Toward Cloud-based Vehicular Networks with Efficient Resource Management

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Abstract—In the era of Internet of Things, all components in intelligent transportation systems will be connected to improve transport safety, relieve traffic congestion, reduce air pollution and enhance the comfort of driving. The vision of all vehicles connected poses a significant challenge to the collection and storage of large amounts of traffic-related data. In this article, we propose to integrate cloud computing into vehicular networks such that the vehicles can share computation resources, storage resources and bandwidth resources. The proposed architecture includes a vehicular cloud, a roadside cloud, and a central cloud. Then, we study cloud resource allocation and virtual machine migration for effective resource management in this cloud-based vehicular network. A game-theoretical approach is presented to optimally allocate cloud resources. Virtual machine migration due to vehicle mobility is solved based on a resource reservation scheme.

Index Terms—cloud computing, mobile cloud, vehicular networks, Internet of vehicles, resource management, cloudlet, virtual machine migration.

I. Introduction

Vehicular networks are in the progress of merging with the Internet to constitute a fundamental information platform which is an indispensable part of Intelligent Transport System (ITS) [1]. This will eventually evolve into all vehicles connected in the era of Internet of Things (IoT) [2]. By supporting traffic-related data gathering and processing, vehicular networks is able to notably improve transport safety, relieve traffic congestion, reduce air pollution, and enhance driving comfortability [3]. It has been reported that, in Western Europe, 25% of the deaths due to car accidents could be reduced by deploying safety warning systems at the highway intersections [4]. Another example is that real-time traffic information could be collected and transmitted to data center for processing, and in return, information could be broadcasted to the drivers for route planning. City traffic congestion is alleviated and traveling time is reduced, leading to greener cities.

A variety of information technologies have been developed for intelligent vehicles, roads, and traffic infrastructures such that all vehicles are connected. Smart sensors and actuators are deployed in vehicles and roadside infrastructures for data acquisition and decision. Advanced communication technologies

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are used to interconnect vehicles and roadside infrastructures, and eventually access to Internet. For instance, Dedicated Short Range Communications (DSRC) is specifically designed for Vehicle-to-Vehicle (V2V) and Vehicle-to-Roadside (V2R) communications. The IEEE 802.11p, called Wireless Access in Vehicular Environments (WAVE) [5], is currently a popular standard for DSRC. Besides, the Long-Term Evolution (LTE), LTE-Advanced and Cognitive Radio (CR) [6][7] are all fairly competitive technologies for vehicular networking [8][9].

Despite of the well-developed information technologies, there is a significant challenge that hinders the rapid development of vehicular networks. Vehicles are normally constrained by resources, including computation, storage, and radio spectrum bandwidth. Due to the requirements of smallsize and low-cost hardware systems, a single vehicle has limited computation and storage resources, which may result in low data processing capability. On the other hand, many emerging applications demands complex computation and large storage, including in-vehicle multimedia entertainment, vehicular social networking, and location-based services. It becomes increasingly difficult for an individual vehicle to efficiently support these applications. A very promising solution is to share the computation and storage resources among all vehicles or physically nearby vehicles. This motivates us to study the new paradigm of cloud-based vehicular networks.

Recently, a few research works are reported to study the combination of cloud computing and vehicular networks. In [10], the concept of Autonomous Vehicular Clouds (AVC) is proposed to exploit the under-utilized resources in vehicular ad hoc networks (VANETs). A Platform as a Service (PaaS) model is designed in [11] to support cloud services for mobile vehicles. The work in [12] proposes architectures of Vehicular Clouds (VC), Vehicles using Clouds (VuC) and Hybrid Clouds (HC). Vehicles play as cloud service providers and clients respectively in VC and VuC, and as hybrids in HC.

In this article, we propose a hierarchical cloud architecture for vehicular networks. Our work is different from previous researches in three main aspects. First, we aim to create a pervasive cloud environment for mobile vehicles by integrating redundant physical resources in ITS infrastructures, including data center, roadside units and vehicles. The aggregation of these sporadic physical resources potentially compose massive and powerful cloud resources for vehicles. Second, we propose a three-layered architecture to organize the cloud resources. The layered structure allows vehicles to select their cloud services resiliently. Central clouds have sufficient cloud resources but large end-to-end communications delay. On the

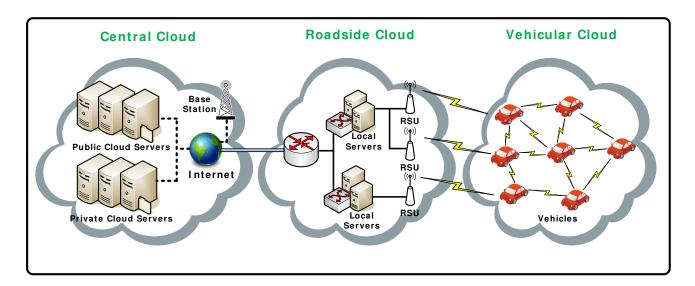


Fig. 1. Proposed cloud-based vehicular networks architecture

contrary, roadside cloud and vehicular cloud have limited cloud resources but satisfying communications quality. Third, we emphasize the efficiency, continuity and reliability of cloud services for mobile vehicles. As a consequence, efficient cloud resources management strategies are elaborately proposed. Countermeasures to deal with vehicle mobility are devised.

The remainder of the article is organized as follows. Section II illustrates the proposed architecture that includes vehicular cloud, roadside cloud, and central cloud. Cloud deployment strategies are discussed for these three layers. Section III envisions several promising applications for different resources sharing in cloud-based vehicular networks. In Section IV, we focus on cloud resource allocation problems and a gametheoretical approach is presented to optimally allocate cloud resources. In Section V, we study virtual machine migration due to vehicle mobility. Illustrative results indicate resource allocation optimization and virtual machine migration performance. The conclusion is presented in Section VI.

II. PROPOSED CLOUD-BASED VEHICULAR NETWORKS ARCHITECTURE

Fig.1 shows the proposed cloud architecture for vehicular networks. It is a hierarchical architecture that consists of three interacting layers: vehicular cloud, roadside cloud, and central cloud. Vehicles are mobile nodes that exploit cloud resources and services.

- Vehicular Cloud: a local cloud established among a group
 of cooperative vehicles. An inter-vehicle network, i.e., a
 vehicular ad hoc network (VANET), is formed by V2V
 communications. The vehicles in a group are viewed
 as mobile cloud sites and they cooperatively create a
 vehicular cloud.
- Roadside Cloud: a local cloud established among a set
 of adjacent roadside units. In a roadside cloud, there are
 dedicated local cloud servers attached to Roadside Units
 (RSUs). A vehicle will access a roadside cloud by V2R
 communications.

• Central Cloud: a cloud established among a group of dedicated servers in the Internet. A vehicle will access a central cloud by V2R or cellular communications.

This architecture has several essential advantages. First, the architecture fully utilizes the physical resources in an entire network. From vehicles to roadside infrastructures and data center, the computation and storage resources are all merged into the cloud. All clouds are accessible to all vehicles. Second, the hierarchical nature of the architecture allows vehicles using different communication technologies to access to different layers of clouds accordingly. Hence, the architecture is flexible and compatible with heterogeneous wireless communication technologies, e.g., DSRC, LTE/LTE-Advanced and CR technologies. Third, the vehicular clouds and the roadside clouds are small-scale localized clouds. Such distributed clouds can be rapidly deployed and provide services quickly.

A. Vehicular Cloud

In a vehicular cloud, a group of vehicles share their computation resources, storage resources, and spectrum resources. Each vehicle can access the cloud and utilize services for its own purpose. Through the cooperation in the group, the physical resources of vehicles are dynamically scheduled on demand. The overall resource utilization is significantly enhanced. Compared to an individual vehicle, a vehicular cloud has much more resources.

Due to vehicle mobility, vehicular cloud implementation is very different from a cloud in a traditional computer network. We propose two customization strategies for vehicular clouds: Generalized Vehicular Cloud Customization (GVCC) and Specified Vehicular Cloud Customization (SVCC).

In GVCC, a *cloud controller* is introduced in a vehicular cloud. A cloud controller is responsible for the creation, maintenance, and deletion of a vehicular cloud. All vehicles will virtualize their physical resources and register the virtual resources in the cloud controller. All virtual resources of the vehicular cloud are scheduled by the cloud controller. If a

vehicle needs some resources of the vehicular cloud, it should apply to the cloud controller. In contrast to GVCC, SVCC has no cloud controller. A vehicle will specify some vehicles as candidate cloud sites, and directly apply for resources from these vehicles. If the application is approved, the corresponding vehicles become cloud sites, which will customize virtual machines (VMs) according to the vehicle demand.

These two strategies, GVCC and SVCC, are quite different. With respect to resource management, GVCC is similar to a conventional cloud deployment strategy in which cloud resources are scheduled by a controller. A vehicle is not aware of the cloud sites where the VMs are built up. The cloud controller should maintain the cloud resources. During a cloud service, if a cloud site is not available due to vehicle mobility, the controller should schedule a new site to replace it. In SVCC, since there is no cloud controller, a vehicle has to select other vehicles as cloud sites and maintain the cloud resources itself. In terms of resource utilization, GVCC is able to globally schedule and allocate all resources of a vehicular cloud. GVCC has higher resource utilization than SVCC. However, the operation of the cloud controller will need extra computation. Therefore, SVCC may be more efficient than GVCC in terms of lower system overhead.

B. Roadside Cloud

A roadside cloud is composed of two main parts: dedicated local servers and roadside units. The dedicated local servers virtualize physical resources and act as a potential cloud site. RSUs provide radio interfaces for vehicles to access the cloud. A roadside cloud is accessible only by the nearby vehicles, i.e., those locate within the radio coverage area of the cloud site's RSU. This fact helps us recall the concept of a cloudlet. A cloudlet is a trusted, resource-rich computer or cluster of computers that is connected to the Internet and is available for use by nearby mobile devices [13]. In this article, we propose the concept of a roadside cloudlet. A roadside cloudlet refers to a small-scale roadside cloud site that offers cloud services to bypassing vehicles. A vehicle can select a nearby roadside cloudlet and customize a transient cloud for use. Here, we call the customized cloud a transient cloud because the cloud can only serve the vehicle for a while. After the vehicle moves out of the radio range of the current serving RSU, the cloud will be deleted and the vehicle will customize a new cloud from the next roadside cloudlet in its moving direction.

When a vehicle customizes a transient cloud from a roadside cloudlet, it is offered by virtual resources in terms of virtual machine (VM). This VM consists of two interacting components: the VM-base in the roadside cloudlet and the VM-overlay in the vehicle. A VM-base is a resource template recording the basic structure of a VM, while a VM-overlay mainly contains the specific resource requirements of the customized VM. Before a cloud service starts, the vehicle will send the VM-overlay to the roadside cloudlet. After combining the VM-overlay with the VM-base, the roadside cloudlet completes the customization of a dedicated VM. During a cloud service, as the vehicle moves along the roadside, it will switch between different RSUs. For the continuity of cloud service, the customized VM should be synchronously transferred between the respective roadside cloudlets. This process is referred to as VM migration. VM migration scenarios will be further elaborated in Section V.

C. Central Cloud

Compared to a vehicular cloud and a roadside cloud, a central cloud has much more resources. The central cloud can be driven by either dedicated servers in vehicular networks data center or servers in the Internet. A central cloud is mainly used for complicated computation, massive data storage, and global decision. There already exist mature open source or commercial software platforms that could be employed for the deployment of a central cloud. Openstack is an open source cloud platform using Infrastructure as a Service (IaaS) model. Other potential commercial platforms are Amazon Web Services, Microsoft Azure and Google App Engine.

III. PROMISING APPLICATIONS OF CLOUD-BASED VEHICULAR NETWORKS

With powerful cloud computing, cloud-based vehicular networks can support many unprecedented applications. In this section, we illustrate potential applications and explain the exploitation of a vehicular cloud, a roadside cloud, and a central cloud to facilitate new applications.

A. Realtime Navigation with Computation Resources Sharing

In a realtime navigation application, the computation resources in the central cloud is utilized for traffic data mining. Vehicles may offer services that use resources that are outside their own computing ability. Different from traditional navigation that can only provide static geographic maps, realtime navigation is able to offer dynamic three-dimensional maps and adaptively optimize routes based on traffic data mining.

In Fig. 2(a), vehicle A is using realtime navigation during its traveling. It will first request cloud service from the central cloud and the roadside cloud. Then, a VM cluster and a VM are established in the central cloud and the roadside cloud, respectively. The VM cluster-A in the central cloud is in charge of traffic data mining and will suggest several routes based on the current traffic conditions. Once a route is selected by A, realtime navigation starts. VM-A in the roadside cloud acts as an agent to push messages to vehicle A, updating the driver with traffic conditions on the road. As vehicle Amoves on, VM-A will migrate to different roadside cloud sites. During the entire travel, VM cluster-A in the central cloud will keep updating the route information based on realtime traffic condition. Once there is an unexpected event, e.g., traffic congestion, VM cluster-A will report the situation timely and compute a new route.

B. Video Surveillance With Storage Resource Sharing

Video surveillance is an important application that utilizes shared storage resources. Currently, many buses in a city have installed High-Definition (HD) camera systems to monitor inbus conditions. A very large-volume hard-drive is needed to

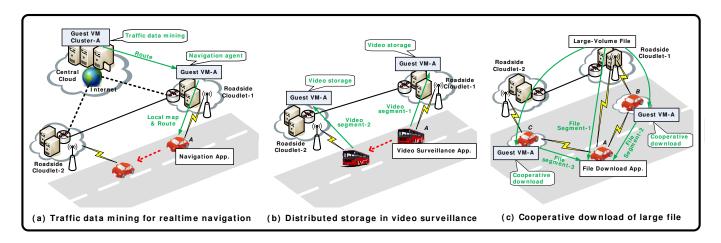


Fig. 2. Applications of cloud-based vehicular networks

TABLE I APPLICATIONS OF CLOUD-BASED VEHICULAR NETWORKS

Potential Applications	Relevant Cloud Assistance			Resource Sharing		
	Central Cloud	Roadside Cloud	Vehicular Cloud	Computation	Storage	Bandwidth
Realtime Traffic Condition Analysis and Broadcast	\checkmark	\checkmark		\checkmark	\checkmark	
Realtime Car Navigation	\checkmark	\checkmark		\checkmark		
Video Surveillance		\checkmark			\checkmark	
LBS Commercial Advertisement		\checkmark	\checkmark		\checkmark	\checkmark
Vehicular Mobile Social Networking	\checkmark		\checkmark	\checkmark		\checkmark
In-Vehicle Multimedia Entertainment		\checkmark	\checkmark	\checkmark		\checkmark
Inter-Vehicle Video and Audio Communications			√			\checkmark
Remote Vehicle Diagnosis		√		√		

store video content for a couple of days. This video storage scheme has several disadvantages. First, to save HD video content for days, the hard-drive should have very large storage, which leads to high cost and big size. Second, video content can only be checked in an off-line manner, the department of transportation is not able to make timely and proper decisions immediately after an accident. In cloud-based vehicular networks, a new distributed storage paradigm can address this problem. The storage capability of in-bus video camera systems is significantly extended.

In Fig. 2(b), bus A exploits the roadside cloud to facilitate storage of in-bus video surveillance content. Specifically, the bus applies for cloud services and receives a VM in the roadside cloud. The video content is uploaded to the guest VM-A in the roadside cloudlet-1 in a realtime manner. When the bus moves along the road and is located in the coverage area of the roadside cloudlet-2, VM-A will be migrated accordingly. As a result, the video content is divided into several segments and separately stored in different roadside cloudlets along the road. The video segments in the roadside cloudlets will be transmitted to a data center on demand. When an accident is reported, department of transportation can request roadside cloudlets to send back video to the data center.

C. Cooperative Download/Upload with Bandwidth Sharing

Cooperative downloading and uploading services are interesting applications that share bandwidth resources. Many

new applications involves large-volume data uploading or downloading. Typical examples include in-vehicle multimedia entertainment, location-based rich-media advertisements, and big-size e-mail services. Due to limited wireless bandwidth and vehicle movement, it is very difficult to download an entire large file from a specific RSU. While the vehicle drives by, there is not enough time to complete the download of large amount of data. Here, we illustrate that the usage of a vehicular cloud will make such applications feasible.

In Fig. 2(c), vehicle A is going to download a large file from the roadside infrastructure. The cooperative downloading has two phases. In the first phase, vehicle A observes neighboring vehicles B and C and then setups a vehicular cloud for cooperative downloading. Then, a guest VM will be constructed in both B and C. The file downloading will be carried out by the vehicular cloud that consists of vehicle A and the two VMs on B and C. Since the file is downloaded by three vehicles in a parallel manner, the total transmission rate becomes much faster. In this way, vehicle A has high possibility to finish downloading before vehicle A moves out of the range of the roadside infrastructure. In the second phase, the VMs in B and C will further cooperatively transmit two separated segments of the file to A. Since only V2V communications is involved, the second phase can be performed without the roadside infrastructure. After that, A will reassemble the file segments into an entire file.

Table I summarizes potential applications in cloud-based

vehicular networks. We also show the relevant cloud resource sharing in each application.

IV. GAME-THEORETICAL APPROACH FOR RESOURCE ALLOCATION

Vehicle and roadside clouds are both resource-intensive components. Resource management is very crucial for these two types of clouds. Resources in vehicle and roadside clouds are represented in form of VMs. In the literature, VM research has been mainly studied in computer networks. In the recent study [14], VM migration is considered for dynamic resource management in cloud environments. In [15], VM replication and scheduling are intelligently combined for VM migration across wide area network environments. However, there are few studies on VM resource management in mobile cloud environments. In [13], cloudlet is discussed and customized in the mobile computing environments.

In this section, we mainly focus on VM resource allocation in vehicular clouds and roadside clouds. In a roadside cloud, there are multiple VMs since a cloud site provides services to several vehicles simultaneously. In this case, the resources in a cloud site should be appropriately allocated. VM resource allocation should consider several aspects. i) Efficiency: VM resource allocation strategy should be efficient such that the limited resources are fully utilized. ii) Quality-of-Service (QoS): the allocated resources to a specific VM should be sufficient for the accomplishment of the VM's tasks to achieve its QoS requirements. iii) Fairness: VMs with the same workload should be offered statistically equal resources. Here, we formulate the competition among the VMs for cloud resources as a non-cooperative game.

A. Game-theoretical Model

Consider a roadside cloudlet with N VMs, i.e., players of the game. The VMs will apply to the cloud site and compete for resources. These VMs are selfish in the sense that they aim to obtain as much resources as possible for their own usage. The cloud will allocate the total available resources to the VMs in proportion to the number of requested resources.

Let C and M represent the total available computation and storage resources of the cloud site, respectively. Let c_i $(0 < c_i \le C)$ and m_i $(0 < m_i \le M)$ denote the number of requested resources from the i-th VM in computation and storage, respectively. Define $c_{-i} = \sum_{n=1, n \neq i}^{N} c_n$ and $m_{-i} =$ $\sum_{n=1,n\neq i}^{N} m_n$. The *i*-th VM will be allocated computation and storage resources $\frac{c_i C}{c_i + c_{-i}}$ and $\frac{m_i M}{m_i + m_{-i}}$, respectively. For the sake of fairness, the cloud site sets up two Virtual Resource Counters (VRCs) for each VM. These two VRCs are used to record the accumulative number of applied resources, one for computation and the other for storage. When a VRC reaches its maximal value, the VM is not allowed to apply for that type of resource. By using VRCs, the total amount of allocated resources are equal for all VMs from a long-term perspective. Let α_i and β_i ($\alpha_i > 0$, $\beta_i > 0$), respectively, denote the predefined resource weights that indicate the importance of computation and storage resources in the workloads of the i-th VM, and let λ_i and γ_i ($\lambda_i > 0$, $\gamma_i > 0$) denote

the pricing factors associated with applied computation and storage resources, respectively, of the *i*-th VM. The utility function, or *payoff*, for the *i*-th VM is given by

$$U(c_{i}, m_{i}) = \frac{\alpha_{i} c_{i} C}{c_{i} + c_{-i}} + \frac{\beta_{i} m_{i} M}{m_{i} + m_{-i}} - (\lambda_{i} c_{i} + \gamma_{i} m_{i}). \quad (1)$$

The proposed game-theoretical model is specially devised for mobile cloud applications in vehicular networks. In particular, the resource weights α_i and β_i in the utility function make the game model adaptable to resources preference in different applications. The pricing factors λ_i and γ_i are set to prevent from resource waste imposed by excessive competition, and thus, potentially enhance resource utilization. These key parameters α_i , β_i , λ_i and γ_i are elaborately selected regarding the mobile environment of the cloud-assisted vehicles. For example, vehicles may have different quality of radio links to the cloud site. Their VMs should be provided with different α_i , β_i , λ_i and γ_i according to the link quality. Typically, in a mobile multimedia application where scalable video coding (SVC) technique is involved, the VM is responsible for adaptive video decoding in the cloud site. The required VM resource mostly depends on the link quality. Because the link rate restricts the affordable quality of video stream, and consequently, determines the amount of VM resources for video processing.

B. Nash Equilibrium

In a non-cooperative game, a Nash equilibrium is a balanced state with a strategy profile, from which no game player has any incentive to deviate. In the proposed VM resource allocation game, by computing the second order derivative of $U(c_i, m_i)$ with respect to c_i and m_i respectively, we get $\frac{\partial^2 U}{\partial c_i^2} = -\frac{2\alpha_i c_{-i} C}{(c_i + c_{-i})^3} < 0$ and $\frac{\partial^2 U}{\partial m_i^2} = -\frac{2\beta_i m_{-i} M}{(m_i + m_{-i})^3} < 0$. This means that, $U(c_i, m_i)$ is a concave function with respect to c_i or m_i . Therefore, the existence of a Nash equilibrium is proven in the VM resource allocation game model [16]. Given the other VMs' applications, say, c_{-i} and m_{-i} , we define $(c_i^*, m_i^*) \in \arg\max U(c_i, m_i)$ as the best response, t or called optimal strategy, of the i-th VM in each iteration. We have

$$\begin{cases}
c_i^* = \min\left(C, \sqrt{\frac{\alpha_i c_{-i} C}{\lambda_i}} - c_{-i}\right), \\
m_i^* = \min\left(M, \sqrt{\frac{\beta_i m_{-i} M}{\gamma_i}} - m_{-i}\right).
\end{cases} (2)$$

To prove the uniqueness of Nash equilibrium in the VM resource allocation game, we can validate that the best response function is a standard function, which has three features: positivity, monotonicity and scalability [16]. Follwing (2), it is easy to prove that the sufficient conditions for the uniqueness of Nash equilibrium are $\forall i, \alpha_i \geq 4(N-1)\lambda_i$ and $\beta_i \geq 4(N-1)\gamma_i$.

Fig.3 shows a numerical example of resource allocation in our game-theoretical model. In the example, there are three VMs in a roadside cloud. The total available resources in computation and storage are set to 50 and 100 units, respectively. The VMs have different resource demands. VM-1 has the highest demand on computation while VM-2 has

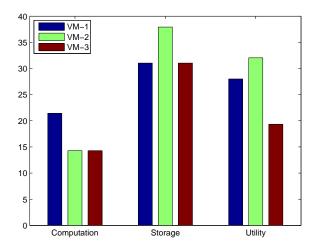


Fig. 3. Resource allocation result in roadside cloud

the highest demand on storage. We randomly select initial values of the resource applications for the three VMs, say, $c_{\{1,2,3\}} = \{10,5,5\}$ and $m_{\{1,2,3\}} = \{5,15,10\}$. In the simulation, it is observed that the game iteration converges fast. The game reaches its Nash equilibrium after nearly 10 rounds of iterations. Results indicate that the resources are appropriately allocated based on demand. In particular, VM-1, VM-2 and VM-3 are allocated 21.4, 14.3, 14.3 units in computation, respectively. VM-1, VM-2 and VM-3 are allocated 31.1, 37.8, 31.1 units in storage, respectively.

V. RESOURCE RESERVATION SCHEME FOR VIRTUAL MACHINE MIGRATION

A. Virtual Machine Migration Scenarios

VM migration refers to the process that an operating VM is transferred along with its applications across different physical machines. In a VM migration, a VM image has to be copied from the source to the destination roadside cloudlets. Different from traditional VM migration, VM migration in cloud-based vehicular networks has several different scenarios due to different deployments of roadside clouds and vehicles movements.

- Inter-Cloudlet Case: In Fig. 4(a), when vehicle A moves from the coverage area of RSU-1 to that of RSU-2, a VM migration is needed. Since RSU-1 and RSU-2 connect to different cloudlets, guest VM-A should be transferred from roadside cloudlet-1 to roadside cloudlet-2. After that, A will access cloudlet-2 via RSU-2 to resume its service.
- Intra-Cloudlet Case: In Fig. 4(b), vehicle A moves from
 the coverage area of RSU-1 to that of RSU-2. Since these
 two RSUs connect to the same roadside cloudlet, there is
 no need for VM migration. However, radio handoff from
 RSU-1 to RSU-2 may still take a short period. During
 handoff, the interaction between vehicle A and guest VMA may be temporally suspended.
- Across Roadside-vehicular cloud Case: In Fig. 4(c), vehicle A moves from the coverage area of RSU-2 to that

- of RSU-1. Before A's movement, nodes A, C and D have connection in an ad hoc manner. Vehicle C access the roadside cloud through vehicle A. The movement of A will cause the disconnection of C from the roadside cloud. In this case, guest VM-C will be transferred from the roadside cloud to the vehicle cloud in D. Then, vehicle C can continue its service through D.
- Across Roadside-Central Cloud Case: The scenario in Fig. 4(d) is similar to that in Fig. 4(c), except that there is no direct link between vehicles C and D in Fig. 4(d). In this case, guest VM-C has to be migrated from the roadside cloud to the central cloud. After that, C will access the central cloud to resume its service by long-distance communications, e.g., 3G/4G cellular.

B. Resource Reservation Scheme

The discussion about VM migration indicates that the VM migration process involves resource re-allocation in roadside cloud. If the resources of the destination cloud have been intensively occupied, after a VM migration and resource reallocation, some of the VMs may not have sufficient resources and may not even resume their services. In order to avoid resource over-commitment, the target cloud site has to deny the VM migration so as to maintain the services of the existing VMs. In this case, the cloud service of a vehicle with VM migration is said to be dropped. To reduce service dropping, we propose a resource reservation scheme. In this scheme, a small portion of the cloud site resources are reserved merely for migrated VMs, but not for local VMs. When there are dedicated resources for VM migration, the dropping rate of cloud services will be significantly decreased.

In the proposed resource reservation scheme, resources are divided into two categories: reserved resources and common resources. Let C_r and M_r denote the reserved resources, and $C_c = C - C_r$ and $M_c = M - M_r$ the common resources in computation and storage, respectively. In VM migration, a VM arrival refers to the event that a VM is created either for a new local VM or a migrated VM. A VM departure refers to the request of a VM deletion, either for an ending of VM service or VM migration to another cloud site. The resource reservation scheme operates as follows:

- Local VM arrival: When there is a request for creating a new local VM, resource allocation will be carried out, e.g., using the proposed game-theoretic allocation scheme. Since a part of the resources are reserved, the local VMs can only share the common resources. If the resource allocation result satisfies all existing VMs, the new local VM is admitted; otherwise, it is blocked.
- Local VM departure: Resource allocation is also performed when the service of a local VM ends or migrates to another cloud site.
- Migrated VM arrival: Upon a request for a VM migration, the target cloud site will re-allocate resources. In this case, the reserved resources will be also taken into account. Specifically, the existing local VMs and the migrated VM will share all available resources. After reallocation, if all the VMs (including the migrated VM)

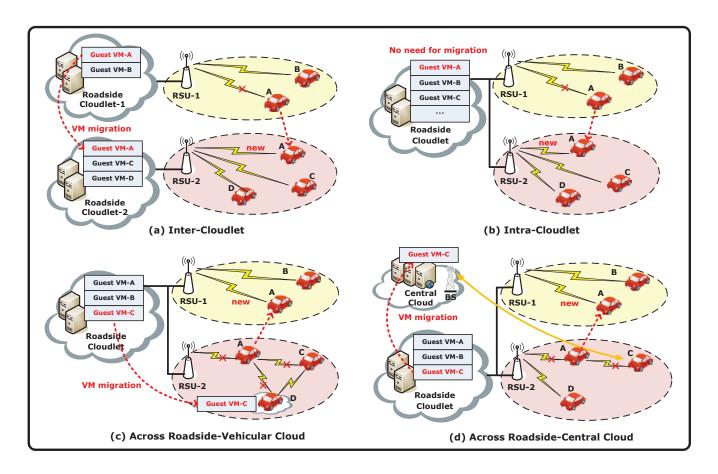


Fig. 4. Virtual machine migration scenarios

- resource requests are satisfied, VM migration is approved; otherwise, the VM migration request is rejected.
- Migrated VM departure: Resource allocation is also performed when the service of a migrated VM ends or it migrates to another cloud site. It is noticeable that, if there is no migrated VMs in a cloud site, the resource allocation can only use common resources. The reserved resources will be conserved for further usage upon another VM migration.

C. Optimal Resource Reservation

We consider K classes of VMs. Let c_k and m_k represent the amount of required resources by the k-th class of VMs in computation and storage, respectively. Let n_k^l and n_k^g denote the number of local and migrated VMs of class k, respectively. Suppose that the arrivals and departures of both local and migrated VMs follow a Poisson process model. The system state transition may be formulated as continuous-time Markov process. Let $\mathbf{n}_l = (n_1^l, \cdots, n_k^l, \cdots, n_k^l)$ and $\mathbf{n}_g = (n_1^g, \cdots, n_k^g, \cdots, n_K^g)$. We represent the system state by $\mathbf{s} = (\mathbf{n}_l, \mathbf{n}_g)$ and the state space by \mathcal{S} . Let $\pi_{\mathbf{s}}$ denote the steady state probability of state \mathbf{s} . Given the arrival and departure rates of new and migrated VMs, the steady state probability matrix $\Pi = \{\pi_{\mathbf{s}} | \mathbf{s} \in \mathcal{S}\}$ will be derived by a 2K-dimension Markov chain model.

Let R_b and R_d denote the blocking rate and the dropping rate, respectively. Then, a new local VM is blocked if the total amount of required resources of the local VMs (including the new one) exceeds that of the common resources, i.e., $\sum_{k=1}^K n_k^l c_k > C_c$ or $\sum_{k=1}^K n_k^l m_k > M_c$. A migrated VM is dropped if the total amount of required resources of all VMs (including the migrated one) is more than that of all resources, i.e., $\sum_{k=1}^K (n_k^l + n_k^g) c_k > C$ or $\sum_{k=1}^K (n_k^l + n_k^g) m_k > M$. Let λ_k^l , μ_k^l , λ_k^g and μ_k^g denote the arrival and departure rates of local and migrated VMs, then S_b and S_d the sets of states that encounter blocking and dropping, respectively. We can derive $R_b(C_r, M_r) = \sum_{\mathbf{s} \in \mathcal{S}_b} \sum_k \pi_{\mathbf{s}} \lambda_k^l$, and $R_b(C_r, M_r) = \sum_{\mathbf{s} \in \mathcal{S}_d} \sum_k \pi_{\mathbf{s}} \lambda_k^g$. Let R_b^c denote the constraint of the blocking rate. The optimal number of reserved resources is derived by solving the following optimization problem.

min
$$R_d(C_r, M_r)$$
,
s.t. $R_b(C_r, M_r) < R_b^c$. (3)

Fig.5 shows a performance comparison with and without resource reservation. The total resources of the roadside clouds are 50 and 100 units in computation and storage, respectively. Two classes of VMs are considered. VMs of class-1 are mainly for computation-type applications, which needs 20 units in computational resources and 15 units in storage resources. VMs of class-2 are mainly for storage-type applications, which need 10 units in computational resources and 40 units in

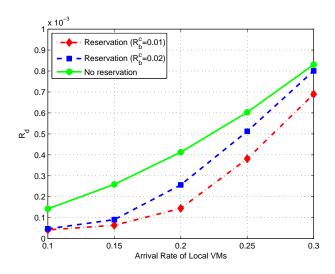


Fig. 5. Dropping rate in terms of local VM arrival rate

storage resources. The two classes of VMs are assumed to have identical in arrival and departure rates. We set the range of local VM arrival rate from 0.1 to 0.3, the local VM departure rate by 2.0, the arrival and departure rates of migrated VM by 0.05 and 0.1, respectively. The simulation results show that the dropping rate of migrated VMs is significantly reduced with resource reservation, which demonstrates the efficiency of our proposed mechanism.

VI. CONCLUSIONS

In this article, we first discussed the opportunities and challenges in exploiting cloud computing in vehicular networks. Then, we presented a hierarchical architecture for cloud-based vehicular networks that facilitates sharing of computational resources, storage resources and bandwidth resources among vehicles. Furthermore, we focused on efficient resource management in the proposed architecture. The resource competition among virtual machines is formulated and solved in a game-theoretical framework. Virtual resource migration due to vehicle mobility is addressed based on a resource reservation scheme. Finally, illustrative results indicated a significant reduction of the service dropping rate during virtual machine migration.

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