Vehicular Cloud Computing: A Survey

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***Abstract*—With the proliferation of automobile industry, vehicles are augmented with various forms of increasingly powerful computation, communication, storage and sensing resources. A vehicle therefore can be regarded as "computer-on-wheels". With such rich resources, it is of great significance to efficiently utilize these resources. This puts forward the vision of vehicular cloud computing. In this paper, we provide an extensive survey of current vehicular cloud computing research and highlight several key issues of vehicular cloud such as architecture, inherent features, service taxonomy and potential applications.**

I. Introduction

Thanks to the development of computation and communication technologies, the automotive industry is undergoing a revolutionary change. Nowadays, more and more "smart cars" are introduced to drivers for daily use. A typical smart car today is likely to be enhanced with following forms of devices: an on-board computer, a large storage device, a GPS device, a radio transceiver, a short-range rear collision radar device, even various sensing devices which can sense the road and environment conditions to ensure the driving safety. Therefore, it is natural to regard a vehicle as a "computer-on-wheels". Meanwhile, cloud computing has been attracting individual users and organizations to move their data and services from local to remote cloud servers. Many enterprizes, such as Amazon, Google, Microsoft and Dropbox, have also released their cloud infrastructure services and have attracted millions of users. It is a clear trend that cloud is becoming a promising and pervasive service to replace traditional local systems.

As a result, it could be envisioned that the future automobiles will heavily rely on the Internet cloud. However, with the increasingly powerful computation ability on vehicles, pioneering researchers have advocated to take them into the concept of cloud computing as service providers, rather than pure service consumers, so as to fully explore the potential of vehicular resources. We believe that, given the right incentives, the owners of vehicles shall be willing to share their resources or data to constitute a participatory cloud computing platform, just as the Peer-to-Peer (P2P) networks widely used today. For example, Liu et al. [1], [2] explore the communication resources of roadside parking cars to promote the network connectivity so as to help content distribution in Vehicular Ad hoc Networks (VANETs). Eckhoff et al. [3] utilize the sensing capabilities of parked cars such that cars not in line-of-sight can sense each other with an improved driving safety. We even already see a successful commercial case built in this paradigm. A crowdsourcing traffic-mapping and navigation company WAZE [4], which was acquired by Google with 1.3 billion dollars recently, builds their community-edited map services upon the volunteering posting about the real-time traffic and road information from drivers. Actually, far beyond the communication resources, more others like computation, storage, sensing, etc., are expected to be explored.

Recently, Olariu et al. [5]–[7] advocate the concept of *vehicular cloud*, which coordinates the computing, sensing, communication and storage resources to provide services to authorized users. Different from conventional Internet cloud with dedicatedly installed hardware, vehicular cloud leverages the already available resources on vehicles. According to a recent statistics, there have been more than one billion cars around the world, and most vehicles spend many hours per day in a parking garage, parking lot, or driveway, where their computing and storage resources are usually untapped. The vehicular cloud consisting of cooperative vehicles that collaborate with each other to share various resources including communication, computation, sensing and storage in order to empower existing cloud computing infrastructure or individually provide local vehicular cloud services. If all these resources are well exploited, vehicular cloud could be a promising auxiliary, or even an alternative in many cases, to conventional cloud platform [1]–[3], [8], [9].

In this paper, we make an introduction to vehicular cloud and a survey to summarize current related studies in vehicular cloud. The rest of this paper is structured as follows. Section II introduces the general vehicular cloud architecture and lists several features of vehicular cloud. Section III presents some key enabling technologies. The vehicular cloud service taxonomy and potential applications are presented in Section IV. Finally, Section V concludes our work.

II. Two-tier Vehicular Cloud Architecture

A. Architecture

In vehicular cloud, vehicles can be either the service providers to enrich exiting cloud services by providing various on-road information (e.g., traffic condition like Pics-on-Wheels proposed by [10]) or be the service consumers to enjoy existing centralized Internet cloud services. In this case, vehicles communicate with the data centers where the wanted cloud services locate using vehicle-to-infrastructure (V2I) communications, e.g., LTE, WiMax. In addition, vehicles can also work in a autonomous way solely relying on the vehicle-to-vehicle (V2V) communication capabilities. Accordingly, we

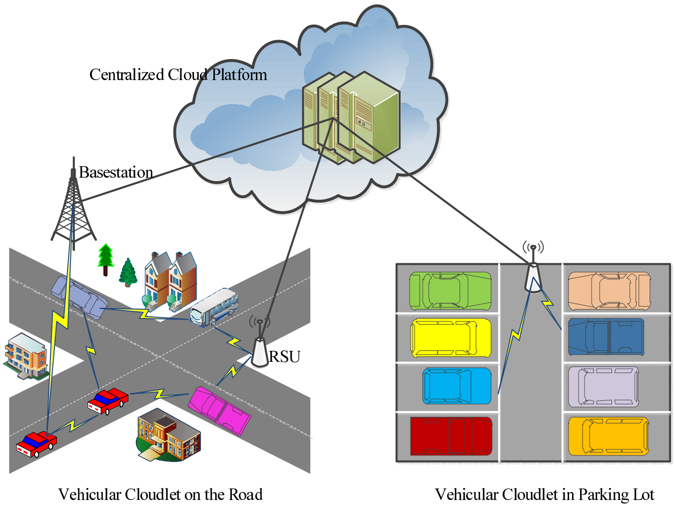

Fig. 1. Two-tier Vehicular Cloud Architecture

think that vehicular cloud can be described by a loose two-tier architecture. The first-tier is the Internet cloud computing platform (i.e., data centers) while the second-tier consists of many *vehicular cloudlet*. A user can acquire cloud services from either the first-tier data center or the second-tier vehicular cloudlet. An architecture example is illustrated in Fig. 1.

A vehicular cloudlet is a group of vehicles and can share resources and information with each other via V2V communication or indirectly via V2I communication. According to the mobility of vehicles, two different vehicular cloudlets can be defined, i.e., mobile and static, which consist of vehicles in movement and statically parked ones, respectively. Different types of vehicular cloudlet are suitable for different vehicular cloud services. For example, the mobility of vehicles in mobile vehicular cloudlet makes them ideal for data ferrying service. Static vehicular cloudlet is with comparatively stable resources and therefore is more suitable for computation or storage resource provision. For example, a recent study performed on teens shopping at malls in 2008 shows that 95% of shoppers spent more than one hour at the mall while 68% of them spent more than two hours. The under-utilized resources in these parked vehicles are ideal for building static cloudlet to provide temporary storage or computation services.

B. Features

Compared to existing Internet cloud computing, vehicular cloud has several distinguishing features as follows.

1) Instability: One of the key features of vehicular cloud is the volatile resource availability since there is no guarantee on the vehicles behaviors, or the resource availability. For example, a car may unexpectedly get into or leave out a parking lot. Actually, this is also the major difference between vehicular cloud and Internet cloud. Vehicular cloud must be built to withstand such inherent instability.

2) Heterogeneity: Different vehicles manufactured by different companies are usually with different platforms and provide resources in heterogeneous types and capabilities. This feature challenges the interoperation and coordination of these heterogeneous resources.

3) Resilience: Note that each vehicular cloudlet can work on two different communication modes, i.e., V2V and V2I. This implies that even without Internet connection, some vehicular cloud services are still available. A vehicular cloudlet can be regarded as a completed systematic system.

4) Selflessness: Unlike conventional cloud service paradigm where there are distinct service providers and service users, a vehicle's role in vehicular cloud is ambiguous as it could be either a service provider or a service consumer. A vehicular cloudlet can be regarded as a cooperative community consisting of many selfless vehicles. Any vehicle in this community willingly contributes its resources and enjoys the services from the community meanwhile.

5) Greenness: It can be anticipated that a large number of installed but under-utilized on-board resources on vehicles can be rented out to needed user to improve their efficiency and reduce unnecessary resource waste. This enables the realization of green computing by leveraging excessive resources on vehicles such that unnecessary hardware deployment and investment are avoided.

III. Enabling Technologies

Besides the development of cloud computing and automotive, there are also several other enabling technologies that put forward the concept of vehicular cloud.

A. Virtualization Technology

Automobiles produced by different manufacturers may have different computing and communication hardwares. To enable cooperative vehicular cloud, it is essential to abstract them into a uniform format such that they are transparent to application developers. Virtualization technology is able to abstract these heterogenous resources into a uniform one, i.e., virtual machine, which then can be used freely without concerning the underlying hardware details. On the other hand, it is risky to absolutely open a vehicle's resource to any others. Fortunately, virtualization technology provides trusted computing capability by running isolated multiple virtual machines under hypervisor.

B. Access Technologies

Hybrid Access Network Technologies including Wifi, 4G as well as V2V communications, provide vehicular cloud a diversity of access methods with different communication capabilities. Two decades of study on vehicular networks has provided us with rich experience and solid technical reserves. IEEE 802.11p is an approved amendment to the IEEE 802.11 standard to add wireless access in vehicular environments (WAVE) [11]. It defines enhancements to 802.11 (the basis of products marketed as Wi-Fi) required to support Intelligent Transportation Systems (ITS) applications. This includes data exchange between high-speed vehicles and between the vehicles and the roadside infrastructure in the licensed ITS band of 5.9 GHz (5.85-5.925 GHz). IEEE 1609 is a higher layer standard based on the IEEE 802.11p.

IV. Vehicular Service Taxonomy and Applications

A. Service Taxonomy

We divide the vehicular cloud services into four types according to the resource mainly utilized, i.e., "Network-as-a-Service" (NaaS), "Collaboration-as-a-Service", "Storage-as-a-Service" (StaaS), and "Sensing-as-a-Service" (SeaaS).

1) Network-as-a-Service: NaaS mainly exploits the communicability of vehicles. For example, previous research has considered the content dissemination for delay-tolerant applications with the cooperation of communication nodes in a "store-and-forward" way. Much pioneering work has been done to efficiently utilize communication resources on vehicles. Malandrino et al. [12] address the cooperative content downloading in vehicular networks. Acer et al. [13] study the timely data delivery issue by exploring the opportunistic contacts between WiFi-enabled buses using two different routing policies.

Besides exploring the vehicles' mobilities, many studies also suggest that the parked vehicles can be also utilized. Liu et al. [1] invent PVA (parked vehicle assistance) to promote the network connectivity by incorporating parked vehicles as static nodes into traditional vehicular networks. Later on, they introduce the idea of ParkCast [2] that leverages roadside parking to distribute contents in urban VANETs. Malandrino et al. [8] exploit parked vehicles to extend the service coverage of RSUs (road-side units) for content downloading. Crepaldi et al. [9] propose LoadingZones that leverages parked cars to behave as relays and to provide opportunistic access to non-time-sensitive applications for moving vehicles.

2) Storage-as-a-Service: The recent fast development in storage technologies makes the storage become gradually inexpensive. Nowadays, it is common to have a handhold device attached with hundred of Gigabytes, or even multiple Terabytes storage. Even higher storage capacity can be expected in future vehicles. However, eventually these resource are usually under-utilized, especially the one in a parked vehicle. Therefore, it is also significant to explore the storage resources in vehicular cloud by providing storage-as-a-service. Arif et al. [6] develop a framework for analyzing the behaviors in a long-term parking lot of an international airport under an infinite parking capacity assumption. They also mention the idea of using the parking lot as a data center but they do not specify how to use the storage resources. In our recent work [14], we trade the vehicular storage resources in parking lots for communication cost and propose a two-tier data center system that consists of both stable first-tier and unstable second-tier storage resources to lower the total data access cost.

3) Sensing-as-a-Service: To guarantee the driving safety, many sensors, for either the vehicle itself or the ambient environment, have been built into vehicles. One distinguishing feature of sensors on vehicles is that they can take advantage of vehicle mobility to improve the sensing coverage. Furthermore, by aggregating the sensing data from geographically distributed vehicles, we may acquire sensing data far beyond the scale of what was possible before. We even do not have to invest a lot of money on sensor network deployment. The cost-effective sensing-as-a-service thus becomes a charming option to urban sensing and attracts much attention in the literature. Yu et al. [15] investigate a cooperative data sensing and compression approach for urban environment surveillance in vehicle sensor networks (VSNs). Eckhoff et al. [3] propose the utilization of parked cars to sense the vehicles that are not in line-of-sight to improve driving safety. Liu et al. [16] develop a system called POVA for traffic light sensing in large-scale urban areas. Recently, Ma et al. [17] propose a user-driven Cloud Transportation System (CTS) which employs a scheme of user-driven crowdsourcing to collect user data for traffic model construction and congestion prediction including data collection, filtering, modeling, intelligent computation and publish. Yang et al. [18] proposes two incentive mechanisms for platform centric model and user-centric model, respectively, to recruit smartphone users to provide sensing services. Palazzi et al. [19] present a solution leveraging the time interval during which the query is active for gathering data from a certain geographic area within a specified delay bound.

4) Computation-as-a-Service: The computers-on-wheels are becoming increasingly powerful over time. It could even be equivalent to a desktop computer. The vehicles therefore can be treated as attractive computation resource provider candidates. Consider a large parking lot in airport parked with hundreds of vehicles. If all these excessive computation resources are efficiently utilized, we can build a vehicular data center with huge computing power. This realizes the vision of computation-as-a-service. Since we are still at the very beginning of vehicular cloud computing, there is not much related work directly talking about exploring the computation resource on vehicles. However, some work has started to figure out how to utilize the opportunistically available computation resources. Shi et al. [20] investigate the computing in cirrus clouds where the connectivity between the service providers and users is intermittent.

B. Potential Applications

1) Autonomous Driving Management: Autonomous driving requires a great quantity of information and intensive computation. Basically, we may outsourcing all the computation tasks to the distant cloud platform [17]. With the introduction of vehicular cloud, many tasks actually can be handled by the proximate vehicular cloudlet, without resorting to Internet cloud. In this case, vehicles perform as both information collector and processing units. This not only saves much communication bandwidth but also makes the autonomous driving management resilient to the Internet availability. Some prototypes using robots already have been developed by researchers. Hu et al. [22] propose a cloud robotic architecture by extending the computation and information sharing capabilities of networked robotics. Kumar et al. [23], [25] present Carcel, a cloud-assisted system for autonomous driving. Carcel utilizes the Internet cloud to analyze the sensor data from both vehicles and the roadside infrastructure so as to assist

TABLE I
OVERVIEW OF SOME REPRESENTATIVE VEHICULAR CLOUD PROTOTYPES AND PROPOSALS

	V2I	V2V	Computation	Storage	Sensor	Internet Cloud Independency
Smart Traffic Cloud [21]	√	√	√			√
Cloud Transportation System [17]	√	√				√
Cloud Robotics [22]	√	√		√		√
Datacenter At the Airport [6]	√		√	√		√
Carcel [23]	√	√		√	√	√
CRoWN [24]	√			√		√
CarSpeak [25]	√	√	√		√	√
MobEyes [26]		√		√	√	
VAM [27]	√	√	√		√	√
PVA [1]		√		√		
LoadingZones [9]		√		√		
POVA [16]	√				√	√
Sharing at Roadside [2]		√			√	
Pics-on-wheels [10]	√	√		√		√

autonomous driving.

2) Intermediate Cache: The recent rapid development of smart devices like smartphone has posed a heavy burden on existing network infrastructure. Researchers have tried various means to deal with the insatiable data access needs, e.g., dense base-station deployment, wider bandwidth allocation, new physical techniques, etc. It is suggested that an efficient way is to trade the intermediate cache to the communication cost by deploying many distributed caches. For example, Golrezaei et al. [28] propose a network architecture called FemtoCaching for video content delivery in the next generation wireless network to reduce the backhaul communication by exploring content reuse. Other than requiring dedicatedly deployed distributed caches, we may also explore the underutilized storage on vehicles in parking lots to play the role as intermediate caches. Arif et al. [6] first suggest the significance of such means by exploring the storage resources in the airport parking lot. Later, Gu et al. [14] propose a two-tier data center architecture that exploring the vehicular storage resources in parking lots. Their analysis study shows that substantial communication cost can be reduced by such means.

3) Participatory sensing: All the vehicles, no matter in mobility or in parking, can be utilized to conduct participatory sensing. An important application of vehicular participatory sensing is to construct augmented maps of different phenomena (e.g., traffic condition, temperature, road condition, etc.). For example, Leontiadis et al. [29] apply the crowd-sourcing concept and propose an opportunistic traffic management system using the information reported from all the vehicles. Liu et al. [16] develop a system called POVA that utilizes the traffic light statuses report from vehicles for traffic management. Wang et al. [21] discuss a smart traffic cloud which incorporate the crowd-sourcing data into cloud platform for traffic management (e.g., real-time traffic condition map as developed by the authors). Besides supporting the vehicle community, participatory sensing built on cooperative vehicles is also be able to benefit the users outside the vehicle community. Lee et al. [26] propose MobEyes which exploits vehicle mobility to opportunistically diffuse summaries about sensing data to support proactive urban surveillance.

4) Personal Cloudlet: To deal with the delays, jitter, congestion and failures in Internet connection, it is suggested that proximate cloud service, i.e., “Personal Cloudlet”, can be explored by leveraging the abundance in memory capacity of mobile devices, e.g., smartphones, to migrate the latency and energy issues when accessing cloud services [30]. Vehicles are inherently with powerful communication, computation and storage capacities and therefore are quite fit for hosting cloud services locally. Personal cloudlets built in a vehicle could drastically improve the user experience. Since all or portions of the information resides on the vehicle, users can instantly get access to the information they are looking for during driving. This can also mitigate pressure on cellular networks.

5) Content Sharing: Content sharing applications shall utilize both the storage and communication capabilities of vehicles to build a cooperative community. Without requirement of Internet, both the request and content transmissions are conducted using V2V communications. For example, Amadeo et al. [24] design CRoWN, a framework for content-centric content sharing among vehicles using V2V communications. Yu et al. [31] recently also discuss a content sharing protocol in vehicular cloud where bloom filter is used for the proactive discovery of shared contents to tackle the mobility challenges.

6) Traffic Management: Vehicular cloud offers the ability to control the signal system municipally by making use of vehicle sensing data to make decisions on traffic flow scheduling. One simple solution is aggregate all the sensing data in the Internet cloud, which then analyze these data to optimize the traffic flows. For example, Wang et al. [21] discuss a smart traffic cloud, a software infrastructure to outsource traffic sensing data to build an interactive map with real-time traffic conditions. Besides relying on the Internet cloud, we may also resort to local processing resources on the vehicular cloud nearby to provide on-demand solutions. This is quite significant to many emergency events, e.g., evacuation after a disaster, where Internet is downdown and any pre-assigned assets fail to work. Gupte et al. [27] present an approach called VAM for autonomous and adaptive traffic management through vehicular cloud. By allowing data exchange between vehicles about route choices, congestions and traffic alerts, a vehicle makes a decision on the best course of action.

Table I summarize some representative vehicular cloud services prototypes (some of them are built using robotics) or proposals according to the communication mode, resources utilized and Internet cloud dependency. We can see a clear trend that most vehicular cloud services are expected to be provided in an autonomous manner without relying on the Internet cloud and researchers have tried to explore any available resources on vehicles.

V. Conclusion

The recent fast development in automobiles brings up the vision of vehicular cloud computing, which is expected to introduce much benefit to our society. In this paper, we make an introduction of vehicular cloud and present a two-tier architecture. According to the resources used in different services, we also classify the services into four categories. Some key enabling technologies are also introduced. Finally, we summarize some potential applications of vehicular cloud and classify them into different taxonomies. Although still in its infancy, we believe that vehicular cloud computing is expected to become the dominant model for mobile applications and be an essential part of our daily life in the future.

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