Context-Aware Vehicular Cyber-Physical Systems with Cloud Support: Architecture, Challenges, and Solutions

Jiafu Wan, Daqiang Zhang, Shengjie Zhao, Laurence T. Yang, and Jaime Lloret

ABSTRACT

The advances in wireless communication techniques, mobile cloud computing, and context-aware technologies boost a growing interest in the design, development, and deployment of vehicular networks for emerging applications. This leads to an increasing evolutionary tendency to change from vehicular networks toward cloud-assisted context-aware vehicular cyber-physical systems. In this article, we first propose a multi-layered context-aware architecture and introduce two crucial service components, vehicular social networks and context-aware vehicular security. Then we propose an application scenario regarding the context-aware dynamic parking services by illuminating the cloud-assisted architecture and logic flow. Finally, we investigate the challenges and possible solutions, including context-aware safety hazard prediction, context-aware dynamic vehicle routing, and context-aware vehicular clouds.

INTRODUCTION

With the development of mobile cloud computing (MCC), context-aware technology, and dedicated short-range communication, vehicular networks with the capabilities of decision making and autonomous control can be upgraded to cloud-assisted context-aware vehicular cyber-physical systems (CVCs). In our view, the CVC can be regarded as an evolution of vehicular networks by utilizing more intelligent and interactive operations. The applications and services in a CVC often form multiple end-to-end cyber-physical flows that operate in multi-layered environments to provide quality of service (QoS) assurance such as timeliness, reliability, and convenience.

MCC can provide a flexible method of handling massive computing, storage, and software services in a scalable and virtualized manner [1]. The integration of MCC and vehicular networks is expected to promote the development of cost-effective, scalable, and data-driven CVC. The promising CVC highlights some emerging applications and services. For example, we hope to offer a number of safety applications to improve road safety and traffic efficiency, as well as to enable a clean environment. As for the scalability of cloud services and computation layers, the architecture of a CVC may be divided into three interactive layers: the vehicle computational layer, the location computational layer, and the cloud computational layer.

Recently, a few research projects have reported studies on the combination of cloud computing and vehicular networks. In [2], the concept of autonomous vehicular clouds was proposed to exploit the underutilized resources in vehicular ad hoc networks (VANETs). The work in [3] proposed architectures of vehicular clouds, vehicles using clouds, and hybrid clouds. Vehicles act as cloud service providers and clients. In [4], the hierarchical cloud architecture for vehicular networks was proposed, and the proposed architecture included a vehicular cloud, a roadside cloud, and a central cloud.

The introduction of context-aware technology [5] may provide more convenience and safety guarantees for drivers, passengers, and pedestrians, and may enable the emergence of numerous novel applications in the domain of vehicular environments. For example, a context-aware service could be a real-time traffic update or even live video feed of a planned route for the driver. In the vehicle computational layer, in-vehicle context-aware systems aim at taking into account more contextual information related to the driving task in order to produce adapted or customized actions [6]. The work in [7] developed a driver behavior detection system using context-aware technology to detect abnormal behaviors exhibited by drivers, and warn other vehicles on the road to prevent accidents from happening. In [8], a solution for the collection, management, and provision of context-aware information on traffic and current location for the road environment was designed. Also, context-aware technology could be exploited for location and cloud computational layers to realize dynamic vehicle routing, as well as richer service contents.

In this article, we propose a context-aware

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architecture with mobile cloud support for vehicular cyber-physical systems (VCPS). Our work is different from previous research in three aspects. First, we aim to create a context-aware pervasive system for mobile vehicles, drivers, passengers, and relevant traffic authorities by designing a multi-layered architecture with cloud capability. Also, each layer may provide multiple context-aware services. Second, we analyze two remarkable service components (vehicular social networks and context-aware vehicular security) in CVC, and then present a context-aware application scenario exemplified by dynamic parking services to improve the QoS of VCPS. Third, we emphasize the challenges and possible solutions, including context-aware safety hazard prediction, a context-aware routing protocol, and a context-aware vehicular cloud.

The remainder of this article is organized as follows. We illustrate the proposed architecture, including multi-layered features and crucial service components, in the next section. After that, we envision a promising application to alleviate the parking difficulties in the current situation. Next, we focus on the challenges and possible solutions to the problem of VCPS, and some rational suggestions are proposed to improve the safety and convenience services. Finally, our conclusion is presented.

Cloud-Assisted Context-Aware Architecture

According to hierarchical spatial regions, the applications and services in CVC can be divided into three different computational layers: vehicle, location, and cloud. In this section, we propose a context-aware architecture with mobile cloud support and two crucial service components. Figure 1 shows a considered cloud-assisted context-aware architecture.

Multi-Layered Architecture

In the vehicle range, onboard equipment (OBE) installed in the vehicle can provide all kinds of services (e.g., GPS navigation and entertainment). Above all, it can acquire both environment and body parameters, and provide versatile man-to-machine interaction by the aid of wired/short-range wireless technologies and some special sensors. For example, we may design a context-aware safety system by capturing the static and temporal aspects of behavior, and then performing probabilistic inference.

In the location computational layer, roadside equipment (RSE) deployed at strategic locations can exchange information with OBE installed on vehicles passing by. Both RSE and neighboring OBE are interconnected and share context-aware traffic information and entertainment resources. Vehicles outside the range of any RSE may still be connected to the rest of the vehicle and infrastructure network via neighboring vehicles. This vehicle and infrastructure network can generate accurate real-time traffic information based on some fundamental traffic problems related to efficiency, which can be addressed well from a brand new perspective [9].

In the cloud computational layer, an increasing number of applications and services (e.g., vehicle multimedia contents and historical traffic information) supplied by diverse corporations and related traffic authorities are gradually becoming a reality. In Fig. 1, an inter-cloud environment in CVC includes multiple cloud systems running with different policies working with each other to share resources so that end-to-end QoS to users can be maintained even in the event of large fluctuations in computing load which cannot be handled by a single cloud system. The interactions among the different types of clouds are achieved through inter-cloud root data centers that are connected to a wireless network environment under the help of a service gateway such as the one described in [10].

Crucial Service Components

In CVC, the service components include the vehicular cloud, different kinds of smart terminals (e.g., OBE and smartphones), vehicular social networks, context-aware vehicular security, and so on. In particular, online and/or vehicular social networks can be relevant and helpful for traffic efficiency and infotainment. Also, security and privacy are two primary concerns in the design of CVC. Therefore, we focus on two remarkable service components (vehicular social networks and context-aware vehicular security) in this subsection.

Vehicular Social Networks — With the support of vehicular social networks, VCPS will open up some emerging services (e.g., real-time traffic information prediction) that are user-oriented beyond on-road safety. It is expected that vehicular social networks will be a growth area in terms of deployment and applications. Thus, the CVC will increasingly incorporate the analysis of vehicular social networks into intelligent transportation analytics. The research contents of CVC introduced into vehicular social networks include not only traffic status studies, but also analysis modeling of traffic development forecasting and planning, traffic safety and education, and the study of traffic organizations and systems. The methods discussed (e.g., traffic data mining and mobile crowd sensing) are mainly applied to this emerging field.

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Context-Aware Vehicular Security — The security and privacy issues in CVC are reflected in the different layers. Context-aware vehicular security mechanisms (CVSMs) may dynamically adapt to a user's situation based on the provided context. Context can be incorporated into various security services, such as access control, encryption, and authentication. Context can also be incorporated into security in different ways such as supplementing user attributes and replacing user attributes.

In order to implement CVSMs, we should design a context-aware vehicular security framework that may include several functional units (e.g., data collection, policy management, misbehavior detection, and trust management). The data collection unit is mainly responsible for collecting vehicular context data and vehicular behavioral data, and then sending them to the policy management unit, the malicious detection unit, or the trust management unit. The trust management unit assesses the trustworthiness of each vehicle. Through the use of various pieces of vehicular context information (e.g., road conditions, speed and time factors), a vehicle can determine the circumstances under which misbehavior occurs.

A Case Study: Context-Aware Dynamic Parking Service

As the number of vehicles increases, there is an increasing trend of insufficient parking spaces in many large cities, and this problem is gradually getting worse. In addition to employing multilevel parking garages, we believe that, with the support of some emerging technologies such as wireless sensor networks (WSNs) and cloud computing, the potential exists to alleviate this problem using context information (e.g., road conditions and status of parking garages) to provide context-aware dynamic parking services (Fig. 2). In this section, we describe cloud-assisted parking services that address two types of scenarios for drivers: traditional parking garages and dynamic parking services along the road. In addition, we describe support for a parking reservation service using smart terminals such as smartphones.

We propose a framework for a context-aware parking service system with MCC capability, and emphasize cloud-assisted architecture, the decision making process of traffic authorities, and

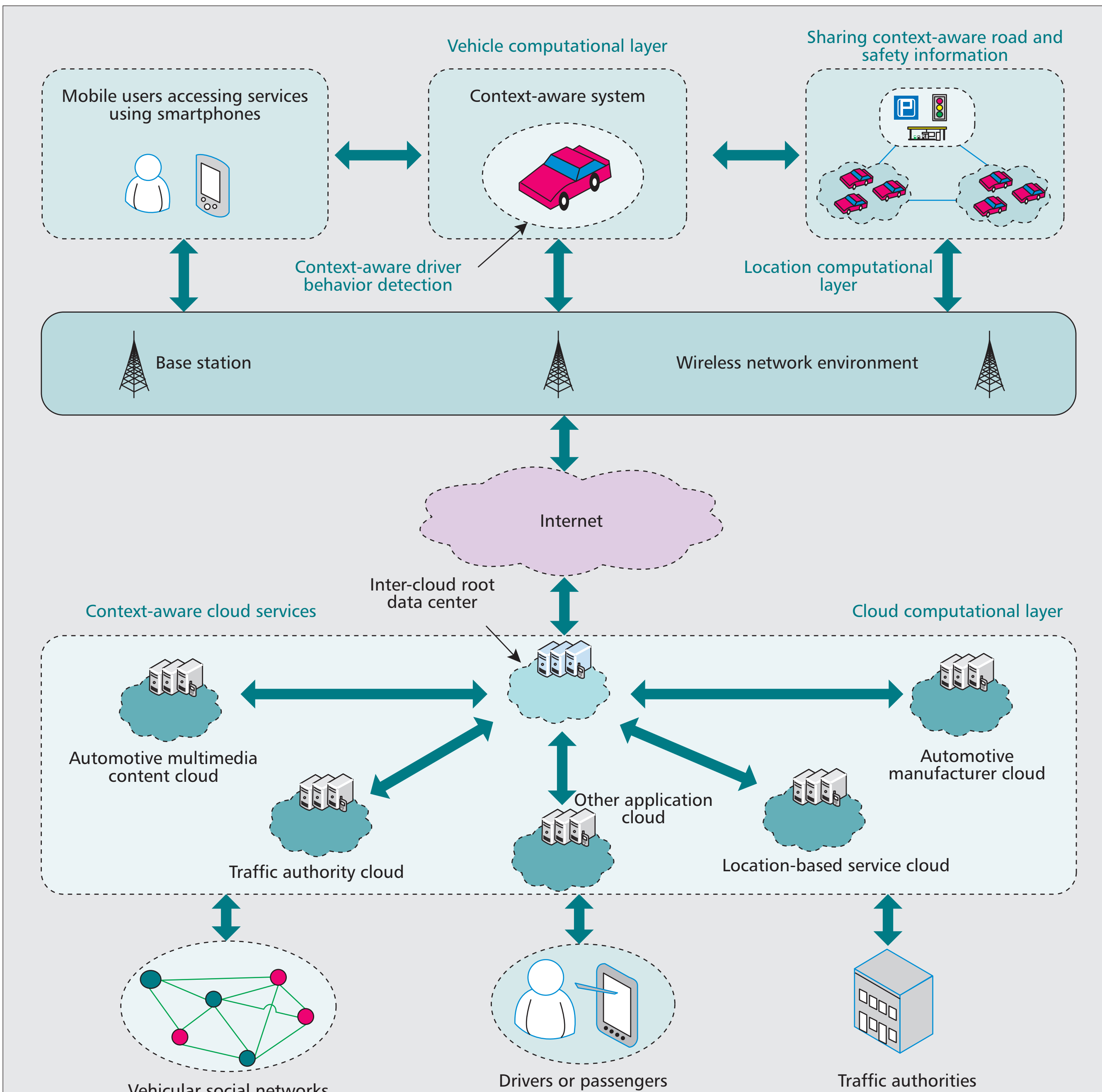

Figure 1. Example cloud-assisted context-aware architecture.

parking reservation service. The following introduces two types of parking spaces.

Traditional parking garages: The context information of each parking space detected by a WSN is forwarded to the traffic cloud by WSNs, third-generation (3G) communications, and the Internet. The collected data are processed in the cloud and then selectively transmitted to the users. This is helpful for providing more convenience services and evaluating the utilization levels of the parking garage. Also, the status of the parking garage may be dynamically published on a nearby billboard to users who have no ability to get the status by smart terminals.

Dynamic parking services: In this scenario, we consider a situation in which we may temporarily park a vehicle along the road if it does not impede the passage of other vehicles or pedestrians. We envision this application scenario based on the common observation that the traffic flow capacity is usually regular for each road. For example, there is usually heavy traffic during morning and evening rush hours. Therefore, considering the context information such as rush hours and road conditions, we may dynamically arrange the parking services for a very wide road. With the support of many new technologies (e.g., MCC and WSNs), the traffic authorities can carry out the dynamic management of this kind of service.

In the proposed framework, we analyze three aspects, including service planning of traffic authorities, reservation service process, and context-aware optimization.

Decision making of traffic authorities: The decision-making process of the proposed scheme heavily depends on many factors, such as historical traffic flow capacity, road conditions, weather conditions, and traffic flow forecasting. In order to make an effective prediction, researchers on vehicular social networks carry out traffic data mining to discover useful information and knowledge from collected big data. The prediction process depends on classifying the influence factors and designing a decision tree. Decision references from academia can also be provided to traffic authorities. By the method of probability analysis, the traffic authorities dynamically arrange whether the road can be authorized to provide context-aware parking services. In some particular cases, a fatal factor may directly affect the decision making. For example, when a typhoon is approaching, traffic authorities may immediately terminate services.

Parking reservation services: As shown in Fig. 2, the status of a parking space can be monitored as determined by the corresponding system, and subsequently updated in the traffic cloud. The drivers or passengers can quickly obtain the parking space's information by various smart terminals such as smartphones. If a proper parking space cannot be found, we may extend the scope for further search. Within a given time, we may log into the traffic cloud and subscribe to a parking space. The logical flowchart of a parking reservation service in CVC is given in Fig. 3.

Context-aware optimization: The context information includes not only road conditions and the status of the parking garage, but also the expected duration of parking as well. Since the purpose of a visit to the place in question can determine the expected duration of parking, this context information can be used to optimize the best parking locations for drivers. For the parked vehicles, the expected duration of parking can be uploaded to the traffic cloud and shared with potential drivers after analysis. In this way, even when the parking garage has no empty parking spaces available, drivers still can inquire as to the status of the parking garage and get the desired service by context-aware optimization.

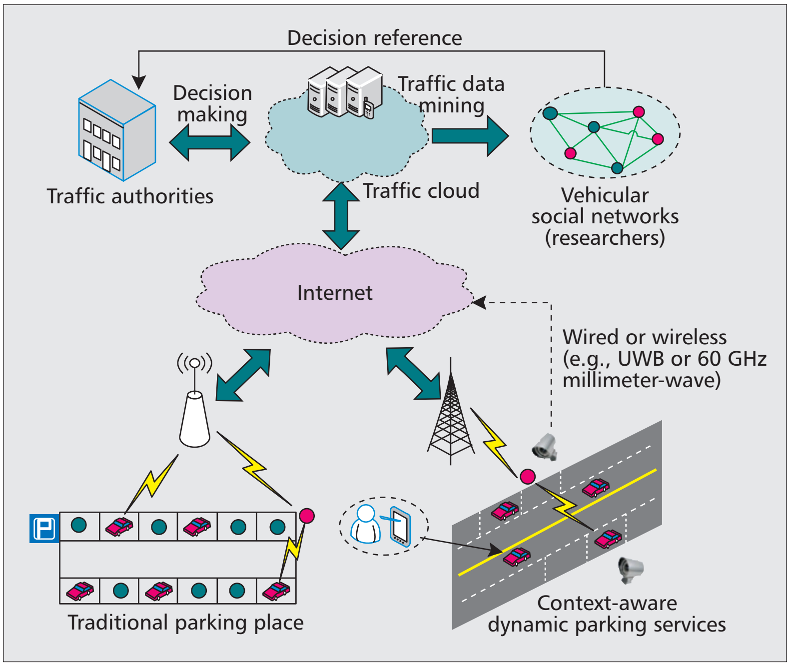

Figure 2. Context-aware dynamic parking services.

The proposed context-aware dynamic parking service is a promising solution for alleviating parking difficulties and improving the QoS of CVC. Many technologies such as WSNs, traffic clouds, and traffic data mining are enabling this application scenario to become a reality. However, we still face some issues and challenges, including a lack of infrastructure, and inadequacy of the related policies and regulations. As of yet, there is still not a prototype platform in this field. From a long-term point of view, this is to be addressed from several perspectives:

1. Design a prototype platform supporting the context-aware dynamic parking services;
2. Establish and improve the related infrastructure;
3. Formulate relevant laws and regulations.

Challenges and Possible Solutions

Although other issues such as security and privacy are equally important and need to be addressed separately, we focus on three aspects (context-aware safety hazard prediction, context-aware dynamic vehicle routing, and context-aware vehicular clouds) to state the challenges and possible solutions.

The fundamental principle of this new system is to establish a motion model that includes context information to predict the motion of this vehicle and its neighbors in the next few seconds. In this way, an imminent collision may be identified.

CONTEXT-AWARE SAFETY HAZARD PREDICTION

Although passive and active systems have been designed to evaluate and improve vehicle safety, it is still necessary to develop a proactive context-aware system to complement existing systems. The fundamental principle of this new system is to establish a motion model that includes context information (e.g., temporary position relationships) to predict the motion of this vehicle and its neighbors in the next few seconds. In this way, an imminent collision may be identified. However, existing vehicle motion models such as [11] are not well suited for safety hazard prediction because they are one-dimensional models unable to consider hazards or vehicles in adjacent lanes.

Most collision warning algorithms (e.g., [12]) have focused on detecting rear-end collisions without considering the potential danger of side/merging vehicles. In addition, these algorithms are only based on either static trajectory predictions or stopping sight distances; they do not take into account the pre-crash vehicle dynamics. In this article, we propose an approach to predict the safety hazards from other vehicles. This approach is designed by developing a potential field that considers inter-vehicular communication, which helps drivers determine the next best actions. In contrast, in the proposed approach, we can improve the limitations of the previous algorithms.

As shown in Fig. 4, the safety hazard faced by a driver may be expressed as a potential field U. The lateral cross-section of vehicle i's potential field can be shown as $U_{j,y}$. Likewise, vehicle k can be perceived by driver j as a potential field the longitudinal section of which is expressed as $U_{j,x}$, with the base shown as the contour labeled Base k on the ground. When vehicle j is close to vehicle k, the dot at (x_j, y_j) will climb up the potential field of the latter. Obviously, driver j will face more hazards if the field is higher or steeper. Similarly, if driver j runs parallel to vehicle i, driver j possibly faces danger from side collision. With the support of this context-aware system, driver j could try his best to avoid collision from vehicle i.

Recently, some preliminary results have verified the field theory and found some supporting evidence [13]. However, the specific shape of the potential field depends not only on driver characteristics but also the availability of context-aware information. For example, if a driver has more context information (e.g., how quickly she is able to stop her vehicle), the potential field may show different shapes with less variability. Thus, the potential field can be expressed as a function of the availability of information. Since the availability of information depends on both inter-vehicular communication (e.g., real-time performance) and onboard sensors, we can determine the form of a potential field by integrating all kinds of influencing factors. In this way, the proposed approach can be developed to predict the safety hazard.

CONTEXT-AWARE DYNAMIC VEHICLE ROUTING

In [14], a novel method for dynamic vehicle routing was proposed by mining traffic data. In this article, we give some insights from the point of view of context awareness and carry out a simplified experiment.

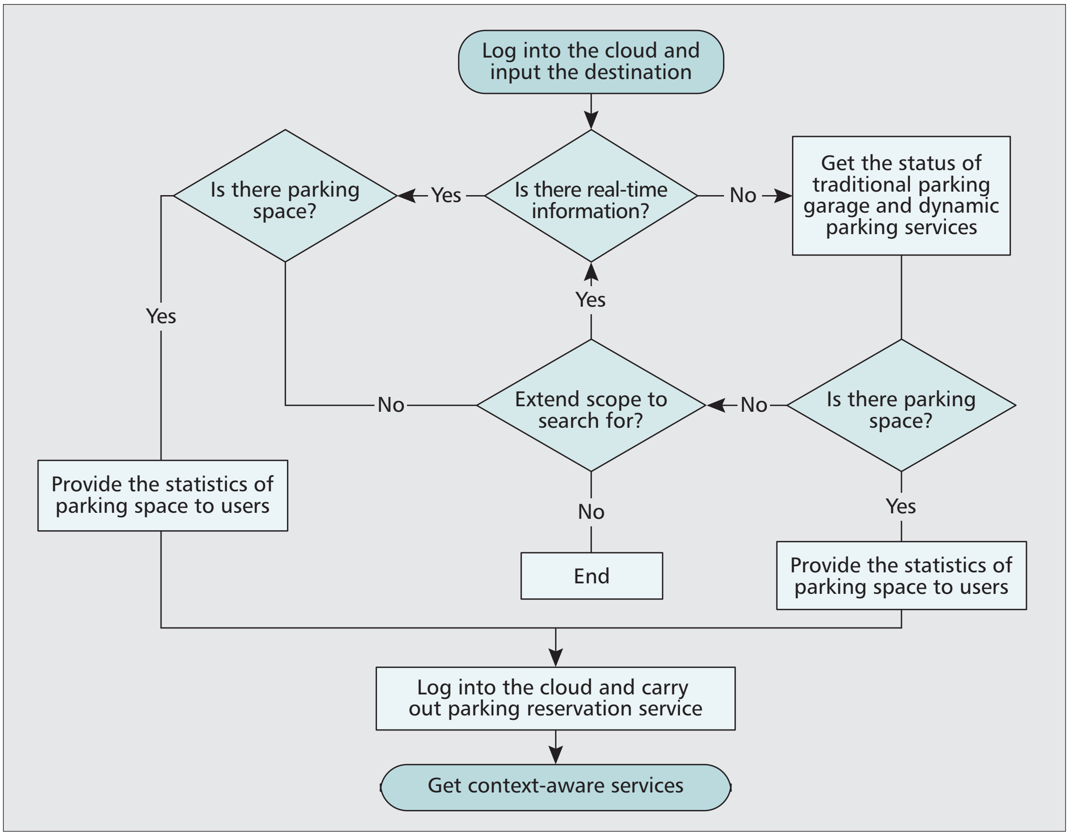

Figure 3. Logical flow chart of a parking reservation service in CVC.

With the support of vehicular ad hoc networks (VANETs), vehicles outside the range of any RSE still have the ability to connect with the rest of the feasible vehicle and infrastructure networks to generate very accurate traffic information. Because of the available context-aware information, we can address some fundamental problems from a brand new perspective. For example, the following problems may be solved:

- Predict future traffic conditions at locations with/without RSE coverage.
- Utilize the predicted context-aware information for improving traffic efficiency.

Taking advantage of infrastructure networks, we can collect traffic data across time and space. Since the characteristics at neighboring locations are often positively or negatively correlated, the traffic data analysis must take account of spatial and temporal autocorrelations. Therefore, the effect of traffic prediction is closely related to the previous context-aware information (e.g., speed) and vehicles in the vicinity. But the reality is that the previous traffic prediction models based on temporal information only could generate unstable parameter estimates. Fortunately, since tensors of higher orders have been proven to be effective data structures to model complex problems, we may adopt tensor feature regression to design a new approach that includes both temporal and spatial traffic flow information (e.g., volume, density, and speed) simultaneously. We analyze fifth-order tensor features (traffic location, speed, time, volume, and density) to express traffic information. In fact, these tensor features are the various pieces of context-aware information. The fifth-order tensor is a matrix that stores traffic information uploaded from OBEs to RSEs. It includes the surrounding traffic information at the same time as spatial information, and time series data in the same location as temporal information.

When a vehicle with an OBE passes by an RSE, it can receive the updated traffic information from the RSE and send its own information (e.g., origin, destination, and vehicle trajectory data) to the RSE. From the trajectory data, some useful context-aware information (e.g., speed and density) can be obtained. Such context-aware information can be correlated with the traffic data obtained from upstream/downstream RSEs and traditional loop detectors. The relationship can then be established using the tensor regression approach. Figure 5 shows the traffic prediction for areas not covered by RSEs.

In order simplify the verification of our proposal, we make three assumptions:

- The distance from A to C is 50 km.
- The vehicle maintains a steady speed.
- The delay of an unexpected accident is about 30 minutes.

The simulation environment is based on Matlab/Simulink. Figure 6 shows the preliminary validation of vehicle routing with and without the above-described context-aware technology in CVC. Normally, if no accidents occur along the way, it takes 60 minutes from A to C. For the existing routing (e.g., the routing given by existing GPS navigation), we may spend some time at B because of an unexpected accident. With support of context-aware technology, a vehicle may acquire the proactive road conditions before reaching B, and then recalculate the path to avoid blocked roads. Therefore, the proposed context-aware dynamic vehicle routing can predict future traffic conditions and improve the QoS of CVC.

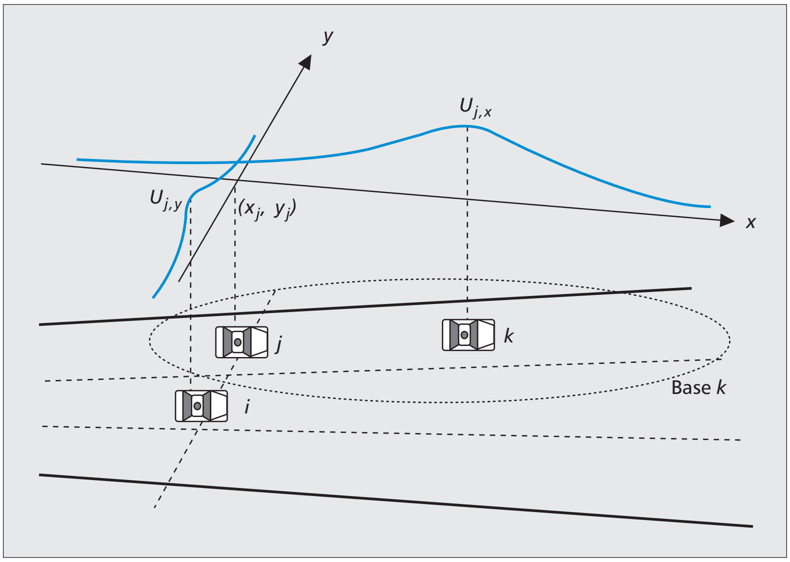

Figure 4. Context-aware safety hazard prediction.

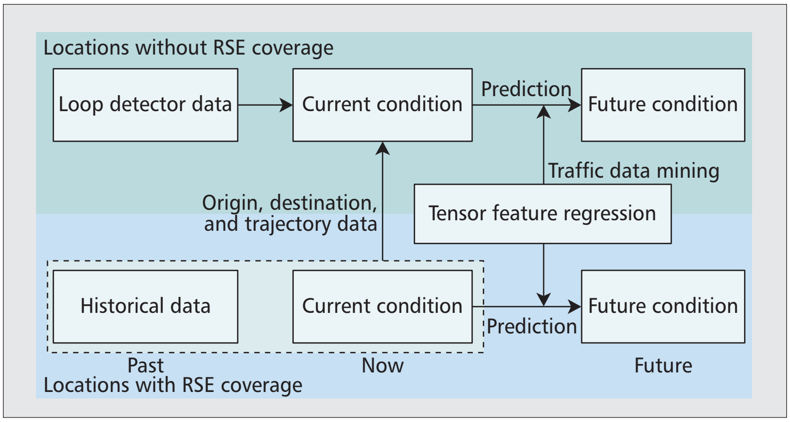

Figure 5. Traffic prediction for areas not covered by RSEs.

Context-Aware Vehicular Clouds

The vehicular cloud consists of three primary architecture types: vehicles to clouds (VTC), vehicles as clouds (VAC), and vehicles with clouds (VWC). For the architecture of VTC, the vehicles on the road can access cloud services from the gateway deployed with the roadside infrastructure to cloud services. The VAC is composed of a set of connected passengers and/or vehicles initially located in the same area as other users. Subsequently, they may selectively allocate their computing resources to other users, forming VCPS data centers. The VWC combines the features of both VTC and VAC to serve the roles of the vehicle as infrastructure and end users simultaneously.

For the context-aware vehicular cloud, we highlight the challenges of developing and running context-aware mobile applications, as well as challenges in utilizing context awareness.

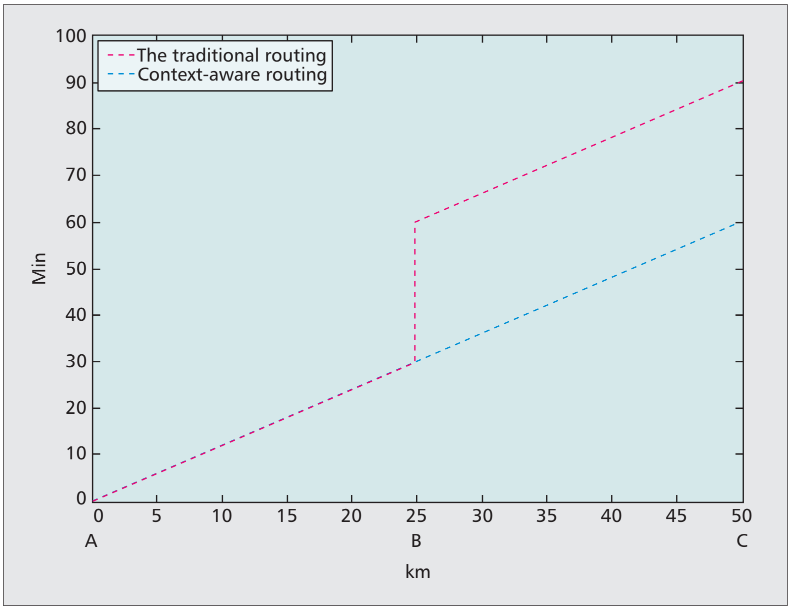

Figure 6. Preliminary validation of context-aware dynamic vehicle routing.

These challenges include many aspects, such as:
- Resource limitations and trade-offs for advanced context processing on mobile devices
- Connectivity, latency, and bandwidth
- Security and privacy
- Apportioning decision for federated deployments
- Managing the context-aware service life cycle

In order to implement the context-aware vehicular cloud services, context awareness authentication is the primary technology [15]. Therefore, context-aware authentication should be applied to identify the driver based on their behavior in the vehicular cloud environment. After collecting context-aware information and considering the spatial factors, the whole authentication will be more reliable. We should emphasize these aspects, including the context-aware architecture, context-aware middleware model, and context-aware and location-based service discovery protocols.

Conclusions

The seamless integration of vehicular networks and MCC provides tremendous opportunities for VCPS. In this article, we provide a brief review and outlook of this promising field, and discuss a cloud-assisted context-aware VCPS architecture for vehicular networks. In particular, we study a case (context-aware dynamic parking service) to show the improvement of QoS in CVC. We also suggest some future research directions and give possible solutions to improve the performance and QoS of cloud-assisted VCPS. We believe CVC will attract enormous attention and research effort in the near future.

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