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Vehicular Cloud Resource Management, Issues and Challenges: A Survey

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ABSTRACT Recent advancements in the automotive industry have led to the design of smart vehicles with high capacity resources for communication, sensing, processing, and storage of data. In the near future, it is envisaged that these resources will be harnessed and utilized to provide cloud services such as storage as a service, computation as a service, and sensing as a service. This paradigm of computing termed vehicular cloud, presents a lot of opportunities for the deployment of delay-sensitive applications in vehicular environment. However, high mobility of vehicles and rapidly changing topology of vehicular networks introduce new challenges such as instability of resources which make the management of resources in vehicular cloud complicated. Therefore, vehicular cloud computing require robust and mobility-aware resource management solutions to be designed. In order to achieve this goal, researchers and engineers need to be abreast with the techniques of resource management in vehicular cloud. This article presents a detailed survey of resource management tasks in vehicular clouds. A thorough introduction to vehicular cloud is presented initially. Then we identify and examine all the resource management tasks that are carried out in vehicular cloud by classifying them into three different phases: pre-resource assignment phase, resource-assignment phase, and post resource assignment phase. Proposed solutions to resource management challenges in literature at each phase are reviewed in detail. Unlike the existing surveys on vehicular clouds, this study covers all aspects of resource management such as resource brokering, resource demand prediction, resource allocation, and resource scheduling. Following the extensive survey, we also propose frameworks for resource monitoring and resource brokering for vehicular cloud. Finally, open issues and research directions for vehicular cloud resource management are presented.

INDEX TERMS Cloud computing, vehicular cloud computing, volunteer computing, vehicular ad-hoc networks, resource management, resource allocation and resource scheduling.

ACRONYMS

AaaS	Application as a Service
CaaS	Computation as a Service
CC	Central Cloud
DSRC	Dedicated Short Range Communication
ITS	Intelligent Transport Systems
IVC	Inter-Vehicular Cloud
MA	Monitoring Agent
MAC	Medium Access Control
MDS	Monitoring and Decision System
MVC	Military Vehicular Cloud
NaaS	Network as a Service
NetFCs	Networked Fog centers
QoE	Quality of Experience
QoS	Quality of Service
RMA	Resource Monitoring Agent
RoI	Region of Interest
RSC	Road Side Cloud
RSU	Road Side Unit
SDN	Software Define Network
SMDP	Semi Markov Decision Process
SOA	Service Oriented Architecture
StaaS	Storage as a Service
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
V2X	Vehicle to Everything
VANET	Vehicular Ad-hoc Network
VC	Vehicular Cloud
VCC	Vehicular Cloud Computing

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VCRBS	Vehicular Cloud Resource Brokering System
VFog	Vehicular Fog
VMM	Virtual Machine Migration

I. INTRODUCTION

The incorporation of advanced technologies in automotive vehicle design has led to the development of smart vehicles that have computing resources embedded in them. These resources include sensors, communication gadgets, processing and storage units. With the aid of communication gadgets, smart vehicles can connect and communicate with Road Side Units (RSUs) and other devices creating a large wireless communication network. This infrastructure-less network of vehicles referred to as Vehicular Ad-hoc Network (VANET), presents a lot of opportunities for the development of Intelligent Transport System (ITS) applications.

ITS safety and entertainment applications such as emergency message dissemination systems have been proposed using the VANET communication standards IEEE 1609.4 [1] and IEEE 802.11p [2]. Real-world testbed deployments of VANET have also been carried out. Cadillac [3], Telstra and Cohda Wireless [4], have tested Vehicle to Infrastructure (V2I) communication deployment over 4G successfully.

With the introduction of 5G [5] communication technology, the VANET communication modes: Vehicle to Vehicle (V2V), Vehicle to Infrastructure(V2I) and Vehicle to Everything (V2X) are expected to have better performance. The enhanced performance of VANET communication modes, will not only allow smart vehicles to communicate efficiently but also share the computing resources embedded in them. This computing paradigm of sharing vehicular resources is termed as vehicular cloud computing.

The idea of vehicular cloud was first proposed in [6]–[8] to fully utilize the huge resources in vehicles and RSUs. Resources in vehicles such as sensors, storage and processing units are rented out and accessed by users through V2V and V2X communication modes. Typifying the concept of utility computing, the resources are accessed and used on pay as you go basis.

As in all cloud computing paradigms, provision and access to vehicular cloud resources are modeled on service-oriented architecture [9]. Storage as a Service (StaaS), Computation as a Service (CaaS), Network as a Service (NaaS) and Application as a Service (AaaS) are some of the proposed vehicular cloud services in literature [10]. In CaaS, compute-intensive tasks of users are submitted to vehicles with idle processing slots for execution. Through StaaS, mobile and parked vehicles can provide sufficient storage units to users. The NaaS provides Internet access to vehicles and other users by serving as access points. Vehicular cloud also provides the platform for hosting and deploying applications in vehicular environment using the AaaS model. Applications such as traffic management systems, urban surveillance systems and video sharing in vehicular environment are some of the applications can be hosted on AaaS platform.

One of the main advantages of vehicular cloud is the provision of resources and services in locations closer to users in vehicular environment. Therefore, it improves response or access times for cloud services by users in vehicular environment. This makes vehicular cloud more feasible for delay-sensitive applications and services in vehicular environment than conventional cloud.

To fully deploy vehicular cloud and achieve the benefits it presents, the challenge of inefficient management of resources should be resolved. Resource management involves all the activities that are carried out to ensure that cloud services are provided to meet users' requirements. It consists of tasks such as resource brokering, resource allocation and resource monitoring. The high mobility of resources in vehicular cloud requires that, robust and mobility-aware resource management techniques are employed in all resource management tasks. This prevents the inefficient management of resources which leads to the failure to meet QoS standards by service providers and increase the monetary cost of cloud services.

In this study, we therefore, examine the key issues and research challenges of vehicular cloud resource management. The rest of this article is structured as follows. Section II examines motivation and related works. Section III and section IV, present an overview of vehicular cloud computing with focus on the genealogy, architecture and provisioning models of vehicular cloud. In section V, an exposition on resource management techniques in vehicular cloud is presented using a phase-based approach. Three main phases consisting of pre-resource assignment, resource assignment and post-resource assignment are identified. In section VI, we discuss open issues and future research directions for resource management in vehicular cloud. Section VII concludes the paper.

II. MOTIVATION AND RELATED WORKS

As in all systems, inefficient management of resources adversely affects the performance and system functionality. It also increases the total cost of systems. To overcome resource management challenges in vehicular cloud, efficient solutions need to be designed. The knowledge of various resource management techniques proposed in literature is therefore significant to researchers and other stakeholders. Research surveys present one of the best sources of such information. However, most surveys on vehicular cloud have concentrated on architecture, applications and research challenges. Table 1 presents a summary of survey works carried out in vehicular cloud computing.

In [10], [13], [19], [20], the different architectures, services and taxonomy of vehicular cloud were surveyed. Lin Gu *et al.* [21], in their survey, also identified the characteristics of vehicular cloud that distinguish it from conventional cloud as high heterogeneity of resources, instability of resource nodes, selflessness and greenness. In [15], the authors surveyed the different services of vehicular cloud and the simulation tools that are used to test protocols in

TABLE 1. Summary of existing surveys and reviews on vehicular cloud computing.

Publication	Main Theme	Key Contributions
Lin Gu [11]	Vehicular cloud architecture, services and applications	Presented a two-tier physical architecture of vehicular cloud consiting of the internet or conventional cloud and the inter-vehicular cloud. The paper also reviewed ealier works on vehicular cloud with focus on vehicular cloud architecture, services and applications.
Whaiduzzaman [12]	Vehicular cloud formation, applications and services	The study presented a taxonomy of vehicular cloud formation, services and applications. A comparative analysis of the features conventional cloud and vehicular cloud was also carried out.
Tesnim [13]	Vehicular cloud architecture	The study presented a taxonomy and classification of vehicular cloud architectures based of factors such as the level of centralization and deployment approaches.
Aliyu [14]	Vehicular cloud architecture	Proposed a layered design architecture for vehicular cloud and discussed the vehicular cloud network components and their roles. A detailed review of vehicular cloud applications, data dissemination and security was also presented.
B. Ahmed [15]	Vehicular cloud services, applications and simulation platforms	Presented a survey of proposed vehicular cloud services and applications. Existing VANET simulation platforms and mobility generators that can be adopted for vehicular cloud were also reviewed.
Skondras [16]	Vehicular cloud Medium Access Control (MAC)	Reviewed VANET medium access control schemes such as Time Division Multiple Access (TDMA), Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and discussed how they can be enhanced for 5G based vehicular cloud computing.
Goumidi1 [17]	Vehicular cloud security challenges	The study presented a general overview of vehicular cloud including vehicular cloud architecture, services and applications. A detailed survey of the security challenges and proposed solutions were also captured in the study.
Olariu [17]	Vehicular cloud services, applications and research trends	The paper presented a general overview of vehicular cloud with concentration on features and applications of vehicular cloud. Proposed solutions to challenges of VCC such as security, privacy, reliability and availability of vehicular cloud services were analyzed in detail.
Boukerche [18]	Resource management	This study provided an overview of resource management in vehicular cloud. The main focus of the survey was on studies carried out on resource scheduling, resource allocation and resource migration
This survey	VCC formation, Architecture and resource management	Our study presents the genealogy of vehicular cloud, vehicular cloud architecture, formation and provisioning models. A detailed review of all recent studies carried out on vehicular cloud resource management such as service discovery, resource monitoring and resource brokering was also carried out.

vehicular cloud. A survey of the role of vehicular cloud in traffic management was carried out in [22]. Despite the existence of these studies, detailed surveys on vehicular cloud resource management have received little attention. Most of the resource management surveys in literature such as [23]–[26], have focused on conventional cloud, edge and Fog computing.

A thorough search in literature leads to just one survey on vehicular cloud resource management by Boukerche and Meneguette [18]. The study classified and analyzed resource management in vehicular cloud into two groups: infrastructure-based resource management and vehicular based resource management. In infrastructure-based resource management, roadside units are considered to be the resource manager while vehicles are selected as resource managers in the vehicular based resource management scheme.

Although the study gives an overview of resource management in vehicular cloud, it focused on only resource allocation and resource scheduling. Other important issues such as resource estimation, resource stabilization, virtual machine migration and resource brokering were not covered in their work.

To address this gap in literature, this study offers an overview of vehicular cloud and a detailed survey on all resource management techniques in vehicular cloud.

III. GENEALOGY OF VEHICULAR CLOUD

In this study, we define vehicular cloud as a distributed computing paradigm where resources of connected vehicles are harnessed to provide cloud services. Based on this definition, vehicular cloud can be considered as a multi-computing paradigm with contributions from different computing or technology disciplines. To distinguish vehicular cloud from the contributing computing paradigms, we present the genealogy of vehicular cloud.

The genealogy of vehicular cloud can be traced from distributed computing through mobile volunteer computing, mobile cloud computing and VANET as shown in Fig. 1. At the root of the figure is distributed computing which is defined by [27] as ‘‘a collection of independent computers that appear to its users as a single coherent system’’. It allows multiple connected computers to solve a problem divided into many tasks.

Distributed computing serves as the underlying basis for all other multi-computer systems where the resources of different computing units are harnessed to execute a task. The main distributed computing models in literature include Grid computing, cloud computing and volunteer computing.

Grid computing consists of graphically dispersed and loosely coupled computers acting together to perform a given task [28]. It involves a large scale resource sharing from multiple administrative domains. The individuals and institutions

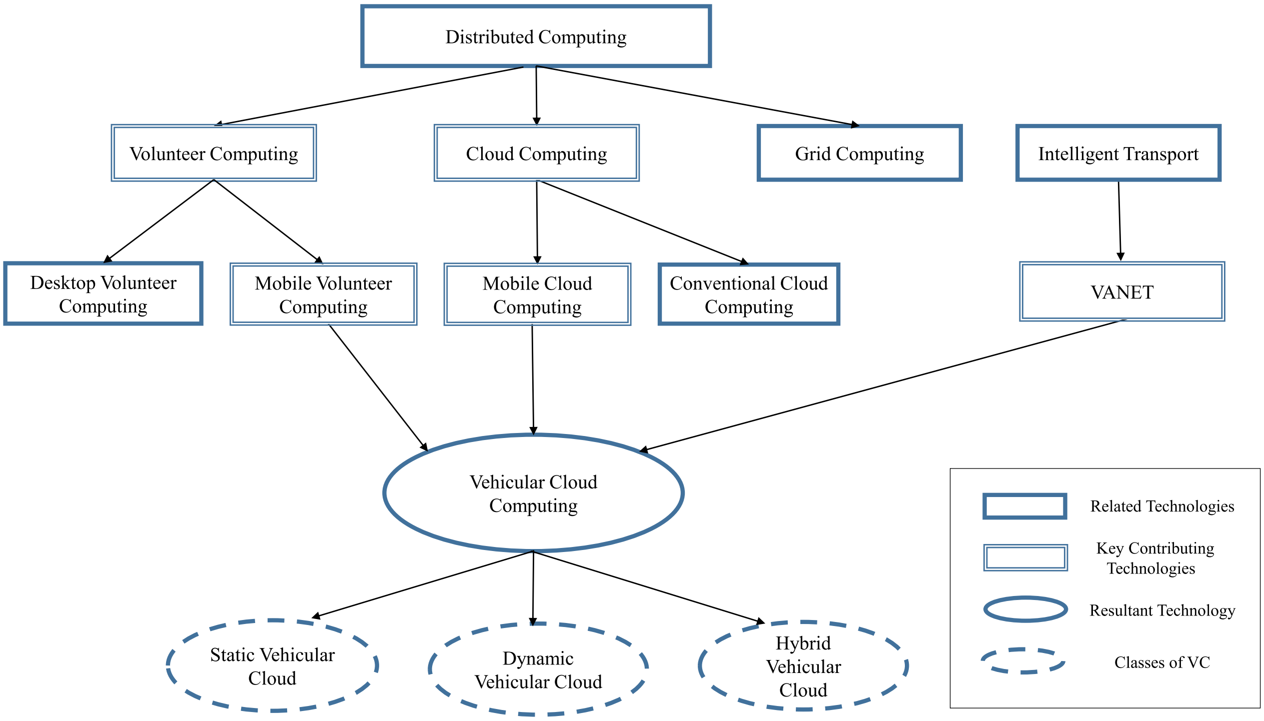

FIGURE 1. **Genealogy of vehicular cloud.**

that are involved in grid computing resource sharing, are referred to as virtual organizations [29].The resources in grid computing may be donated by virtual organizations at no cost through volunteer computing technique.

Volunteer computing according to [30] is defined as the donation of computing resources to a distributed system for the accomplishment of a task. Two distinct classes of volunteer computing exist in literature. Desktop volunteer computing and mobile volunteer computing. Desktop volunteer computing involves non-mobile computing devices such as personal desktop computers while mobile volunteer computing involves mobile devices. Mobile volunteer computing may also be referred to as personal volunteer computing as it involves the leveraging of resources of personal devices such as smartphones and laptops for the execution of compute intensive applications [31]. Volunteer computing plays a significant role in vehicular cloud. Vehicle owners may donate their resources to form autonomous vehicular cloud to execute tasks or applications that are of benefit to the community using vehicular volunteer computing concepts [32].

According to [33], ''Cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction''. The key concepts behind cloud computing include the virtualization of resources and the use of Service Oriented Architecture (SOA) to configure and access hardware or software resources. Cloud computing enables computing resources to be accessed by clients as a utility and use on a pay as you go basis [34], [35]. Two distinct classes of cloud computing can be identified as conventional cloud and mobile cloud. In conventional cloud, resources in a data center are located in different geographical locations from users and are accessed over the internet.

Mobile cloud computing is explained by [36], as an infrastructure that enables both data storage and processing to be performed in a system other than the actual mobile device. A classic example of mobile cloud involves mobile devices like mobile phones using public cloud infrastructure in its proximity such as on-campus cloudlet to run applications. According to the definition of mobile cloud presented in [37], vehicles accessing vehicular cloud for the execution of tasks can be considered as a subclass of mobile cloud computing. However, there exist some differences between them.

A comparison of mobile cloud (based on the definition presented in [36], [37]) and vehicular cloud is shown in Table 2. From the table, the main motivation for mobile cloud computing is to provide applications or services to mobile devices. On the other hand, vehicular cloud seeks to utilize resources embedded in vehicles via the provision of cloud services. Although the idea of close proximity to users is a common trait of both paradigms, vehicular cloud resources are mostly located in vehicular environment, that is, along roads and at parking lots. Mobile cloud resource availability is relatively

TABLE 2. Comparison of mobile cloud and vehicular cloud.

Characteristics	Mobile cloud	Vehicular cloud
Motivation	Carrying out storage and processing in systems other than mobile devices	Utilizing vehicular resource via the provision of services
Communication Mode	Internet and local area network	Internet and V2X
Resource Availability	High availability	Low availability
Resource Heterogeneity	Low heterogeneity	High heterogeneity
Resource Location	Close proximity to cluster of users	Vehicular environment
Resource Ownership	Owned by service provider	Owned by individual vehicle owners
Resource Management	Central management	Distributed and central management

higher as compared to that of vehicular cloud. Resources in mobile cloud are relatively static at a location while vehicles with their resources are highly mobile with intermittent network connection. This leads to a relatively higher unavailability of resources.

The level of resource heterogeneity from the service provider's perspective is higher in vehicular cloud than in mobile cloud computing. In mobile cloud, resources of similar processing architecture, operating systems and hardware can be purchased by service providers to reduce the level of heterogeneity. In vehicular cloud, resources in a region of interest are rented from or donated by different resource owners. Therefore, the acquisition of sufficient resources with similar processor architectures, operating systems and other hardware may not be possible.

Due to the differences in vehicular cloud and mobile cloud computing characteristics, resource management solutions applied in vehicular cloud computing are different from that of mobile cloud computing. In the subsequent section, we examine the general factors that affect resource management solutions in vehicular cloud.

IV. FACTORS THAT AFFECT RESOURCE MANAGEMENT TECHNIQUES

In vehicular cloud deployment, different vehicular cloud types, architecture and provisioning models can be considered. The choice of vehicular cloud type, architecture and provisioning model has a direct bearing on resource management techniques to employ. A general overview of these factors and their impact on some resource management techniques in vehicular cloud are discussed in this section.

A. TYPES OF VEHICULAR CLOUD

Based on the mobility of vehicles, three main classes of vehicular cloud has been identified in literature. Shown as leaf nodes in Fig. 1, the vehicular cloud types are the static vehicular cloud, dynamic vehicular cloud and hybrid vehicular cloud [10].

In static vehicular cloud, vehicles with their resources are stationary at a place for a given time. Parked vehicles with sufficient resources are connected to power source and network to provide cloud services. Static vehicular cloud is also referred to as static vehicular data center. It includes vehicles parked at airports, shopping malls and university parking lots.

A data center at airport model proposed by [11], considered the large number of vehicles stationed at airports for hours to provide vehicular cloud services such as computation as a service, storage as a service and network as a service. Dressler *et al.* [12], proposed the use of static vehicular cloud formed by parked vehicles along roads to provide storage services to moving vehicles and other cloud users.

A sensing as a service framework that uses parked vehicles along the road to sense and share traffic scenarios with vehicles that are in non-line of sight region was proposed by Eckhoff *et al.* [38]. In the proposed system, parked vehicles and connected RSUs including traffic lights capture city-wide traffic scenarios through sensors and offer the results as a service to other vehicles and road users. Another service that is offered by static vehicular cloud is network as a service, where vehicles parked along the road serve as access points to provide Internet access to mobile vehicles [39].

One of the main challenges of static vehicular cloud is power management that is, how and when parked vehicles get powered to start cloud services. It was suggested in [11], that parked vehicles can be connected to the main power source only when they become part of the provisioned vehicular cloud.

In dynamic vehicular cloud, vehicles and their resources are mobile. Dynamic vehicular cloud is considered a mobile data center or data center on roads. It has unique characteristics such as intermittent network connection and rapidly changing topology. Services such as Storage as a Service, Computation as a Service and Sensing as a Service are the main services that can be provisioned by dynamic vehicular cloud.

Dynamic vehicular cloud can be merged with static vehicular cloud. In such instance, resources in mobile vehicles, parked or static vehicles and infrastructure along roads are provisioned to provide cloud service. This type of vehicular cloud is referred to as hybrid vehicular cloud in this article. Studies in [7], [34], [40], adopted the hybrid vehicular cloud model in their studies.

Resource management techniques in both static, dynamic and hybrid vehicular cloud need to consider the mobility characteristics of vehicles. The relative differences in the mobility of resources imply that resource management techniques vary among the vehicular cloud types. For instance, in dynamic vehicular cloud, resource management tasks such as virtual machine migration is more complex than static vehicular cloud due to the high mobility of resources. Access to service in dynamic vehicular cloud may be abruptly disconnected without any notice for virtual machine migration to be carried out. In static cloud, the departure times of vehicles from parking lots may be known in advance which leads to better virtual machine migration design and configuration.

B. VEHICULAR CLOUD ARCHITECTURE

Different vehicular cloud architectures have been proposed in literature. A survey on vehicular cloud architectures is presented by [41]. In this study, we categorize all vehicular cloud architectures under the three-tier architecture proposed by [42], [43]. The three-tier architecture referred to as Cloud-Fog-IVC in [44], consists of the Central Cloud (CC) layer, the Road Side Cloud (RSC) or Fog layer and the Inter-Vehicular Cloud (IVC) layer. Fig. 2 shows the three-tier architecture of vehicular cloud.

The central cloud layer is similar to the conventional cloud. It consists of data centers with dedicated servers that have high capacity computing resources. The services of the central cloud are accessed by vehicles through the roadside cloud layer. The main objective of the central cloud is to offer high storage and computation capabilities that can provide vehicular cloud services such as the simulation of complex traffic scenarios and the storage of large data in vehicular environment. It also serves as a backup for the roadside and the vehicular cloud layers. The main drawback of the central cloud layer usage is the high latency involved. This is due to the intermittent connection and long distance between data centers and vehicles that access cloud services.

The roadside cloud layer is designed to overcome the drawbacks of the central cloud layer. Termed as vehicles using cloud (VuC) [40], it consists of RSUs that have sufficient resources to provide cloud services to vehicles. It can is also be considered as a form of Fog Computing [45]–[47] or edge computing, where small sized self-powered cloudlets, fog or edge nodes are installed at RSUs to provide cloud services, data analysis and intelligence closer to the edge of the vehicular network where data is generated.

The roadside cloud layer provides services such as computation as a service, network as a service and storage as a service to vehicles via the V2I communication protocol. The roadside cloud layer, however requires infrastructures such as fog nodes to be installed along roads. Although the installation of fog nodes to cover large areas such as a city-wide deployment have a high initial installation cost, it presents a relatively closer form cloud service that vehicles can access.

For the inter-vehicular cloud layer, resources embedded in vehicles are configured to provide cloud services. Using V2V communication techniques, vehicles can provide and also access cloud services provided by other vehicles. The inter-vehicular cloud layer does not require additional hardware installation. Compared to the central cloud and roadside cloud, latency in the access of inter-vehicular cloud layer services by vehicles is considerably low due to their proximity to vehicles.

In the design and evaluation of vehicular cloud protocols, each layer of the three-tier architecture can be considered independently. Researchers can therefore, focus on a specific layer of the three-tier architecture. Studies conducted by [44] focused on the roadside cloud layer to design energy efficient resource scheduler for fog nodes that provide cloud services to vehicles. Gu et. al. [48] also used the roadside cloud layer as a backup data center to store duplicated data for the vehicular cloud layer.

The layer of the architecture that one chooses for the design of protocols affects the nature of the resource management technique used. For instance, in roadside cloud layer, resource management techniques such as virtual machine migration involve the transfer of virtual machines from one RSU or Fog node to another. In this scenario, when to migrate the virtual machine and the location of the best RSU or fog node to migrate to can be configured in advance. However, if only the inter-vehicular cloud layer is considered, when to migrate and to which vehicular node to migrate may have to be determined through some predictive techniques. This is due to the high mobility and sporadic nature of mobile resources in the inter-vehicular cloud layer.

In this study we focus on resource management in the inter-vehicular cloud layer. Therefore other critical issues such as Software Define Network (SDN), Network Function Virtualization (NFV) and content caching which are carried out in the roadside cloud layer are not covered.

C. PROVISIONING MODELS OF VEHICULAR CLOUD

Vehicular cloud provisioning models entail the techniques, nature of formation and mode of access of vehicular cloud services. Two main types of provisioning models can be considered in vehicular cloud, namely peer-to-peer (P2P) and federated provisioning models.

The peer-to-peer model is a decentralized management approach where a vehicle with sufficient available resource provides cloud service to clients. It is most suited for services that do not require huge capacity beyond what an individual vehicular node can provide. Examples of services provided by P2P vehicular cloud include Sensing as a Service (SaaS) and Network as a Service (NaaS).

In the peer-to-peer model, a resource registry may be required in a region of interest to keep details of vehicles, the type of services they provide and the cost of services. Prospective cloud users can then query the resource registry for available services. Where a central resource registry is not available, vehicle owners may broadcast their service to all prospective clients in its region of interest. The later model, however, generates unnecessary traffic that causes poor network performance or leads to a complete loss of network service.

The federated model is centrally provisioned. In a region of interest, vehicles with underutilized resources are organized in a pool as a single unit to provide vehicular cloud services

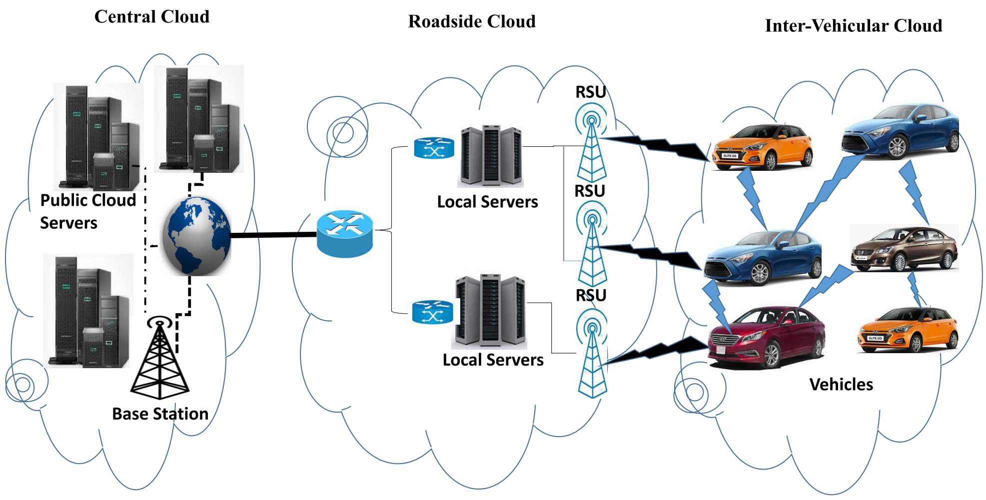

FIGURE 2. The Three-Tier architecture of vehicular cloud.

under centralized management. The central cloud controller undertakes all the resource management activities such as resource allocation and task scheduling.

Compared to the peer-to-peer model, the federated provision model leads to more efficient utilization of resources. Available resources of individual vehicles that single-handedly may not be sufficient for any task, can be pooled to provide services that require a large capacity of resources. The large pool of resources available in the federated provisioning model enables complex applications that require a large capacity of resource to be executed in vehicular environment.

Studies conducted in [32], considered the federated provision model to propose a city-wide vehicular cloud framework to provide security as a service. Another application of the federated provisioning technique is the unique business model where a platoon of vehicles such as taxis or commercial vehicles belonging to an organization, offer vehicular cloud services in a city.

A hybrid of the two provisioning models is also possible. At a point in time, a vehicle owner that does not want to be part of the federated vehicular cloud, can rent out resources to other vehicles that need them using the peer-to-peer model. The crown framework proposed in [49], uses the hybrid provision model. In the framework, the nearest RSU serves as a central registry for all vehicles and their available resources. If no individual vehicle owner can meet the capacity requirement of a client, multiple resource providers can form a federated vehicular cloud under the management of the RSU to execute the client's task.

Resource management techniques employed in the federated provisioning model vary from the peer-to-peer provisioning model. The federated model, involves a large number of resources from different vehicle owners under the management of a central administrator while in the peer-to-peer model, resource management tasks are carried out by the individual vehicular node that provides the cloud service.

In the next section, we examine the different resource management tasks that are carried out in vehicular cloud. A detailed review of literature on proposed solutions to resource management tasks in vehicular cloud is also presented. Table 3, is a comparative analysis of selected publications on resource management in vehicular cloud considering the type of vehicular cloud, provisioning model, architecture and experimental platform.

V. VEHICULAR CLOUD RESOURCE MANAGEMENT

Resource Management in cloud computing can be explained as the processes that are undertaken to make computing resources available and accessible to clients in the form of a service. It involves all the activities from the preparation of resources before they are assigned for task execution until the completion and release of the resource. The process of resource management in vehicular cloud involves different tasks and techniques. To identify and understand the activities involved in resource management in vehicular cloud, we propose a three-phased-based categorization of the vehicular cloud resource management process.

In Fig. 3, the phases identified are the pre-resource assignment phase, resource assignment phase and post-resource assignment phase. Each phase is made up of resource management tasks that are carried out sequentially from the preparation of resource for assignment to users, till the completion task execution and release of resource by the user.

A. PRE-RESOURCE MANAGEMENT PHASE

The main aim of the pre-resource assignment phase is to prepare resources before they are assigned for task execution. Resource stabilization, available resource prediction and modeling, resource discovery, and resource virtualization are the main tasks at the pre-resource management phase.

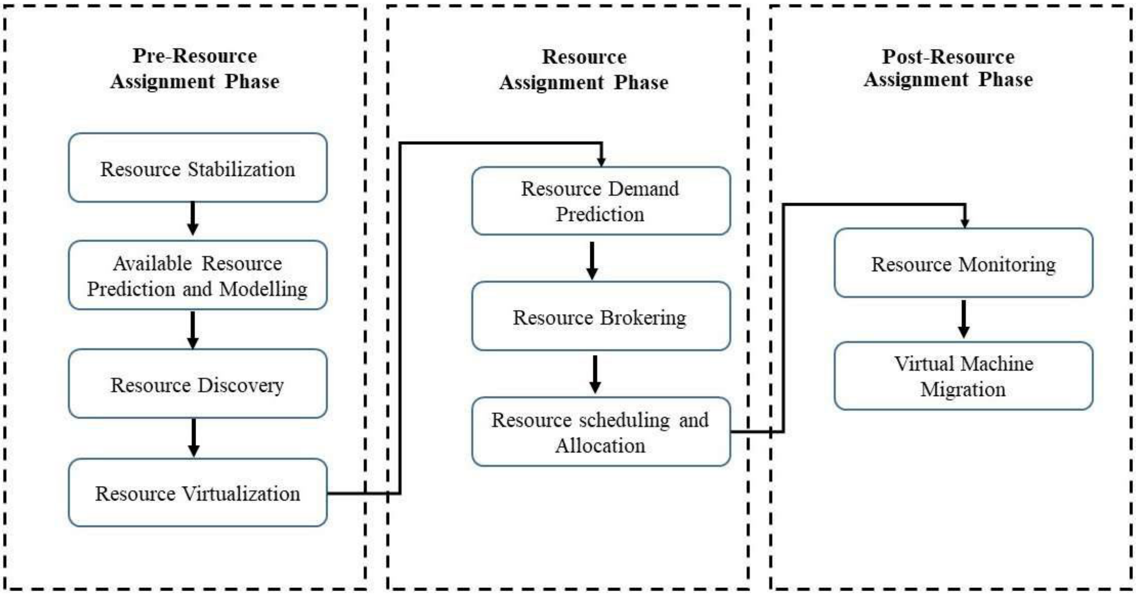

FIGURE 3. **Vehicular cloud resource management tasks grouped under three phases.**

Although tasks such as incentive modeling and detection of malicious resource donors can be considered at this phase, they are not discussed in this article. Readers can refer to [50], [51] for more information.

1) RESOURCE STABILIZATION

The high mobility of vehicles presents a lot of challenges in vehicular cloud. It affects the availability of resources in a region of interest at any given time. Resource stabilization increases the availability of resources and also prevents challenges such as frequent virtual machine migration.

Two main techniques that are used to stabilize resource in vehicular cloud are the formation of clusters and the prediction of the future location of vehicles. Clustering or grouping of vehicles based on given criteria has been extensively explored in VANET. It ensures that vehicles achieve some level of stability in a highly dynamic and rapidly changing topology of vehicular environment [52].

Different clustering techniques have been proposed in literature to overcome node instability and offer an efficient message dissemination strategy in VANET. Studies such as [53], [54], have reviewed the different algorithms and techniques for clustering in VANET. Clustering in VANET however, has its main focus as making network protocols such as routing and medium access control more scalable [55]. It therefore, considers all vehicles on the road at RoI as the part of clusters formed, vehicular cloud clustering, on the other hand, seeks to optimize the selection of vehicles with sufficient resources as part of clusters to provide cloud services.

Clustering in vehicular cloud also aide in resource management. Resources of vehicles belonging to a cluster are managed by the cluster head selected from the cluster members. According to [56], creation, maintenance, addition and deletion of vehicular resource nodes from a vehicular cloud cluster can be done by the cluster head. Fig. 4 is an illustration of an external user accessing the services provided by vehicular cloud clusters in a RoI. Each cluster provides specific service such as CaaS, StaaS and NaaS. The Vehicular cloud service broker is installed as a RSU to keep details of all clusters and the services they offer. The resource broker is responsible for submitting clients' tasks to cluster head for scheduling to the best cluster member nodes.

Arkain *et al.* [56], posited that the formation of clusters is efficient for vehicular cloud resource management tasks such as service discovery. In their studies, they considered fuzzy logic to select the cluster head based on a fit factor. The cluster head was then assigned the responsibility of managing the cloud. The cluster algorithm and criteria used for the formation of clusters were however not stated in their studies.

The formation of non-overlapping clusters was considered by Azizian *et al.* [57] to make vehicles more stable for vehicular cloud formation. They proposed the DHCV: a distributed D-hop clustering algorithm for VANET to support vehicular cloud services, specifically Data as a Service. In [12], the clustering of nodes in static vehicular cloud was considered. Parked vehicles along the road were organized into clusters to provide storage services to vehicles. Vehicles at the border of clusters were then selected as cluster heads to manage the cluster members.

Although some studies do not categorically consider the formation of vehicular cloud clusters with specific clustering algorithms, partitions of RoI of the road into logical cluster sections have been proposed. Partitions with enough vehicular resources then organized into vehicular cloud clusters. The nearest roadside unit or the leading node in the region of interest is then selected as the cluster head or resource manager.

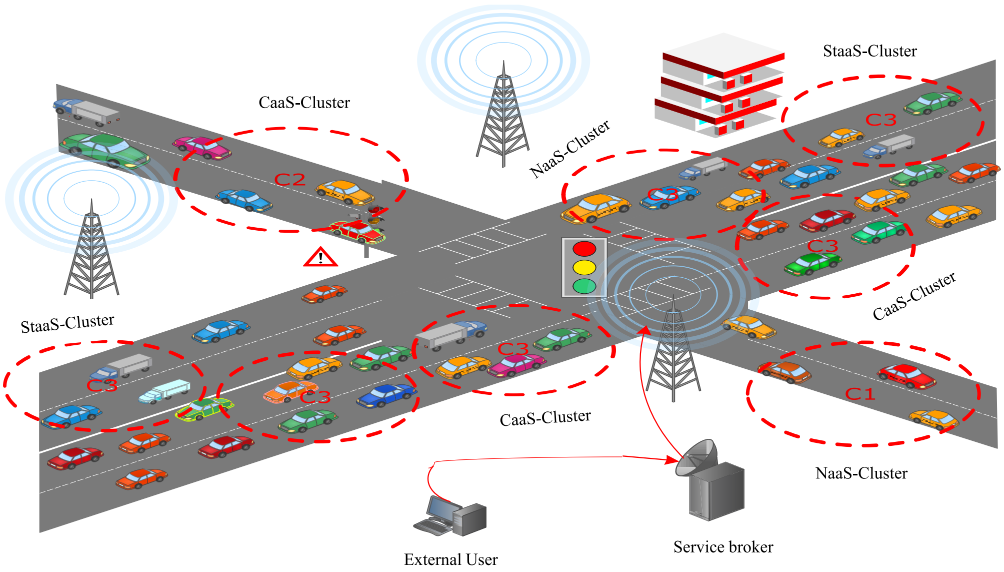

FIGURE 4. **Service based clustering in vehicular cloud.**

Bravo-Torres *et al* [58], considered this approach and named the partitions of the road that provide cloud services as virtual nodes regions.

In most clustering frameworks proposed for vehicular cloud, it does not consider the type of resource or service that is provided by vehicular nodes in the formation of clusters. Arguably, this does not reflect the characteristics of vehicular cloud and may lead to inefficient resource management. To overcome this challenge, Ridhawi *et al.* [59], proposed a service provision scheme that formed the clusters of vehicles according to the similarity in the mobility patterns and services offered by vehicular cloud nodes. Through simulations, they showed that the formation of service-specific clusters, achieved better performance in terms of service discovery delay and service hit ratio than in non-clustering scenarios.

The prediction of the future location of vehicles is another resource stabilization technique in vehicular cloud is . Knowledge of the possible future location of vehicles ensures that resource management tasks such as resource discovery and brokering are more efficient and simplified. Different location prediction techniques have been considered in vehicular environment.

Research in [60], [61] also provide studies on the prediction of bus arrival time at bus stops. The availability of services provided by buses at stops can then be determined. To ensure the continuous delivery of service to meet the Quality of Experience (QoE) of users, [59], predicted the future location of service provider nodes for efficient service discovery and selection.

Deterministic arrivals of vehicles are also significant in ensuring stability in vehicular cloud. In a region of interest on the road, the availability of some vehicles can be guaranteed at specific times of the day. Examples of such vehicles include public transports, students and staff shuttle buses that move at specific times of the day via determined routes. The time and possible duration that a vehicle can be part of vehicular cloud can be known ahead. Florin [62], considered the scenario of deterministic arrivals to estimate job completion times in vehicular cloud. Studies in [63] also employed public transports with known arrival and stop times on a section of a road as the best destination nodes for virtual machine migration.

2) AVAILABLE RESOURCE PREDICTION AND MODELING

In this study, we define available resource prediction and modeling as the determination of the capacity of vehicular resources available in a region of interest on the road or at a parking lot. Prediction of the total capacity of resources available in vehicular cloud involves the estimation of number resource vehicles in a region of interest from which the total available capacity is computed.

Arif *et al.* [11] proposed a parking lot occupancy model to determine the number of vehicles parked at an international airport. The parking lot at airport was assumed to have infinite parking capacity. They considered that, at the initial stage (time t = 0), there are zero or more cars at the parking lot after which cars arrive and depart at a time-dependent rate. By modeling the arrival and departure rate as a stochastic counting process, they evaluated the probability of the number of cars in the parking lot at a given time.

Zhang *et al.* [64], used stochastic models to predict the number of vehicles available in a section of the road. They considered two types of traffic flows, free-flow traffic and queued-up traffic. Using free-flow traffic where there exist low or medium traffic, they presented an analysis of the expected number of vehicles and the average occupancy time in a section of the road. In the queued-up traffic, stochastic queuing process was used to model traffic to determine the average number of vehicles, mean waiting time in the queue, and the average length of the queue.

3) RESOURCE AND SERVICE DISCOVERY

The discovery of services or available resources in vehicular cloud is a challenge due to the distributed ownership and volatile nature of vehicular resources. To overcome this challenges, studies in [49], [65], devised systems that enable users to discover vehicles and the services they offer. Vehicles register their services with the nearest RSU which serves as the cloud controller. In [49], a distributed dynamic index of the locations and resources or services is created at the RSU from which clients can query to find the most suitable services. The shortfall of these schemes is the over-reliance on RSU as a registry of cloud services. In highway scenarios where there exist little or no RSUs, it may lead to system malfunctioning as it does not support the use of vehicles as service or resource registry points.

To overcome the disadvantages of using only RSU as the registry of available services for service discovery, Arkian *et al.* [56], proposed an alternative solution to resource discovery using a cluster-based protocol. The cluster head was tasked with the responsibility of registering vehicles of the cluster and the services they offer. Clients then query the cluster head for their required service.

4) RESOURCES VIRTUALIZATION IN VEHICULAR CLOUD

The virtualization of resource can be explained as creating virtual machines over existing operating system and hardware. Virtualization ensures that multi-tenancy, which is, allowing several virtual machines on a single physical resource is achieved. Multi-tenancy leads to efficient utilization of resources in vehicular cloud as multiple applications from different users can run on the same physical resource at the same time. Resource virtualization improves efficiency, increases service reliability and service security [66]. It also provides fault and performance isolation between applications sharing the same resource [67].

In vehicular cloud, a lot of security concerns exits. The virtualization of resources is therefore very important as it provides some level of security to underlying physical resource [68], [69]. Virtualization of resources is also one of the solutions to the high resource heterogeneity in vehicular cloud. According to [70], providing heterogeneous hosts in cloud computing environment with a uniform virtual machine homogenizes the resources.

To realize the advantages of virtualization in vehicular cloud, Baron *et al.* [63], proposed a framework for virtualization of resources. The framework consists of a three-layer virtualization architecture made up of the mobile infrastructure provider, mobile service provider and mobile end user. The mobile infrastructure provider has the responsibility of slicing vehicular resources into virtual machines. The controller at the mobile infrastructure provider layer then assigns suitable virtual machines to users. Their study also identified the communication between virtual machines, scalability of virtual machines and the isolation of individual virtual machines as important issues to be considered in vehicular cloud resource virtualization.

B. RESOURCE ASSIGNMENT PHASE

At the resource assignment phase, jobs of clients are assigned to selected vehicular resource nodes for execution. As in all cloud systems, when resource assignment tasks are not carried out efficiently, it leads to problems such as:

- Resource contention: This situation occurs when multiple clients are assigned to and access the same available resource at the same time. This leads to failure in task execution or delay in task execution.
- Over-provisioning: When more than the required resource of a client's application is provided, over-provisioning of resource occurs. This leads to inefficient utilization of resource.
- Under-provisioning: In resource assignment, if the capacity of resource provided is less than the application requirements of a client, it results in the under provisioning of resource.

Resource assignment problems such as resource contention, over-provisioning and under-provisioning of resources lead to a reduction in the Quality of Service. To overcome these challenges, the resource assignment phase tasks namely, prediction of application resource demand, resource brokering, resource schedule and allocation should be carried out efficiently in vehicular cloud.

1) RESOURCE DEMAND PREDICTION

Manvi *et al.* [25], explained resource demand prediction as the process of guessing based on some calculations to determine the actual resources required by an application. Resource demand prediction is important to cloud users as well as service providers. It enables users to make the appropriate financial budget decisions as the resource demand of applications determine the cost of service.

Different techniques have been employed in literature concerning resource demand prediction. A survey conducted by Spinner *et al.* [71], identified and classified published research on resource demand estimation based on prediction techniques such as linear regression, kalman filter, gibbs sampling and machine learning. Ullrich and J [72], also presented a detailed survey of the challenges and approaches for resource demand prediction in cloud computing environment. A resource demand prediction algorithm was proposed in [73] to overcome resource over-provisioning. Using the Fast-Fourier Transform (FFT), burst and noise were eliminated to improve the accuracy of the prediction. To handle the varying cloud resource demand by cloud users, an intelligent regression ensemble prediction approach was proposed by [74]. A meta-heuristic genetic algorithm was then employed in the selection of relevant features. The proposed technique improved the accuracy of prediction and also reduced the execution time and error rate of the prediction.

2) RESOURCE BROKERING

Resource brokering involves the negotiation between service providers and users on the terms of agreement for access to cloud services. It can be carried out by a third party resource broker or by software installed by the user to undertake brokering services.

During resource brokering negotiations, the main focus of cloud users is to ensure that cloud providers guarantee the availability and scalability of resources. For cloud providers, the focus is on selecting suitable clients who can offer an acceptable price for the services they provide. Service level agreement is the output of the negotiations between the service provider and the consumer. It ensures that high Quality of Service (QoS) is achieved. SLA states categorically the obligations and the penalty that must be paid by the cloud provider if agreements are defaulted.

In vehicular cloud environment, resource brokering ensures the commercialization of resources or services provisioned. It is the market-oriented aspect of vehicular cloud computing. Resource brokering in federated vehicular cloud, can also be viewed from the perspective of acquisition of resources from donors by third-party cloud service providers. In this instance, resource brokering is required during the acquisition of resources from donors for the formation of federated vehicular cloud as well as the access of cloud services by users.

Despite the significance of resource brokering, it has received little or no attention in vehicular cloud. Therefore, in this study, we propose a Vehicular Cloud Resource Brokering System (VCRBS).

3) VEHICULAR CLOUD RESOURCE BROKERING SYSTEM

In vehicular cloud, there are frequent disconnections in communication between resource providers and clients due to the high mobility of vehicular resources. The frequent disconnection leads to low reliability and low availability of service. Clients accessing cloud services are at a high risk of having their task not completed in time or even losing service if they select service providers who do not grantee better fault tolerance or fault recovery.

To enable clients to select the most reliable service provider and less-risky services in a region of interest, the proposed VCBRS requires service providers to conduct a risk assessment of their resources or services. The risk assessment includes the probability of failure (PoF) value of their resources and the provisions made for service recovery in case of failure. The PoF is the likelihood that the system (services or resources) will be available and function efficiently for some time t without failure. It is given by the formula: $PoF = e^{-t/MTBF}$. The MTBF (mean time between failures) values are obtained from historic data. It is computed as the total time the system is running divided by the number of breakdowns that occurred over the same period.

The service providers also declare the attributes of their resources including the available duration in a region of interest, risk assessment and cost of the resource. Based on the declared features of the resource, the broker then selects the best resource provider that meets the prospective client's request.

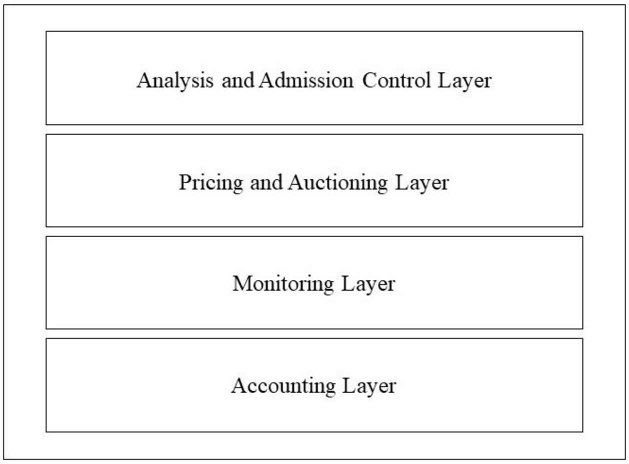

FIGURE 5. **Vehicular cloud resource brokering framework.**

In Fig. 5, the architecture of the VCRBS shown. It is a layered framework where each layer carries out a specific task. The functions of the layers shown in the figure are explained below.

- Service Analysis and Admission Control: This layer is responsible for the analysis of the features of resources or services offered by the cloud provider. At this stage, all the information needed by the resource broker to make a good decision is provided. It includes the PoF, capacity and types of resources available. The resource broker then selects the best resource provider to execute the client's task. The prospective clients of a resource provider may bid for resources in an auction when more than one client request for the same resource at the same time.
- Pricing and Auctioning Layer: This layer is responsible for agreeing on the cost per unit usage of cloud resources or service. Resource providers can either auction available resources or agree to the fixed price stated in the service level agreement. In the instance where auctioning of resources is adopted, the service analyzer and admission control have the responsibility of auctioning. The output of the Analysis and Admission Control Layer and the Pricing and Auction Layer is the Service Level Agreement (SLA).
- Monitoring Layer: At the monitoring layer, the broker analyses monitored data from resource or service usage to ensure that the terms of the SLA are not violated. The results of the analysis from the monitoring layer serve as input for the resource accounting stage.

- Accounting Layer: At the resource or service accounting stage, the payment of cloud usage is done considering the actual resource or service usage. The determination of the type of penalty to be paid by the service provider in case of violation of SLA is also carried out at this layer. The penalty for the defaultment of the SLA could be in the form of discounts for future vehicular cloud use. Defaultment of the SLA also adversely affects the ratings of the service provider.

4) RESOURCE ALLOCATION AND SCHEDULING

Resource scheduling and allocation map client's application demands to assigned resources. Efficient resource allocation and scheduling schemes ensure that the user's requirements agreed in the SLA are met to achieve a high quality of service. It also leads to the efficient utilization of resources.

Aminizadeh et. al. [75], modeled resource scheduling in vehicular cloud as a binary integer programming problem to minimize the cost of application processing. The following constraints were considered:

- All tasks should be completed before the application deadline.
- Tasks should be completed before the expiration of the cloud lifetime.
- There exist a limited number of processing units in each time slot.

They evaluated the effect of the parameters such as data transfer cost, applications deadline, cloud's lifetime and network connectivity in the selection of optimum vehicular cloud resource nodes with the least cost.

Studies carried out in [42], proposed a resource allocation scheme to overcome the problem of intermittent connection in vehicular cloud. Using workflow technology, jobs were divided into tasks and assigned to resources with the least connection fault probability. The connection fault probability of vehicles is the probability of disconnection of a vehicle from the vehicular cloud. It is computed by the contention fault model based on real-time monitoring data from vehicular cloud.

Nabi *et al.* [76], considered scheduling task over unrelated or heterogeneous machines that are not always available. With the assumption that tasks to be scheduled are non-preemptive (tasks that start on a resource cannot be interrupted until completion and if tasks are migrated they resume immediately), they proposed a task scheduling technique that minimizes the cost of renting vehicular resources.

To maximize the number of applications that can be served, a resource scheduling scheme for roadside cloud was proposed by [77]. The scheduling scheme was modeled as a mixed integer linear programming problem to minimize the response time for applications as well as reduce the number of virtual machine migrations.

A resource scheduling scheme for Networked Fog centers (NetFCs) in roadside cloud was proposed by [44]. The scheme provides communication and computing energy improvement through the effective management of input/output traffic, resource reconfiguration and consolidation of virtualized fog platforms. The scheduling scheme also guarantees QoS for compute-intensive and delay-sensitive Infrastructure to Vehicle (I2V) services.

Ghazizadeh *et al.* [78], presented a scheduling technique that aims to resolve the problem of low availability of resources in vehicular cloud. Considering static vehicular cloud, they proposed a job scheduling scheme for non-preemptive and non-parallel executable jobs. The problem was formulated as Mixed Integer Linear Programming (MILP) to determine the optimal job schedule by maximizing the utilization of resources and minimizing the number of virtual machine migrations.

A task scheduling scheme using Mixed Integer Linear Programming (MILP) to increase the computation reliability and reduce job execution delay in vehicular cloud was proposed by Adhikary *et al.* [79]. They considered job execution in a distributed manner by adopting the MapReduce computation model where jobs are decomposed into tasks and scheduled or mapped to dedicated nodes for execution. The results from map tasks are then scheduled to other nodes to undertake to reduce to task. The results are then sent to the cloud controller for onward transmission to the vehicles that requested the execution of the job. Through simulations, they showed that the scheduling scheme minimizes the total execution time.

To enhance reliability and dependability in vehicular cloud, Ghazizadeh [62], proposed the J_n redundancy job scheduling scheme in static vehicular cloud. In the scheduling scheme, n vehicles are selected to execute the same job concurrently. When any of the n vehicles assigned a task is to exit the vehicular cloud before the completion of the task, a new vehicle is selected to continue with the task execution. The mean time to failure (MTTF) of the J_n scheme was examined considering two variants of the J_n scheme : J_2 and J_3 were considered.

The J_n redundancy job scheduling scheme was also implemented in [80] considering Military Vehicular Cloud (MVC). As a unique class of vehicular cloud, MVC involves parked or mobile military vehicles that provide cloud services for military applications. The reliability of J_n job scheduling scheme was also analyzed in the MVC using the dependability metrics Mean Time to Failure (MTTF).

A Cooperative and Adaptive REsource Scheduling Scheme (CARESS) was proposed in [81] to manage and schedule resources without relying on roadside infrastructure. The goal of the technique is to achieve the quality of service requirements of clients by taking into consideration the high mobility and highly dynamic topology of vehicular cloud. The CARESS protocol uses the cache mechanism for resource registration. The cache is created by beacon messages with data from vehicles. The cached data which include the position of vehicular resource, type of available resource, the direction of vehicular node and the identity of the vehicle are updated regularly. Using the time of data received at the cache and position of vehicles, the cloud controller orders the resources of vehicles. Tasks are then assigned to the resource on top of the cache that meets the client's requirements.

Studies in [82], proposed a resource allocation scheme in dynamic vehicular cloud using clustering architecture. The resource allocation problem was formulated as a Semi-Markov Decision Process (SMDP) to minimize the expected average reward of the system and improve the resource utilization time. High expected reward and good resource allocation decisions were obtained by solving the SMDP using the value iteration algorithm.

In order to maximize the parallel execution of tasks across mobile computation resources in vehicular cloud, Kim *et al.* [83] proposed a large scale job partitioning and allocation algorithm. The algorithm determines the optimal number of tasks a job can be divided into and distributed to vehicles to minimize the overall job execution time.

Zheng *et. al.* [84] proposed a resource allocation and scheduling scheme with the design goal as maximizing the total long-term expected reward of the vehicular cloud system in a region of interest. The reward considered both the income and cost of the vehicular cloud system. The characteristics of individual resources that make up the cloud system such as available capacity were also factored in the overall reward of the cloud system. They used the iteration algorithm to determine the best decisions. Their results showed significant reward gains and also indicated that SMDP outperforms simulated annealing and greedy allocation schemes. They also concluded that SMDP based schemes have lower complexity than simulated annealing.

C. POST RESOURCE ASSIGNMENT PHASE

The post-resource assignment phase involves resource management tasks that are carried out after resources are assigned. The tasks that make up this stage consist of resource monitoring and virtual machine migration. The main aim of the post resource assignment phase is to ensure that the tasks of clients being executed are not interrupted. If post resource assignment tasks are efficiently undertaken, it leads to a high quality of service and experience.

1) RESOURCE MONITORING

Monitoring is a crucial task that is taken to evaluate the performance of a system. It has been employed in different distributed computing paradigms such as grid and cloud computing. It is made up of two main components, resource monitoring and application performance monitoring.

Application performance monitoring involves checking the progress of applications to ascertain whether they are running smoothly or not. Application performance monitoring in cloud computing is important for both service providers and consumers [85]. The results from application performance monitoring affect the cost of accessed services. Key metrics for application performance monitoring include bandwidth consumption, memory demand and CPU utilization.

Resource monitoring is the process of determining the status of resources that have been assigned to execute a client's task. It is an important part of cloud computing [86] as other resource management tasks such as virtual machine migration are carried out based on the output from resource monitoring. Resources monitoring also provides application guarantees such as performance, availability and security [87], [88].

To ensure efficient monitoring in cloud computing systems, different monitoring tools such as JTangCMS [89], have been proposed in literature. Commercial cloud providers however, use their in-house designed monitoring systems as they are domain specific. For example, Amazon Web Services (AWS) uses Amazon CloudWatch [90] while Google cloud uses Stackdriver [91].

One of the main challenges of resource monitoring in vehicular cloud computing is the communication overhead caused by the frequent transmission of monitored data. The frequency of transmission of monitored data, however determines the efficiency and consistency of the monitoring system. The relationship between consistency and efficiency of resource monitoring is therefore a challenge [92]. If the frequency is high, the monitored data becomes consistent but less efficient as it leads to more communication overhead.

To overcome the challenge of communication overhead, the client-server architecture and the push and pull communication models are used. In the pull model, the server ''pulls'' data from the monitoring agent installed on the resource at regular time intervals for analysis. In the push model, the monitoring agent installed on the resource ''pushes'' monitored data to the server for analysis whenever there is a change in the status of the resource.

Huang et. al. [92], proposed a combined push and pull model where an intelligent selection of either push or pull model is used. The suitable model is considered after comparing the status of the monitored resources and the required status of the resource. The combined approach leads to a decrease in the updating cost and its more consistent than both the pull and push approaches used independently.

Bradit *et al.* [93], used statistical analysis to scale down the data collected. Studies in [94] proposed the use of prediction mechanisms to determine when to pull or push messages in a monitoring system to overcome the network overhead problem.

Resource monitoring tools in grid and conventional cloud computing are not efficient in vehicular clouds due to the large number of resources, communication overhead and the high mobility of resources. In the peer-to-peer vehicular cloud, there is no central monitoring point. This further complicates the task of resource monitoring in vehicular cloud.

Although many works have been carried out on monitoring resources in grid and cloud computing, vehicular cloud computing resource monitoring is yet to gain the attention of researchers.

In this study, we therefore, propose a framework for resource monitoring in vehicular cloud computing.

2) VEHICULAR CLOUD RESOURCE MONITORING FRAMEWORK

The agent-based monitoring approach presented in [95], is adopted in our proposed framework. A monitoring agent responsible for gathering and transmitting monitored data is installed and configured on all resources in the vehicular cloud.

In Fig. 6, the architecture of the Monitoring Agent (MA) is presented. The layers of the MA are the application monitoring layer, the virtual machine monitoring layer and the physical resource monitoring layer. These layers are responsible for gathering and transmitting the status of the application, virtual machine and physical resource respectively.

The MA transmits monitored data to the vehicular cloud resource controller after cloud services have started.

At the resource controller, the Monitoring and Decision System (MDS) is installed. The MDS is responsible for the analysis of monitored data. The results of the analysis are then communicated to the resource controller for resource management decisions to be carried out.

Using the mobility pattern of resources and monitored data sent from the monitoring agent, the MDS undertakes an online prediction of the status of the system. Whenever there are possible changes in the status of the resource, the MDS pulls monitored data from the Resource Monitoring Agent(RMA).

At the end of each service delivery, the MDS sends a report of the monitored data to the cloud controller for billing and other user-specific decisions to be made. In the peer-to-peer system where there exists no central cloud controller, the monitoring and decision systems are installed on the vehicles providing the services. Since the MDS is a lightweight application, it can be installed on clients' devices so that they can also monitor the progress of services they are accessing.

In the monitoring framework, resources or vehicles that are not part of the provisioned cloud can also be monitored by the cloud controller. This will help to determine prospective service providers in a region of interest. However, it may propound the challenge of large overhead in the transmission of monitored data and invade the privacy of vehicle owners who are not part of the vehicular cloud. Resource monitoring is therefore limited to only the vehicular resources that are part of the cloud.

3) VIRTUAL MACHINE MIGRATION

Virtual Machine Migration (VMM) is the process of transferring the virtual machine from its current physical machine to a new physical machine. VMM can be done whiles the virtual machine is processing a task. This is termed as live or online virtual machine migration. Offline Virtual Machine Migration is where the VM task is paused or halted before migration takes place. In conventional clouds, virtual memory migration is mainly done to ensure load balancing and energy optimization in data centers.

In vehicular cloud, one of the main functions of VMM is to ensure that, tasks being processed are not lost as a result of network disconnection or node failure. When a resource node loses network connectivity with the cloud user or the cloud controller, tasks that are being processed may be lost. Through virtual machine migration, the virtual machine on which the tasks are being executed can be migrated to a new virtual machine before the disconnection from vehicular cloud occurs.

Due to the highly mobile and intermittent connection of nodes, a significant number of virtual machine migration takes place in vehicular cloud. Without efficient VMM technique, tasks execution started by a node that losses connection with cloud or client has to be restarted by a different node. This leads to large delays in job completion time, performance degradation and inefficient utilization of resources.

To overcome the challenge of inefficient virtual machine migration, [96], proposed a resource reservation mechanism where some resources are solely reserved as the destination for virtual machines that are to be migrated. Though they argued that the virtual machine drop rate can be significantly reduced by their proposed technique, resource utilization will not be maximized. This is because a large number of redundant resources may exist if VMMs are not carried out.

K. Rafaat *et al.* [97] in their work, examined different mechanisms and factors to consider in virtual machine migration. The main contribution of the paper was the introduction of mobility in VM migration. To reduce the intervention of RSUs in virtual Machine migration, three different VMM models were proposed and their performance compared through simulations. The VMM models proposed are explained as:

- Vehicular Virtual Machine Migration-Uniform: Uniformly select destination host for VM migration before vehicles depart from the coverage area of RSU.
- Vehicular Virtual Machine Migration-Load Aware: Migrates VM to vehicles with least workload
- Vehicular Virtual Machine Migration-Mobility Aware: Migration to VM with least workload as well as predicted to be within the geographic boundaries of the Vehicular cloud

Through simulations, they showed that if the predicted future location and the current workload on targeted virtual machine migration destination nodes are taken into consideration virtual machine migration achieves the best results in vehicular cloud.

Though the study considered the prediction of mobility in virtual machine migration, they did state the prediction model used in their study. Also, they aimed to reduce the intervention of RSUs in migration. However, it can be argued that the involvement of RSU in resource management tasks in vehicular clouds is an advantage as they introduce some element of stability due to their stationary nature.

Baron *et al.* [63], examined the effect of the number of contacts and the duration of contacts between vehicles during

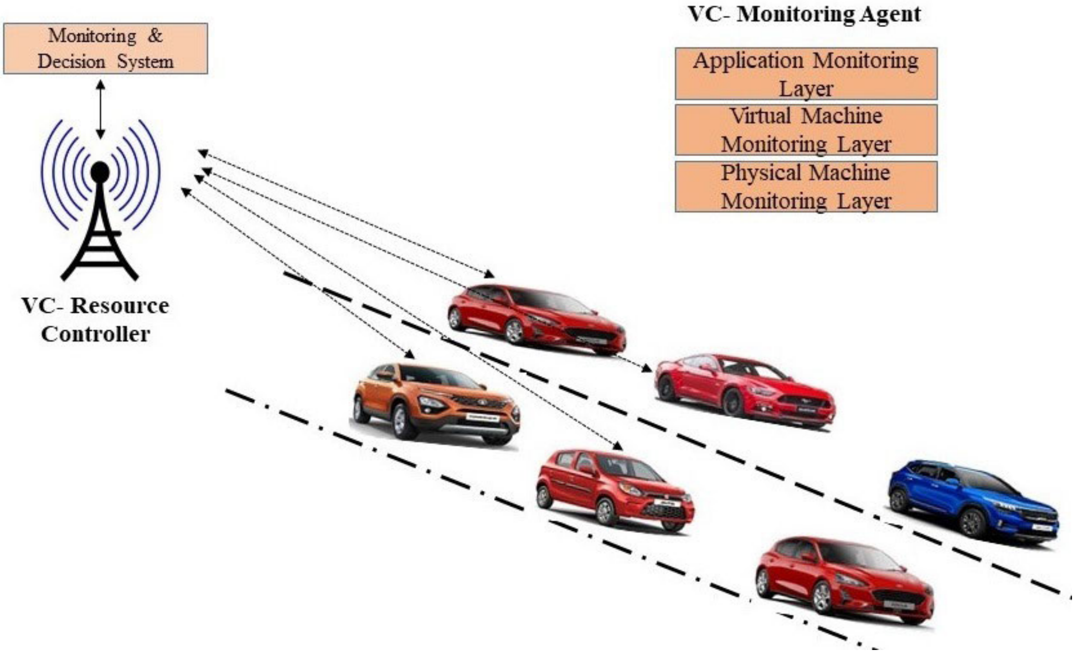

FIGURE 6. Resource monitoring framework for vehicular cloud.

a VMM involving only vehicles. Using realistic vehicular traces of the public transit system of Dublin city for simulations, they showed that using V2V communication among buses with a known number of contacts and the duration of contacts among vehicles, large data or virtual machines can be migrated from source to destination. They concluded that a larger number of contacts and higher duration of contacts among vehicles make virtual migration in vehicular cloud more successful. Though the study showed the effect of number and duration of direct contacts between source and destination of VMM, it is worth pointing out that VMM can still take place without direct contact between vehicles using V2V multi-hop communication between VMM source and destination.

VI. OPEN ISSUES, CHALLENGES AND RESEARCH DIRECTIONS

From the extensive review of literature carried out, we observed that while other distributed computing paradigms such as grid computing and conventional cloud computing can be considered as matured and well developed, vehicular cloud computing, on the other hand, is in its initial or conception stage. This implies that a lot of studies and research need to be carried out to address the many challenges of vehicular cloud before it is fully deployed. In this section, we present some open issues and future research directions for vehicular cloud.

A. DEPENDABILITY OF VEHICULAR CLOUD SERVICES

With the increase in critical and delay-sensitive applications that are expected to be hosted on vehicular cloud, the ability to provide dependable services to clients is very significant. Dependability of cloud service is the ability to perform its required function at a given time. It determines the trustworthiness and level of confidence in a system by stakeholders [98].

For vehicular cloud to be accepted and fully deployed, adequate measures must be put in place to ensure the high dependability of services. In [98], the principles of dependability of a system were identified as reliability, availability, safety, security, and resilience. In this study we adopt, these principles to enforce the dependability of vehicular cloud services.

1) SAFETY AND SECURITY

The safety and security of a system is its ability to resist intrusions and prevent damages to the system, people, and environment [98]. In vehicular cloud, there exist a lot of security and safety concerns. This is because unlike resources in datacenters of conventional cloud that are in a physically secured location, vehicle on the road are without any physical confinement or protection. Also, personal information such as vehicle's location and identity are part of almost all communications in vehicular environment as most services and applications in vehicular cloud such as traffic management systems are location-based. Vehicular cloud is therefore, exposed to both physical and cyber attacks such as Denial of Service (DoS) and spoofing user identity. Advanced security measures such as messages encryption must be employed to make vehicular cloud more secured.

2) AVAILABILITY, RELIABILITY AND RESILIENCE

Availability, reliability and resilience can be collectively explained as a system's ability to deliver services that meet the expectation of users at any given time, even in the presence of disruptive events [98]–[100]. In vehicular cloud reliability, availability and resilience of services is a key challenge. This is due to the high mobility of vehicles which causes unpredictable and short occupancy time of vehicular resources in a region of interest on the road where cloud services are provisioned. Also due to the distributed ownership nature of resources, the ability to provide an illusion of unbounded and scalable access to resources and services may not be guaranteed.

To ensure high availability, reliability and resilience of vehicular cloud services, effective system maintenance, and recovery measures must, therefore, be adopted. Duplication of the execution of task and Check-pointing are key measures that have been considered in vehicular cloud. In duplication of the execution of tasks, multiple execution instances of the same tasks are carried out on different vehicular nodes while Check-pointing involves frequently creating backups of tasks in execution. In the case of failure of a vehicular node, the checkpoints and duplicates are reinstalled on a new node for execution to continue. For check-pointing and duplication of execution to be efficient in vehicular cloud, further studies should be considered to make them more effective by determining when to carry out check-pointing and the number of duplicates that should be taken in order not to have many redundant checkpoints or duplicate execution points and communication overhead.

Other measures include the incorporation of fault tolerance schemes such as job re-submission and job migration in resource management tasks such as task scheduling.

B. LACK OF STANDARDS

In vehicular cloud computing, there are no universally accepted multinational bodies responsible for regulating and coordinating the design, operations and services of cloud providers. This does not only lead to the lack of standards and protocols among different vehicular cloud providers but also the lack of standardized accepted definitions of vehicular cloud terminologies.

Clues can be taken from other computing paradigms such as conventional cloud and telecommunication networks to establish global or national institutions such as the National Institute of Standards and Technology (NIST) and the International Telecommunication Union (ITU), which develop and document standards. In some instances, they may also be responsible for coordinating and monitoring the activities of vehicular cloud service providers.

C. VEHICULAR CLOUD CLUSTERING

From the study carried out, we observed that there is no dedicated infrastructure for the management of resources in vehicular cloud. To overcome this challenge, we recommend the clustering of vehicles to provide efficient management of resources.

Although some studies consider the idea of clustering in vehicular cloud, most of them adopt existing VANET clustering algorithms without modification. This approach has some limitations. Clustering algorithms in VANET were mostly designed for the routing of messages among vehicles and not the provision of cloud services. In most of the existing clustering algorithms, only the mobility characteristics of the vehicles such as speed, direction and location of vehicles are considered in the formation of clusters.

Future works should be focused on designing new clustering protocols or existing VANET clustering protocols should be modified to consider the resource characteristics of vehicles such as type of resource available and the cost of services provided.

D. VIRTUALIZATION OF RESOURCES

Virtualization of resources in cloud environment is very significant. Virtual machine hypervisors and cloud containers enable the configuration of multiple virtual machines on a single physical machine. In conventional cloud, different virtual machine hypervisors and cloud containers such as Xen [111] Docker [112] have been developed. To the best of our knowledge, there exist no standardized virtual machine hypervisors or cloud containers for vehicular cloud in literature. Considering the high mobility characteristics of resources in vehicular cloud, the adoption of conventional cloud virtualization platforms may not produce optimal performance. The design of mobility aware virtual machine hypervisors and containers that have low configuration and set-up time should be considered in future studies.

The sporadic nature of vehicles leads to some vehicles leaving the vehicular cloud before the completion of tasks assigned to them. If the frequency of such occurrences are not properly managed it causes tasks being executed to be lost and decrease in the quality of service provided by the vehicular cloud. To overcome this challenge, the selection of resources (physical machines) to host virtual machines should consider possible future mobility and location of vehicles. Vehicles that are likely to remain in the vehicular cloud for longer period should be selected for execution of critical tasks. Advanced prediction models of vehicular mobility pattern using realistic mobility traces should be proposed. This will help in the design of mobility and location-aware virtual machine placement schemes.

Since frequent virtual machine migration is a key characteristic of vehicular cloud, future works should explore live virtual machine migration (VMM) in vehicular cloud. Live VMM techniques to maximize resource utilization as well as minimize the communication cost or job completion time is an open research in vehicular cloud.

E. RESOURCE BROKERING

The design of efficient resource brokering systems is a challenge in vehicular cloud. This is due to the highly mobile nature of vehicular resources and the lack of centralized infrastructure to carry out resource or service brokering. The negotiation process involved in resource brokering can accept little or no delay due to the high mobility of vehicles. Delay

TABLE 3. **Comparison of key resource management studies in literature.**

Publication	Contributions	VC Type	Architecture	Provision Model	Cloud Service	Experimental Platform
Arif [11]	Predicted of vehicular occupancy periods of in parking lots with time-varying arrival and departure rate. A probability distribution model as a function of time was provided to estimate the expected number of cars and its variance.	Static	IVC	Federated	NaaS CaaS, STaaS	Mathematical modeling
Dressler [12]	Provision of storage services using parked vehicles along roads which are organized into line clusters	Static	IVC	P2P	STaaS	Veins[104], SUMO [105]
Arkain [57]	Clustering of vehicles for the formation of vehicular cloud. Used fuzzy logic for cluster head Selection. The best service provider vehicle in a RoI was selected via the Q-reinforcement learning technique	Dynamic	IVC	P2P	CaaS, STaaS	OMNet++ [106], SUMO [105]
Azizaian[58]	Presented the formation of non-overlapping D-hop clusters of vehicles to provide cloud services. An optimal scheduling scheme to maximize throughput and minimize delay was also proposed.	Dynamic	IVC	Federated	DaaS	NS2[107], SUMO[105], Gurobi Optimization [108]
Ridhawi [60]	Considered the formation of clusters of vehicular resources based on the similarity of mobility and services they provide	Dynamic	IVC	P2P	Not specified	CaaS
Crown [50]	Proposed a service discovery protocol where vehicles register their services with the nearest RSU. Clients are required to search the nearest RSU for the most suitable cloud service provider vehicle in a RoI on the road.	Dynamic	IVC	Hybrid (Federated & P2P)	NaaS, STaaS, Daas	NS2[107], SUMO [105]
Kim [86]	Proposed a capacity distribution model based on sigmoid function to determine the optimal number of job partitions to minimize overall execution time	Static	IVC	Federated	CaaS	Mathematical modeling
Kim [109]	Modeled vehicular datacenter at parking lots using checkpoint mechanism to reduce failure rate caused by frequent departure of vehicles.	Static	IVC	Federated	STaaS	Mathematical modeling
Rafaat [100]	Proposed and compared different physical machine selection schemes for virtual machine migration in dynamic vehicular cloud	Dynamic	IVC & RSC	P2P	Not specified	MATLAB [110]
Li [111]	Proposed a resource discovery framework with different selection schemes to select the best vehicular node for computation offloading.	Dynamic	IVC	Federated	CaaS	Self-developed platform (Java)
Menenguette [84]	Developed a resource scheduling mechanism that considers the mobility and resource characteristics of vehicles.	Dynamic	IVC	Federated	CaaS	Omnet++[106], Veins[104], SUMO [105]
Ghazizadeh [80]	Presented a near-optimal task scheduling scheme based on mixed integer linear programming.	Static	IVC	Federated	CaaS	MATLAB [110], Gurobi Optimization [108]
Petra [78]	Proposed a roadside cloud resource scheduling scheme using MILP. The main goals of the scheme is to maximize the number of applications accepted by the vehicular cloud service provider while reducing the response time and number of virtual machine migrations.	Static	RSC	P2P	STaaS, CaaS	ONE[112], SUMO [105]
Shojafar [79]	Proposed an energy adaptive scheme for Networked Fog Centers (NetFCs) in roadside cloud to support QoS demanding compute intensive and delay sensitive I2V services.	Static	RSC	Hybrid (Federated & P2P)	CaaS, STaaS	MATLAB [110]
Zhang [65]	Presented a stochastic analysis of the number of vehicles available for formation of vehicular cloud in a section of the a road. The two main traffic scenarios: free flowing and queueing-up traffic scenarios were considered.	Dynamic	IVC	Not specified	Not specified	Mathematical modeling
Adhikary [81]	Proposed a task scheduling scheme using MILP to optimize the computation reliability and reduce job execution delay.	Dynamic	IVC	Federated	CaaS	NS-3[113], SUMO [105]
Ghazizadeh [82]	Examined the mean time to failure (MTTF) of redundancy based job scheduling strategies.	Static	IVC	Federated	IaaS	In-house simulator(details not given)

tolerant resource brokering techniques for vehicular cloud computing should therefore, be designed.

It is envisaged that in the future vehicular cloud will fully be deployed in sections of roads in urban areas. This implies that every vehicle with enough resources can be considered as a vehicular cloud service provider. Inter-cloud resource brokering in vehicular cloud will arise if users require resources from different service providers to accomplish a task. Inter-cloud resource brokering in vehicular cloud should therefore be investigated.

In this study, we have proposed a framework for brokering in vehicular environment. For future studies, we will carry out simulations to measure the efficiency of the framework. Improved techniques for ranking and selecting resources to meet the user's requirements would also be incorporated into the proposed framework.

F. RESOURCE SCHEDULING

The volatile nature of resources leads to the challenge of low availability and reliability of vehicular cloud. Some existing resource scheduling algorithms in literature such as [62] have incorporated redundancy-based reliability schemes like multiple resource assignment to a single task. Although such schemes provide some level of availability and reliability, they lead to the inefficient utilization of resources as some redundant resources may remain unused. Accurate availability time of resources must be predicted before assigning tasks to them for execution.

VII. CONCLUSION

Resource management in vehicular cloud computing is an important but complex process that has a lot of challenges. These challenges arise as a result of the unique characteristics of vehicular nodes such as high mobility, resource heterogeneity and intermittent network connection among vehicular nodes. Due to the characteristics of vehicular cloud resource nodes, proposed solutions to resource management challenges in conventional and mobile clouds, may underperform in vehicular cloud. New solutions, therefore, need to be designed and existing ones modified.

In this article, we have examined the challenges and research issues in vehicular cloud resource management. All the main resource management techniques involved in vehicular cloud have been highlighted. Also, proposed solutions in literature for the different resource management challenges have been analyzed in detail. This study, will therefore, serve as a guide in the design of efficient resource management techniques and also provides research directions for new researchers.

Based on the findings from this study, our future works would aim to incorporate mobility-aware schemes in the design of new and more efficient resource management techniques such as mobility-aware virtual machine migration and task scheduling for vehicular cloud.

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