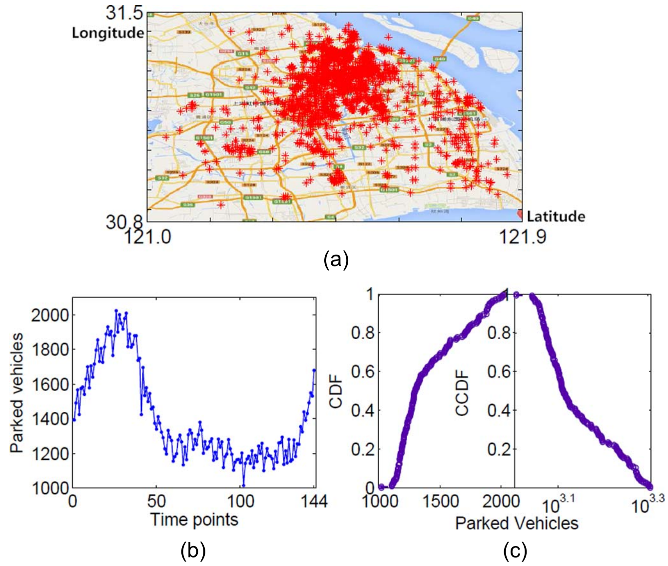


Fig. 10. (a) Geographical distribution and (b) the number of parked vehicles (taxis) over a day covering 24 h, with time points selected every 10 min, and (c) the CDF and CCDF of the number of parked vehicles (taxis).

caused by more active movements of vehicles in daytime compared to nighttime. In addition, not surprisingly, Fig. 9 confirms that the computation capacity offered during rush hours in central Beijing is potentially huge.

C. Parked Vehicles

To have a closer look at parked vehicles as infrastructures, the pattern of vehicular parking is required. We begin our investigation based on the Shanghai trace to obtain the empirical results for the number of parked vehicles (taxis) all over the city and to analyze the potential of these currently underutilized vehicular resources. As shown in Fig. 10(a), the geographical locations of parked vehicles represent an aggregated distribution, and the number of parked vehicles is huge, which offer an overview of the potential for utilizing parked vehicular resources in the whole city. We also observe in Fig. 10(b) that there exists a time-varying change in the number of parked vehicles. In particular, the maximum number of parked vehicles appears around 5:00 a.m., before dawn, while the minimum appears near 17:00 in the afternoon. This matches really well with human routines of working and resting in their daily life. Fig. 10(c) shows the CDF and CCDF of parked vehicles, respectively. During the 24 h covering a day, the probability that the number of parked vehicles (taxis) is larger than 1000 and smaller than 1500 in the whole city is about 70%, which indicates that parked vehicles remain in a large number in most of the time. Thus, we can evaluate and predict how much are the potential capacities, if these vehicular resources are put into utilization.

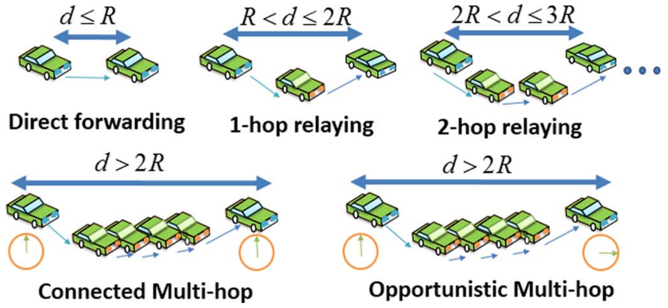


Fig. 11. Transmission between two parked vehicles. The connected multihop delivery occurs when vehicles carry and forward immediately, whereas the opportunistic multihop delivery happens with uncertain transmission delay.

1) Communication: As communication infrastructures, parked vehicles can relay data or store and then forward packets, according to communication demands and conditions, as illustrated in Fig. 11, where R and d denote the radio range and intervehicle distance, respectively. Direct forwarding can be achieved if $d < R$. Under the condition of $R < d \le 2R$, any passing vehicle can relay packets, and therefore, the link between two parked vehicles can be regarded as a reliable connection if the traffic is sufficiently dense to maintain the appearance of vehicles for relaying packets. As also mentioned in [15], the short intervehicle distance, which is less than $2R$, can bring good connectivity. Furthermore, connected multihop relaying can help data transmission, where relays receive packets and forward them immediately. Additionally, store–carry–forward or opportunistic multihop delivery with uncertain transmission delay can be implemented, even if the traffic is sparse, which offers a solution for intermittent and sparse networks.

When considering the communication role of parked vehicles, therefore, we are able to analyze the communication characteristics of parked vehicles in the similar way as moving vehicles. For instance, we can consider the contact time and downloading delay in this process in the future. Moreover, because VFC has unique advantages by utilizing the nearby parked vehicles as infrastructures, we can further study the improvement of communication capacity using VFC compared to conventional networks in our future investigation.

2) Computation: We mainly focus on the existing computation capacity research in this section with a more delicate

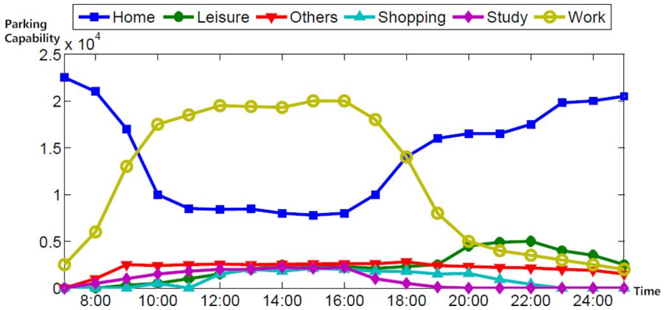


Fig. 12. Parking capability accumulation profile by vehicular activity in Montreal from 6:00 to 24:00. The data are based on the origin–destination survey about a borough of the city of Montreal, QC, Canada, which is described in [37].

and quantitative discussion on the computation capacity when utilizing parked vehicles as infrastructures. Inspired by the emergence of cloud computing, many associated techniques and paradigms are developed by researchers and IT companies [32], [33]. A phenomenal adoption of cloud computing and cloud IT service appears all over the world [34]. However, conventional vehicular networks are not perfect, owing to inadequate utilization of computational resources of parked vehicles. When parked vehicles act as infrastructures, they become perfect candidates for providing lots of "data center on wheel" with significant advantages in computation and storage over moving vehicles, simply because they are better connected with each other. These parked vehicle groups, which are mainly on roadways, along streets, or in parking lots, constitute a large amount of underutilized computational resource. Some research works were conducted to investigate this problem. For instance, Olariu *et al.* [22] proposed the concept of vehicular cloud, which is defined as a group of vehicles whose spare computing, sensing, communication, and storage resources can be coordinated and dynamically allocated to users. Arif *et al.* [35] envisioned a vehicular cloud involving cars in a long-term-stay parking lot of a typical international airport and predicted the parking occupancy to schedule resources and further assign computational tasks. Gu *et al.* [36] also conducted researches on the data center architecture that leverages the extra storage resources in parking lots. These resources can form an auxiliary vehicular data center, such that the pressure on the conventional data center can be mitigated and the total communication cost is also reduced. The vehicular data center's management policies and specific approaches or models about computational capacity estimation are very good research topics in this field.

Moreover, let us consider the computation capability of parked vehicles as the parking capability with the help of the work [37]. In this case, by defining the capability as the total value of each vehicle's parking time, parking capability is presented in Fig. 12, which is a reference from Morency and Trepanier [37], where we observe the obvious patterns regarding, for example, the capacity of parked vehicles for work purposes and the capacity of vehicles parked at home.

IV. CHALLENGES AND OPEN PROBLEMS

As stated previously, various vehicular services cannot be put into practical use in our daily life if the communication and computational capacity are not sufficiently powerful to support them. Therefore, we propose VFC, a system which employs vehicles as infrastructures and makes the best utilization of nearby vehicular resources. Because this is a brand new idea, there exist lots of challenges and open problems about VFC waiting for us to explore. Here, we present and discuss these challenges and open problems, such as building up appropriate mobility vehicular models, analyzing computational capacity, constructing practical operation systems, handling with security problems, and associated applications.

A. *Mobility Model for Vehicles*

In vehicular networks, thousands of vehicles move from place to place, and they attempt to connect with each other as long as the communication condition is permitted. To implement VFC, we need design effective protocols and associated management mechanisms to connect with nearby moving or parked vehicles. Clearly, an appropriate and accurate mobility model is essential to predict and evaluate the movement of surrounding vehicles and, thus, to provide explicit understanding of communication conditions. Therefore, studying the mobility model for vehicles is of fundamental importance in designing a VFC system.

Some mobility models have been addressed in the literature [38]–[40]. However, the existing models are not completely precise and often insufficient for accurate characterizations for the vehicular moving process. We need a better mobility model to give us valuable information about the accurate vehicular behaviors, such as vehicular speeds and distributions in both the time and space domains. Specifically, we need to study vehicular mobility more delicately and quantitatively to derive more specific and accurate mobility models for various environments that are more useful for practical applications. Knowing the underlying mobility patterns and vehicular behaviors will help to conduct better communication and computational resource utilization and assignment and, therefore, to realize an effective VFC system, leading to maximum efficiency in both equipment and energy. It also enables us to further design the associated applications, which serve as vital components of more advanced vehicular networks.

B. *Capacity Analysis and Resource Management*

In this study, we have demonstrated the huge potential computation capacity with VFC by utilizing moving and parked vehicles as infrastructures. However, more capacity analysis and theories are needed to evaluate and quantify the real capacity improvement in practical applications. The research in this critical area is still in its very early stages. In the future, we expect more specific tests and/or simulations to explore the capacity under various practical circumstances of VFC.

Resource management in VFC is another important problem to study to take the full advantage of available vehicular computation and as storage resources. The computational utilization can be promoted by managing the resources and minimizing the cost for computation, such as how the service requester and network operator can interact and how the computational tasks are managed and distributed among numerous nearby vehicular resources. To achieve an efficient cooperation and integration among all surrounding vehicles, we need to design appropriately associated protocols and mechanisms. Thus, more theories and methods are waiting to be explored in this area.

Some approaches have been proposed to encourage the resource share between nodes in networks, such as reward-based approach [41], [42] and punishment-based mechanism [43]. These approaches can also promote the resource utilization in VFC with commercial agreements and guidelines on user behaviors. Users' interaction can seriously affect the performance of VFC, because how the access request to the resource of individual vehicles is accepted or authorized is another important factor that impacts on achievable communication and computation performance. To achieve efficient resource utilization of hundreds of vehicles, we first need to guarantee that these vehicles agree to join the VFC network and authorize to exchange data with each other. Thus, there are also some related work in designing the associated protocols or agreements in authorization and access. VFC can bring people better communication service and support many geodistribution applications catering to entertainment needs, social needs, and users' interaction desires. People will be attracted to let their vehicles join the VFC once they feel that these convenience and powerful features considerably outweigh the "costs" they pay.

C. System Implementation

To support a practical VFC system, a typical vehicle needs to be equipped with certain devices, including an integrated embedded computer, a GPS device, sensing devices, digital maps, and communication devices, along with intelligent algorithms. Integrating these devices has helped drivers acquire real-time information about road conditions and the outside world. By augmenting these devices with VFC, vehicles may become networked computing centers on wheels. Note that many of these enabling devices already exist in current popular vehicle models. Other high-end vehicle models have more sophisticated sensing devices and powerful computational equipment to conduct safety and entertainment tasks [35]. Clearly, new future vehicles will have even better hardware and software to support VFC.

With this integrated wireless communication and computation system, adequate power supply of the individual vehicle plays a vital role in the operation of the whole system. It is noted that, with the help of power supply such as a rechargeable vehicular battery embedded in vehicles, parked vehicles can perform associated VFC tasks when their engines are switched off. In fact, the power consumption of achieving related VFC tasks is very little, as compared to the energy requirements of providing driving assistance, controlling a vehicle system, or supporting certain entertainment applications. Thus, relative communication and/or computation tasks of the VFC can be adequately supported in individual vehicles with the current vehicular battery supply. However, it is highly desired to develop a much more energy-efficient integrated wireless communication and onboard computation system for vehicles to popularize VFC applications.

To effectively utilize vehicles as infrastructures for communication and computation, various new techniques and related supporting facilities must be developed and installed in places to be put into use. For instance, the wireless communication and computational equipments within vehicles are set to support the connections between cloud control center and vehicles. Apart from this, we also need control centers as supporting facilities to manage the cloudlet and to link vehicular networks to the Internet. Moreover, protocols and algorithms for optimizing the computational resources and controlling the process of delaying packets also need to be proposed. Building a complex system, such as VFC, is a comprehensive project, which requires the close collaboration and integration from individual parts of the whole system.

D. Incentives and Security

The incentive of designing VFC is primarily to meet communication and computational demands. VFC will greatly promote the development of advanced vehicular applications and service to offer safer and more enjoyable driving experiences. As VFC can support huge communication and computational demands, various more complex applications and services will no longer stay in the concept phase and are expected to be implemented in the near future. This can bring us great convenience and advantages. Safety-assisted applications enable vehicles to sense threats and hazards of environment in real time with a 360° awareness. Entertainment services also enable us to keep close contact with friends and enjoy colorful Internet applications, and even interesting human–computer interaction (HCI), with great convenience. All these applications require the exchange of a huge amount of information with the outside world, and they critically rely on the powerful communication and computational capacity because they can easily reach hundreds of megabytes or even several gigabytes in operation. Thus, solving these demand problems is the powerful incentive of VFC.

Apart from the aforementioned research incentives of VFC, there also exist the vehicle owners' incentives. Due to the utilization of vehicular computational and storage resources, we need to give some money to vehicle owners to let them rent out their resources. If they get paid from the VFC platform operator, they will be more willing to let their vehicles join the VFC as part of a dynamic data center. Therefore, proposing incentive models for using vehicular resources will also be a hot research area. Because both the VFC users and the vehicle owners can obtain benefits from using or renting the resources, the business about this issue will also attract increasingly more attention.

Given a variety of vehicular applications operating in the VFC system, the security and privacy of the VFC network are extremely important issues. Due to the process of sharing content and accessing data, there exist some security problems, such as weak authentication, lack of sufficient protection, misuse of protocols, and so on [44]. The vehicle operators therefore face more danger from the information stealing, hostile attack, and virus infection. For instance, because many social network sites are not taking adequate steps to protect privacy, some information about the mobile users (e.g., identities, interests, e-mail address, etc.) may be obtained by other users or some third parties, leading to potential malicious usage and privacy leakage [45]–[47]. Thus, it is critical to develop a suite of elaborate and carefully designed security mechanisms for VFC to achieve security and conditional privacy preservation [48]. Considering the limited number of existing studies, we can expect that this security problem will attract increasingly more researchers, and it will remain a hot area to study in the next few decades.

E. Applications

VFC and its novel idea of employing vehicles as infrastructures is expected to be operational in our daily lives soon, and many associated vehicular applications can be envisioned, e.g., driving safety, entertainment services, and emergency networks. In particular, for those applications needing rich computational processing, the VFC framework will play a vital role in speeding up computing and thus reducing the delay. For instance, when an accident happens, we want to envision a solution to reschedule the traffic lights and thus dissipate the huge traffic backlog in an efficient way. This leads to a great demand in computation resources [49]. If VFC is put into use, we can pool all vehicular computational resources together to create the effect of a powerful supercomputer. In this way, with better traffic light schedule, we can decongest the afflicted area as fast as possible. Apart from this, a lot of entertainment applications will also be promoted by stronger computational power. In addition, applications such as data mining [50], HCI [51], and AR [3] also require rich computational resources. They all bring great convenience to our life. Data mining techniques may be utilized to provide high-quality, useful, and real-time context information to services and, hence, to improve its quality and efficiency. HCI and AR will be, in practice, in our daily life with better communication and computation environments. Moreover, for higher level of reliability and adaptation, these applications will be redesigned to suit the unique characteristics of VFC. This brings many research opportunities. For example, because various applications have different purposes and capacities of mobile devices are heterogeneous in real life, an adaptive optimization mechanism that can simultaneously support the system efficiently and allocate computing tasks effectively is necessary [52]. Therefore, there are many open problems and challenges waiting for us to explore in this area.

V. CONCLUSION

In this paper, we have presented an overview of vehicles as the infrastructures for communication and computation, which is a new paradigm referred to as VFC. With increasing number of vehicular terminals, this paradigm brings great opportunities and challenges. We have discussed all the four scenarios of utilizing moving and parked vehicles as communication and computational infrastructures, respectively. Our study has demonstrated the huge potential enhancement in the communication and computation capacity that can be realized by VFC. Specifically, with the help of VFC, better connectivity and more opportunities of relaying packets can be achieved, leading to more reliable communication with higher capacity. VFC also greatly improves the computational performance, as compared to conventional systems, due to making the best use of currently underutilized computational resources of individual vehicles. Once the communication and computational capacity are improved, more advanced developments will appear in the field of vehicular applications and mobile cloud computing. Although still in its infancy, this paradigm is a promising model that can fundamentally reshape vehicular networks and various vehicular applications in the future.

REFERENCES

[1] M. Khabazian, S. Aissa, and M. Mehmet-Ali, "Performance modeling of message dissemination in vehicular *ad hoc* networks with priority," *IEEE J. Sel. Areas Commun.*, vol. 29, no. 1, pp. 61–71, Jan. 2011.

[2] M. Gerla and L. Kleinrock, "Vehicular networks and the future of the mobile Internet," *Comput. Netw.*, vol. 55, no. 2, pp. 457–469, Feb. 2011.

[3] S. Tachi, M. Inami, and Y. Uema, "Augmented reality helps drivers see around blind spots," *IEEE Spectr.*, vol. 31, 2014.

[4] G. Hampel, K. L. Clarkson, J. D. Hobby, and P. A. Polakos, "The tradeoff between coverage and capacity in dynamic optimization of 3G cellular networks," in *Proc. VTC—Fall*, Orlando, FL, USA, Oct. 4–9, 2003, pp. 927–932.

[5] W. Kuo, Y. Tung, and S. Fang, "A node management scheme for R2V connections in RSU-supported Vehicular ad-hoc networks," in *Proc. ICNC*, San Diego, CA, USA, Jan. 28–31, 2013, pp. 768–772.

[6] D. Huang, T. Xing, and H. Wu, "Mobile cloud computing service models: A user-centric approach," *IEEE Netw.*, vol. 27, no. 5, pp. 6–11, Sep./Oct. 2013.

[7] N. Fernando, S. W. Loke, and W. Rahayu, "Mobile cloud computing: A survey," *Future Gener. Comput. Syst.*, vol. 29, no. 1, pp. 84–106, Jan. 2013.

[8] A. Tuli, N. Hasteer, M. Sharma, and A. Bansal, "Exploring challenges in mobile cloud computing: An overview," in *Proc. 4th Int. Conf. Next Gener. Information Tech. Summit*, Noida, India, Sep. 26–27, 2013, pp. 496–501.

[9] J. Sousanis, "World vehicle population tops 1 billion units," in WardsAuto.com. Web Portal, Aug. 2011. [Online]. Available: http://wardsauto.com/ar/world-vehicle_population_110815

[10] F. Bonomi, "Connected vehicles, the Internet of Things, and fog computing," in *Proc. VANET*, Las Vegas, CA, USA, Sep. 23, 2011, pp. 13–15.

[11] F. Bonomi, R. Milito, J. Zhu, and S. Addepalli, "Fog computing and its role in the Internet of Things," in *Proc. MCC*, Helsinki, Finland, Aug. 17, 2012, pp. 13–16.

[12] "Fog computing," Ecosyst., Archit. Appl., Cisco, San Francisco, CA, USA, Cisco RFP-2013-078.

[13] I. Stojmenovic and S. Wen, "The fog computing paradigm: Scenarios and security issues," in *Proc. FedCSIS*, Warsaw, Poland, Sep. 7–10, 2014, pp. 1–8.

[14] T. H. Luan, L. Gao, Z. Li, Y. Xiang, and L. Sun, "Fog computing: Focusing on mobile users at the edge," arXiv preprint arXiv:1502.01815, 2015.

[15] N. Liu, M. Liu, W. Lou, G. Chen, and J. Cao, "PVA in VANETs: Stopped cars are not silent," in *Proc. INFOCOM*, Shanghai, China, Apr. 10–15, 2011, pp. 431–435.

[16] F. Malandrino, C. Casetti, C.-F. Chiasserini, C. Sommer, and F. Dressler, "The role of parked cars in content downloading for vehicular networks," *IEEE Trans. Veh. Technol.*, vol. 63, no. 9, pp. 4606–4617, Nov. 2014.

[17] M. Aazam and E. N. Huh, "Fog computing and smart gateway based communication for cloud of things," in *Proc. IEEE Conf. FiCloud*, Aug. 2014, pp. 464–470.

[18] M. Aazam and E. N. Huh, "E-HAMC: Leveraging Fog computing for emergency alert service," in *Proc. IEEE Conf. PerCom Workshops*, Mar. 2015, pp. 518–523.

[19] M. Aazam and E. N. Huh, "Dynamic resource provisioning through Fog micro datacenter," in *Proc. IEEE Conf. PerCom Workshops*, Mar. 2015, pp. 105–110.

[20] M. Aazam, P. P. Hung, and E. N. Huh, "Smart gateway based communication for cloud of things," in *Proc. IEEE Conf. ISSNIP*, Apr. 2014, pp. 1–6.

[21] S. Olariu, M. Eltoweissy, and M. Younis, "Towards autonomous vehicular clouds," *ICST Trans. Mobile Commun. Appl.*, vol. 11, no. 7–9, pp. 1–11, 2011.

[22] S. Olariu, I. Khalil, and M. Abuelela, "Taking VANET to the clouds," *Int. J. Pervasive Comput. Commun.*, vol. 7, no. 1, pp. 7–21, 2011.

[23] M. Whaiduzzaman, M. Sookhak, A. Gani, and R. Buyya, "A survey on vehicular cloud computing," *J. Netw. Comput. Appl.*, vol. 40, pp. 325–344, 2014.

[24] T. S. Abraham and K. Narayanan, "Cooperative communication for vehicular networks," in *Proc. ICACCCT*, Ramanathapuram, India, May 8–10, 2014, pp. 1163–1167.

[25] M. Shiraz, A. Gani, R. H. Khokhar, and R. Buyya, "A review on distributed application processing frameworks in smart mobile devices for mobile cloud computing," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 3, pp. 1294–1313, 3rd Quart. 2013.

[26] H. Zhu *et al.*, "Impact of traffic influxes: Revealing exponential intercontact time in urban VANETs," *IEEE Trans. Parallel Distrib. Syst.*, vol. 22, no. 8, pp. 1258–1266, Aug. 2011.

[27] M. Li, H. Zhu, Y. Zhu, and L. M. Ni, "ANTS: Efficient vehicle locating based on ant search in Shanghai Grid," *IEEE Trans. Veh. Technol.*, vol. 58, no. 8, pp. 4088–4097, Oct. 2009.

[28] Y. Li, D. Jin, P. Hui, Z. Wang, and S. Chen, "Limits of predictability for large-scale urban vehicular mobility," *IEEE Trans. Intell. Transp. Syst.*, vol. 15, no. 6, pp. 2671–2682, Dec. 2014.

[29] X. Hou, Y. Li, D. Jin, D. O. Wu, and S. Chen, "Modeling the impact of mobility on the connectivity of vehicular networks in large-scale urban environment," *IEEE Trans. Veh. Technol.*, vol. 65, no. 4, pp. 2753–2758, Apr. 2016.

[30] C. Wang *et al.*, "JamCloud: Turning traffic jams into computation opportunities," *IEEE Trans. Mobile Comput.*, to be published.

[31] W. Li, "3m vehicles is good and bad news," *China Daily*, Beijing, China, May 28, 2007.

[32] B. Hayes, "Cloud computing," *Commun. ACM*, vol. 51, no. 7, pp. 9–11, Jul. 2008.

[33] J. N. Hoover and R. Martin, "Demystifying the cloud," *Inf. Week Res. Rep.*, pp. 30–37, Jun. 2008.

[34] L. Badger, T. Grance, R. Patt-Corner, and J. Voas, "Draft cloud computing synopsis and recommendations," *NIST Special Pub.*, vol. 800, p. 84, 2011.

[35] S. Arif *et al.*, "Datacenter at the airport: Reasoning about time-dependent parking lot occupancy," *IEEE Trans. Parallel Distrib. Syst.*, vol. 23, no. 11, pp. 2067–2080, Nov. 2012.

[36] L. Gu, D. Zeng, S. Guo, and B. Ye, "Leverage parking cars in a two-tier data center," in *Proc. WCNC*, Shanghai, China, Apr. 7–10, 2013, pp. 4665–4670.

[37] C. Morency and M. Trepanier, "Characterizing parking spaces using travel survey data," CIRRELT, Montreal, QC, Canada, RRELT-2008-15, p. 24, May 2008.

[38] D. Naboulsi and M. Fiore, "On the instantaneous topology of a large-scale urban vehicular network: The Cologne case," in *Proc. ACM MobiHoc*, Bangalore, India, Jul. 29–Aug. 1, 2013, pp. 167–176.

[39] P. E. Luo, H. Y. Huang, and M. L. Li, "Characteristics of trace data for a large scale *ad hoc* network—Shanghai urban vehicular network," in *Proc. IET CCWMSN*, Shanghai, China, Dec. 12–14, 2007, pp. 742–745.

[40] W. Viriyasitavat, O. K. Tonguz, and F. Bai, "Network connectivity of VANETs in urban areas," in *Proc. IEEE SECON*, Rome, Italy, Jun. 22–26, 2009, pp. 1–9.

[41] L. Buttyan and J.-P. Hubaux, "Enforcing service availability in mobile ad-hoc WANs," in *Proc. MobiHOC*, Boston, MA, USA, Aug. 11, 2000, pp. 87–96.

[42] S. Zhong, J. Chen, and Y. R. Yang, "Sprite: A simple, cheat-proof, credit-based system for mobile *ad hoc* networks," in *Proc. INFOCOM*, San Francisco, CA, USA, Mar. 30–Apr. 3, 2003, pp. 1987–1997.

[43] K. Balakrishnan, J. Deng, and P. K. Varshney, "TWOACK: Preventing selfishness in mobile *ad hoc* networks," in *Proc. WCNC*, New Orleans, LA, USA, Mar. 13–17, 2005, pp. 2137–2142.

[44] P. Kleberger, T. Olovsson, and E. Jonsson, "Security aspects of the in-vehicle network in the connected car," in *Proc. IEEE Intell. Veh. Symp.*, Baden-Baden, Germany, Jun. 5–9, 2011, pp. 528–533.

[45] A. Tootoonchian, K. K. Gollu, S. Saroiu, Y. Ganjali, and A. Wolman, "Lockr: Social access control for web 2.0," in *Proc. 1st Workshop Online Soc. Netw.*, Seattle, WA, USA, Aug. 17–22, 2008, pp. 43–48.

[46] T. Anantvalee and J. Wu, "A survey on intrusion detection in mobile *ad hoc* networks," in *Wireless Network Security*, Y. Xiao, X. Shen, and D.-Z. Du, Eds. New York, NY, USA: Springer-Verlag, 2007, pp. 159–180.

[47] D. Djenouri, L. Khelladi, and A. N. Badache, "A survey of security issues in mobile *ad hoc* networks," *IEEE Commun. Surveys Tuts.*, vol. 7, no. 4, pp. 2–28, 4th Quart. 2005.

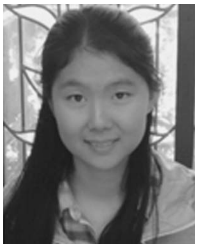
[48] X. Lin, X. Sun, P.-H. Ho, and X. Shen, "GSIS: A secure and privacy-preserving protocol for vehicular communications," *IEEE Trans. Veh. Technol.*, vol. 56, no. 6, pp. 3442–3456, Nov. 2007.

[49] M. Eltoweissy, S. Olariu, and M. Younis, "Towards autonomous vehicular clouds," in *Ad Hoc Networks*. Berlin: Springer-Verlag, 2010, pp. 1–16.

[50] B. Shen and X. Wang, "Research on data mining models for the Internet of Things," in *Proc. IASP*, Xiamen, China, Apr. 12–14, 2010, pp. 127–132.

[51] K. K. Lee, Y. T. Lee, and M. Xie, "Designing a human vehicle interface for an intelligent community vehicle," in *Proc. IEEE/IEEJ/JSAI Int. Conf. Intell. Transp. Syst.*, Tokyo, Japan, Oct. 5–8, 1999, pp. 740–745.

[52] X. Hu, T. H. S. Chu, H. C. B. Chan, and V. C. M. Leung, "Vita: A crowdsensing-oriented mobile cyber-physical system," *IEEE Trans. Emerging Topics Comput.*, vol. 1, no. 1, pp. 148–165, Jun. 2013.



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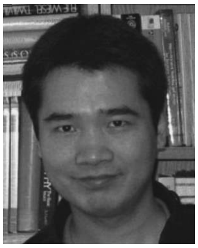

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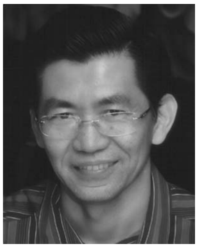

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