Vehicular Cyber-Physical Systems
with Mobile Cloud Computing Support

Hehua Yan[1], Jiafu Wan[1(✉)], Yingying Wang[1], Zhonghai Wang[2],
and Zhumei Song[3]

[1] College of Information Engineering, Guangdong Jidian Polytechnic,
Guangzhou, China
{jiafuwan_76,wyybaby}@l63.com
[2] Jiangxi University of Science and Technology, Ganzhou, China
[3] Shenzhen Institute of Information Technology, Shenzhen, China

Abstract. In recent years, Vehicular Cyber-Physical Systems (VCPS) for
high-level applications have led to an increasing demand on connecting Mobile
Cloud Computing (MCC) users to VCPS and accessing the richer services. In
this paper, we first introduce the conceptual architecture for VCPS with MCC
capability. Based on the conceptual architecture, we propose a VCPS and MCC
Integration Architecture (termed VMIA), which provides mobility support for
mobile users (e.g., drivers or potential passengers) to access mobile traffic
cloud. In addition, we analyze two crucial cloud-supported components
including traffic-aware mobile geographic information system and dynamic
vehicle routing algorithms. The proposed VMIA can provide the flexibility for
enabling diverse applications.

Keywords: Vehicular cyber-physical systems · Architecture · Vehicular ad
hoc networks · Mobile cloud computing

1 Introduction

Cyber-Physical Systems (CPS) are increasingly composed of services and applications
deployed across a range of communication topologies, computing platforms, and
sensing and actuation devices [1–3]. Nowadays, vehicular networking serves as one of
the most important enabling technologies, and is producing some novel telematics
applications. Vehicular networking with the capabilities of decision-making and
autonomous control can be upgraded to Vehicular Cyber-Physical Systems (VCPS)
[4]. We believe that VCPS is an evolution of vehicular networking by the introduction
of more intelligent and interactive operations. The services and applications in VCPS
often form multiple end-to-end cyber-physical flows that operate in multi-layered
environments. In such operating conditions, each service must process events
belonging to other services or applications, while providing quality of service
assurance (e.g., timeliness, reliability, and trustworthiness).

Recently, Mobile Cloud Computing (MCC) is gradually becoming a promising
technology, which provides a flexible stack of massive computing, storage and soft-
ware services in a scalable and virtualized manner at low cost [5, 6]. The integration

of VCPS and MCC is expected to facilitate the development of cost-effective, scalable and data driven VCPS platforms, which must be able to guarantee safety and improve Quality of Service (QoS) for drivers or passengers. The new mobile applications for VCPS can be rapidly provisioned and released using MCC with minimal effort. We consider MCC technology to highlight some innovative applications (e.g., historical traffic data and in-vehicle infotainment) for VCPS with richer traffic mobile video streaming, more supporting functionalities, and more reliable QoS.

For the burgeoning integration, VCPS and MCC still possess their own issues and challenges [7–9]. At the same time, this seamless integration will introduce some new problems such as system architecture. To address this challenge, we focus on the integration architecture and two crucial components in this paper. In my view, though other issues such as reliable vehicle communication are equally important for VCPS platform with MCC capability, we highlight the features and contributions as follows:

- Integrate MCC with VCPS: By incorporating the dynamic interactions between MCC and VCPS, we propose a VCPS and MCC Integration Architecture (termed VMIA) to provide more services (e.g., driving assistances).
- Analyze the Crucial Service Components in VMIA: The cloud-supported VCPS has multi-layered features, each layer provides different service contents. We analyze the crucial service components including traffic-aware mobile Geographic Information System (GIS) and dynamic vehicle routing algorithms to determine the research directions and challenges.

The remainder of the paper is organized as follows. Section 2 analyzes the multi-layered VCPS and gives the conceptual architecture for VCPS with MCC capability. In Sect. 3, we propose a cloud-supported VCPS architecture. Section 4 outlines two crucial components in VMIA, and Sect. 5 concludes this paper.

2   Developing VCPS with MCC Support

In this section, we analyze the multi-layered VCPS, and propose the conceptual architecture for VCPS with MCC capability.

2.1   Multi-layered VCPS

In VCPS, the multi-layered VCPS is shown in Fig. 1. According to the range of spatial regions, VCPS can be divided into three deferent layers (i.e., micro layer, meso layer and macro layer) described as follows:

- Micro Layer: In the vehicle range, digital platform of vehicle acquires both environment and vehicle body parameters and integrates human factors for providing high-quality man-machine interaction by means of wired/short-range wireless technologies and advanced control algorithms [10]. In this layer, the design principle is to ensure safety first and infotainment second.
- Meso Layer: The vehicular clusters usually formed by Vehicular Ad Hoc Networks (VANET) give more comfort and convenience (e.g., sharing of entertainment
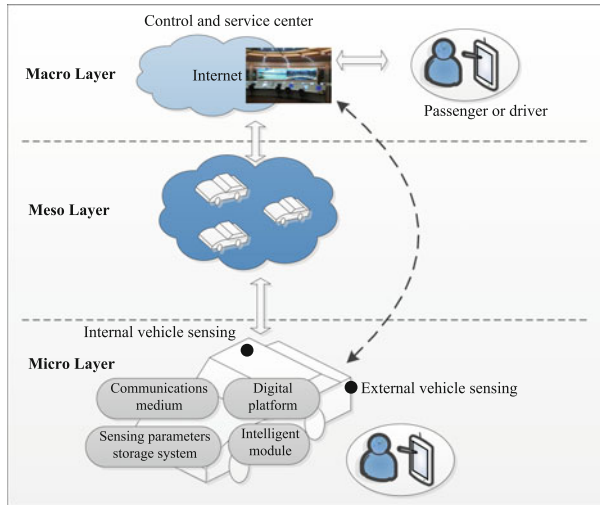
Fig. 1. Multi-layered VCPS

resources and safety information) to drivers or passengers. For the meso layer, the conspicuous challenges are computation offloading and network bandwidth limit.

- Macro Layer: The control and service center provides all kinds of services (e.g., real-time traffic information and traffic contingency plans) to improve QoS. For example, the real-time traffic information can help drivers conduct path planning and reduce congestion. With the MCC support, the macro layer can offer more services such as traffic mobile video streaming.

2.2   Conceptual Architecture for VCPS with MCC Capability

VCPS has emerged as an indispensable technology for intelligent transportation systems. In [11], the research focused on the micro layer to improve road safety and efficiency using cyber technologies such as wireless technologies and distributed real-time control theory. This research considers human factors and integrates vehicle dynamics and communication with a field theory model to predict vehicle motion in the near future for identifying safety hazards and proactive collision warning.

In this paper, the research contents extend from micro layer to multi-layers with the MCC support. The development of VCPS with MCC capability is based on two observations:

- We can develop and deploy numerous mobile applications for VCPS platforms, which can access larger and faster data storage services and processing power from the traffic cloud.
- Many mobile applications have been developed for diverse MCC environments, and these examples have provided some useful references for incorporating MCC capabilities into VCPS.

Figure 2 shows the conceptual architecture of VCPS with MCC capability. The mobile devices (e.g., digital platform installed in the vehicle or smart phone) serve as gateways for VCPS, and access the Internet via Wi-Fi or cellular networks to coordinate with application servers. The mobile devices will then offload the tasks to the traffic cloud accordingly. Once the requests from drivers, passengers or digital platform have been received, the cloud controllers will schedule the tasks on Virtual Machines (VM), which are rented by application service providers, and return the results. In some situations, the application servers can be also deployed in the traffic cloud.
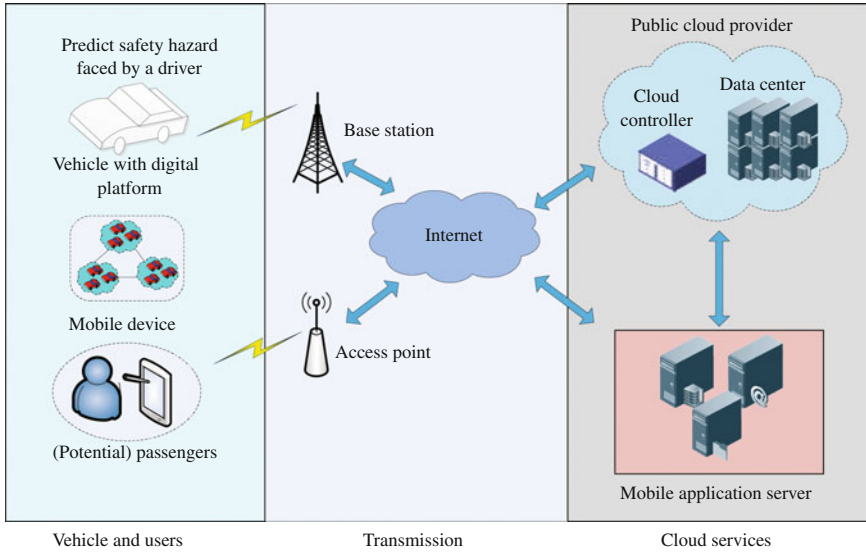

Fig. 2. Conceptual architecture for VCPS with MCC capability

3   Cloud-Supported VCPS Architecture

This paper designs cloud-supported VCPS to provide more service contents (e.g., historical traffic data) for drivers, passengers or traffic controllers. In this section, we propose a framework for an emerging vehicular networking system (i.e., VCPS) with MCC capability. Figure 3 depicts the proposed framework for VCPS platform with MCC support. This platform is comprised of three layers (micro layer, meso layer and macro layer) as follows:

- In the micro layer, the core research topic is to focus on the following two aspects: (1) design and evaluate new applications for improved traffic safety and traffic operations by integrating human factors, and (2) develop an integrated traffic-aware mobile GIS.
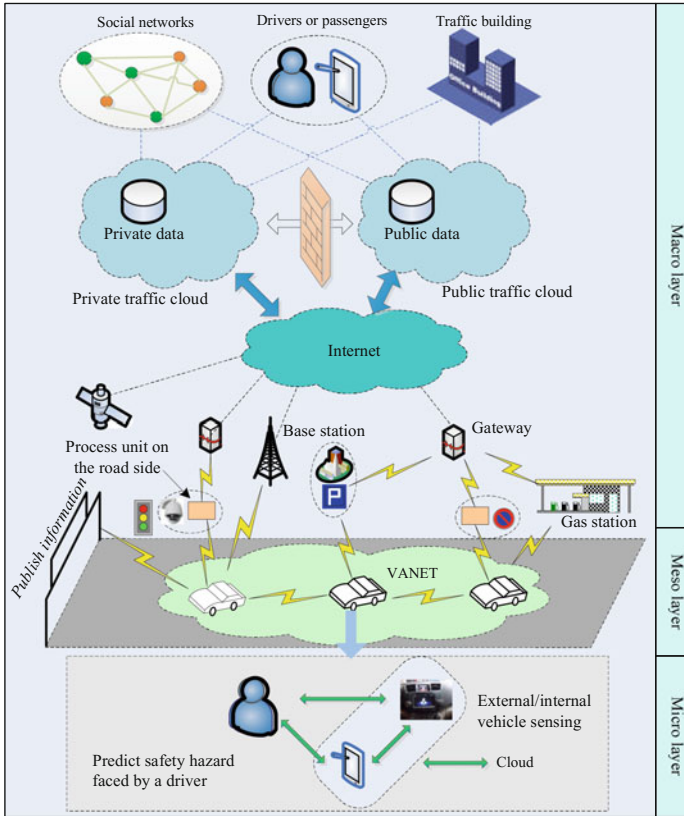
Fig. 3. VMIA: VCPS and MCC integration architecture

- In the meso layer, the vehicular clusters formed by VANET usually share entertainment resources and safety information to drivers or passengers. For example, the traffic accident information can be forwarded to the near drivers for a timely reminder when a traffic accident happens.
- The macro layer includes wired/wireless transmission, cloud services, and users. The traffic video streaming from cameras are transmitted to the adjacent routing equipment via wired or wireless transmission, and then to the traffic cloud server via Internet. The traffic cloud servers possess powerful VM resources such as CPU, memory, and network bandwidth in order to provide all kinds of cloud services such as entertainment resources. The different users such as drivers, traffic controllers, researchers, or even passengers ubiquitously acquire multiple cloud services by a variety of interfaces such as personal computers, TVs and smart phones.

For the VMIA, we further stress an important aspect: hybrid traffic cloud. In general, a hybrid cloud computing architecture can accelerate the migration from existing IT resources in transportation departments to cloud computing, make full use of resources, and reduce costs. Important traffic data and applications such as traffic contingency plans and traffic violation records can be deployed on a private traffic

cloud to guarantee security, while operations related to system upgrade and testing can be carried out on a public traffic cloud. Moreover, when there are not enough resources on the private traffic cloud at the peak load time, some work can be switched to the public traffic cloud.

4   Cloud-Supported Service Components

In this section, we outline two crucial service components for QoS improvement VCPS platforms, including traffic-aware mobile GIS and traffic data mining for dynamic vehicle routing.

4.1   Traffic-Aware Mobile GIS with Traffic Cloud Support

With the traffic cloud support, we can achieve the new mobile GIS functions by integrating traffic dynamics with basemap management to provide driving assistances. In our view, the location-specific nature of transportation data and the recent technological advances of GIS will firmly help designers realize the integration of GIS and transportation models. It is well known that ESRI ArcGIS provides a conceptual transportation data models UNETRANS (Unified Network for Transportation) and later a revised version [12]. The UNETRANS model includes an underlying structure by a geometric network, and the revised model has four object packages: inventory, network, events, and users (e.g., drivers or passengers). It closely matches class behaviors to the real-world entities, such as link crashes to the intersections by handling crash and intersection object classes. Recently, this model has been designed by larger agencies as the basis for their transportation database.

Fortunately, the recently published roads and highways data model provides the best-practice templates for integrating static transportation network data and time-varying traffic flow data from a traffic cloud. However, current ArcGIS lacks necessary calculation tools for building a real-time traffic prediction model. Therefore, this is an interesting work to design a novel transportation prediction model by integrating the existing ArcGIS and an extension traffic analyst. With the support of the traffic cloud, we propose to integrate traffic monitoring and analysis with the mobile GIS functions in basemap management, traffic analysis and crash warning, and route selection.

4.2   Cloud-Supported Dynamic Vehicle Routing Algorithms

Figure 4 shows the cloud-supported traffic data mining and prediction. The Roadside Equipment (RSE) units deployed at crucial locations exchange the traffic information with On-Board Equipment (OBEs) installed on passing by vehicles. In the meso layer, both RSEs and neighboring OBEs are also interconnected and share traffic information by means of VANET. Vehicles outside the range of any RSE may still be connected to the rest of the vehicle and infrastructure network via neighboring vehicles. In this way, the vehicle and infrastructure network can generate the real-time traffic information,

based on which some fundamental traffic problems such as efficiency can be well solved from a new perspective, including:

- How to accurately infer current and predict future traffic conditions at locations with or without RSE coverage.
- How to best utilize the inferred/predicted traffic information for improving traffic operations.

With the support of real-time and accurate traffic information, all the drivers will select the optimal route according to some criteria such as travel time or distance. Intuitively, these decisions will collectively result in a state of Dynamic User Equilibrium (DUE). However, for a large-scale distributed system where drivers make their own independent decisions based on the same travel time information, this may possibly lead to an extreme state similar to the result of Dynamic All-or-Nothing (DAN) assignment [13], since all the drivers from the same origin to the same destination will take the same routes. In fact, when the system is in a state of Dynamic System Optimal (DSO), the transportation network performance is optimal.

Based on the above analysis, we outline a decentralized and proactive dynamic vehicle routing algorithm to allow drivers to self-organize the traffic and shift the system state from either DAN or DUE to DSO. For example, the RSEs gather traffic information from passing-by connected vehicles. These data together with loop detector and historical traffic data from the traffic cloud are used to predict future link travel times. To avoid the DAN scenario and account for the uncertainty in travel time prediction results, we outline a stochastic route choice method based on discrete choice models by each OBE to find the optimal route. This decentralized and proactive routing process will help to move the transportation network towards a state of DSO. As shown in Fig. 3, the proposed cloud-supported dynamic vehicle routing algorithms involve two layers (the macro layer and the meso layer) of VMIA.
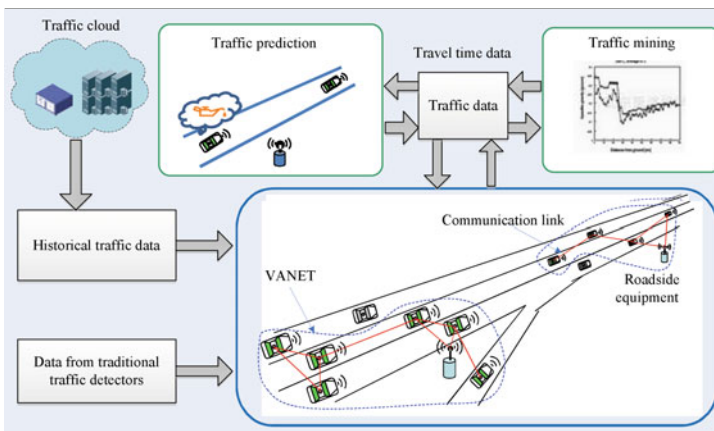

Fig. 4. Cloud-supported traffic data mining and prediction

5   Conclusions

The seamless integration of VCPS and MCC provides tremendous opportunities for future intelligent transportation systems. In this article, we provided a brief review and outlook of this promising field and discussed a cloud-supported VCPS architecture (termed VMIA). In particular, we studied the functionality and reliability of MCC services. We also suggested some crucial service components to improve performance and QoS of cloud-supported VCPS. We believe cloud-supported VCPS will attract enormous attention and research efforts in near future.

References

1. Zou, C., Wan, J, Chen, M., Li, D.: Simulation modeling of cyber-physical systems exemplified by unmanned vehicles with WSNs navigation. In: Proceedings of the 7th International Conference on Embedded and Multimedia Computing Technology and Service, pp. 269–275, Gwangju, Korea, September 2012.
2. Chen, M., Wan, J., Li, F.: Machine-to-machine communications: architectures, standards, and applications. KSII Trans. Internet Inf. Syst. **6**(2), 480–497 (2012)
3. Wan, J., Chen, M., Xia, F., Li, D., Zhou, K.: From machine-to-machine communications towards cyber-physical systems. Comput. Sci. Inf. Syst. **10**(3), 1105–1128 (2013)
4. Li, X., Qiao, C., Yu, X., Wagh, A., Sudhaakar, R., Addepalli, S.: Toward effective service scheduling for human drivers in vehicular cyber-physical systems. IEEE Trans. Parallel Distrib. Syst. **23**(9), 1775–1789 (2012)
5. Wan, J., Liu, Z., Zhou, K., Lu, R.: Mobile cloud computing: application scenarios and service models. In: Proceedings of the 9th IEEE International Wireless Communications and Mobile Computing Conference, Cagliari, Italy, July 2013
6. Chen, M., Wen, Y., Jin, H., Leung, V.: Enabling technologies for future data center networking: a primer. IEEE Netw. **27**(4), 8–15 (2013)
7. Wan, J., Yan, H., Liu, Q., Zhou, K., Lu, R., Li, D.: Enabling cyber-physical systems with machine-to-machine technologies. Int. J. Ad Hoc Ubiquitous Comput. **13**(3/4), 187–196 (2013)
8. Chen, M.: AMVSC: a framework of adaptive mobile video streaming in the cloud. In: IEEE Globecom 2012, Anaheim, California, USA, 3–7 December 2012
9. Yan, H., Wan, J., Suo, H.: Adaptive resource management for cyber-physical systems. In: Proceedings of the 2011 International Conference on Mechatronics and Applied Mechanics, pp. 747–751, HongKong, December 2011.
10. Miloslavov, A., Veeraraghavan, M.: Sensor data fusion algorithms for vehicular cyber-physical systems. IEEE Trans. Parallel Distrib. Syst. **23**(9), 1762–1774 (2012)
11. Qiao, C.: Cyber-transportation systems (CTS): safety first, infotainment second, Presentation Report (2010)

12. Azogu, H.: Privacy-preserving license plate image processing. In: Proceedings of the 2nd IEEE Workshop on Multimedia Communications and Services, IEEE GlobeCom 2011, Houston, TX, 5–9 December 2011
13. Sheffi, Y.: Urban Transportation Networks: Equilibrium Analysis with Mathematical Programming Methods. Prentice-Hall Inc., Englewood Cliffs (1985)