Vehicular Cyber-Physical Systems for Smart Road Networks

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Abstract

This paper proposes the design of Vehicular Cyber-Physical Systems (called VCPS) based on vehicular cloud for smart road networks. Our VCPS realizes mobile cloud computing services where vehicles themselves or mobile devices (e.g., smartphones and tablets of drivers or passengers in vehicles) play a role of both cloud server and cloud client in the vehicular cloud. First, this paper describes the architecture of vehicular networks for VCPS and the delay modeling for the event prediction and data delivery, such as a mobile node's travel delay along its navigation path and the packet delivery delay in vehicular networks. Second, the paper explains two VCPS applications as smart road services for the driving efficiency and safety through the vehicular cloud, such as interactive navigation and pedestrian protection. Last, the paper discusses further research issues for VCPS for smart road networks.

I. Introduction

Vehicular Ad Hoc Networks (VANETs) have been researched and developed for the driving safety, driving efficiency, and entertainment services[1][2]. This VANET has been realized by the technology of Dedicated Short Range Communications (DSRC)[3]. By this DSRC, vehicles can communicate efficiently with other vehicles moving on either the same road segment or adjacent road segments at an intersection for the driving safety. This DSRC technology has been implemented by the standard of IEEE 802.11p, which is an extension of IEEE 802.11a for vehicular networks. In addition, GPS navigation systems are popularly used by drivers for the efficient driving in the form of dedicated navigators[4][5][6] and smartphone navigator Apps[7~10]. Due to the DSRC standardization and navigator popularity, one natural research question is how to design Vehicular Cyber-Physical Systems by utilizing vehicles equipped with DSRC device and navigator for cloud services for the driving efficiency and safety in road networks.

Last decade, cloud computing has been researched and developed intensively, and then opened a new door of the Internet services[11]. This cloud computing has become a norm because mobile devices (such as smartphones and tablets) are popularly used as main computing devices for business, education, and entertainment. Even though these mobile devices have limited computing power and storage, they can obtain almost unlimited computing power and storage from the cloud via wireless communications, such as 3G/4G-LTE[12], WiFi, and WiMAX.

Recently, mobile cloud computing has been introduced as a new paradigm in the cloud computing domain[13], based on mobile devices (i.e., smartphones and tablets) as both cloud clients and cloud servers. These mobile devices can perform sensing around the environments (e.g., streets, shopping malls, buildings, and home) as mobile sensors and play a role of intermediate servers as computing nodes or storage nodes for other mobile devices. This new paradigm for cloud computing will be expected to generate many useful services in many computer networking areas, such as cellular networks, social networks, mobile ad hoc networks, vehicular networks, personal & body networks, and mission critical networks. This paper focuses on the mobile cloud computing in vehicular networks for smart road networks to support the driving safety and efficiency. However, our mobile cloud computing can support various VCPS cloud services for smart road networks, as shown in Fig. 1, such as (i) pedestrian protection for the driving safety, (ii) interactive navigation for the efficient driving, and (iii) location–based services in road networks.

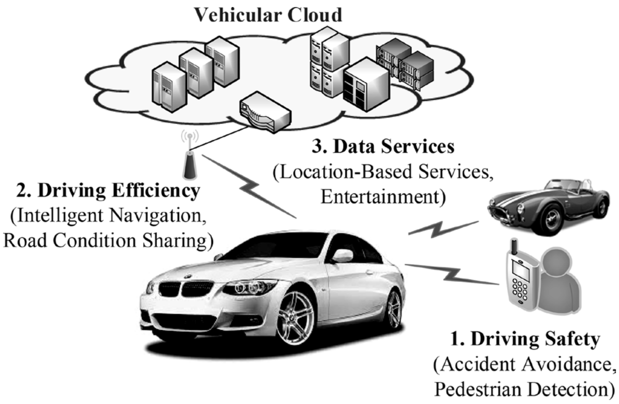


Fig. 1. VCPS Cloud Services in Smart Road Networks

In this paper, we propose the design of Vehicular Cyber–Physical Systems (VCPS) using vehicular cloud computing as a promising branch of mobile cloud computing[13]. In our design, VCPS is managed by Traffic Control Center (TCC)[14] that maintains the road traffic conditions, vehicular traffic statistics (e.g., vehicle density and average speed) per road segment or intersection, and the navigation paths (called vehicle trajectories) of vehicles moving in road networks. Road–Side Units (RSUs)[15] are also deployed as wireless gateway nodes at intersections, interconnecting vehicular ad hoc networks and a wired network (i.e., the Internet). RSUs provide vehicles with the Internet connectivity to the TCC for the vehicular cloud services in road networks. In addition, Relay Nodes (RNs)[16] are deployed as wireless, stand–alone, temporary packet holders at intersections. RNs do not have the Internet connectivity for deployment cost saving, but can assist vehicles at intersections for either the data forwarding to/from the vehicular cloud or the information sharing for the driving safety. Based on the VCPS, we envision useful smart road services for the driving efficiency (e.g., interactive navigation), driving safety (e.g., pedestrian protection), and Internet services (e.g., location–based services), as shown in Fig. 1. As mobile cloud nodes, vehicles and smartphones can interact with each other as mobile cloud server or mobile cloud client via the vehicular cloud for these smart road services.

The remaining of the paper is constructed as follows. Section II summarizes related work. Section III describes the problem formulation for VCPS. Section IV explains the delay modeling for a mobile node's travel delay and packet delivery delay. Section V describes two VCPS applications for the driving efficiency and safety, such as interactive navigation and pedestrian protection. Section VI discusses further research issues for VCPS. Finally, in Section VII, we conclude the paper along with future work.

II. Related Work

Vehicular networks have been being intensively researched for the driving safety and driving efficiency in road networks[2],[16~21]. Currently, many network researchers focus on the vehicular networking in network layer and link layer, such as multihop data forwarding schemes and Media Access Control (MAC) protocols. Data forwarding schemes are categorized into Vehicle–to–Infrastructure (V2I), Infrastructure–to–Vehicle (I2V), and Vehicle–to–Vehicle (V2V) data forwarding schemes. MAC protocols are categorized into V2V MAC protocols and V2I/I2V MAC protocols.

For the V2I data delivery, VADD[2] is proposed as a greedy forwarding scheme. VADD allows a packet carrier to select the next packet carrier with a shorter Expected Delivery Delay (EDD). This EDD is computed using vehicular traffic statistics (e.g., vehicle inter–arrival time and average vehicle speed). As one further step, TBD[17] is proposed to compute a better EDD to expedite the data delivery. The EDD computation in TBD uses vehicle trajectory (i.e., navigation path) as well as vehicular traffic statistics. TBD[17] outperforms VADD in forwarding performance in a privacy preserving manner for individual vehicle trajectories. For the I2V data delivery, the vehicle trajectory of a destination vehicle is used in TSF[16] along with the vehicular traffic density. This multihop I2V data delivery has more challenge than the multihop V2I data delivery because the destination vehicle keeps moving over time. For this multihop I2V data delivery, a target point is selected as a rendezvous point of the packet and the destination vehicle. This target point selection is performed by the estimation of the destination vehicle's travel delay and the packet delivery delay. For the reliable data delivery, TSF requires relay nodes as temporary packet holders to forward packets to the target point along a packet forwarding path. TSF can also support the V2V data delivery between moving vehicles by V2I data delivery and I2V data delivery through infrastructure nodes (i.e., Access Points). For the V2V data delivery, STDFS[18] is proposed without any relay nodes for the E2E data forwarding. The relay-node-free V2V data delivery is possible by fully utilizing the vehicle trajectories of both the destination vehicle and the intermediate vehicles as possible packet carriers in a target road network. STDFS constructs a predicted encounter graph used to facilitate the predicted packet forwarding between the current packet carrier and the next packet carrier. For the efficient data sharing among a multicast group of vehicles, TMA[19] is developed to extend the idea of TSF[16], considering the multiple target points for the multicast group vehicles. With these multiple target points, TMA constructs a minimum Steiner Tree for the multicast data delivery.

For the MAC protocols in vehicular networks, LMA[20] is a V2V MAC protocol using directional antenna and vehicle trajectory for the spatial coordination to reduce wireless channel collision. In LMA, a transmitter tries to minimize the radio transmission area toward its receiver by utilizing the mobility information of the receiver. WPCF[21] is a V2I/I2V MAC protocol using Point-Coordination Function (PCF), which proposes WAVE PCF where WAVE stands for Wireless Access in Vehicular Environments. In WPCF, AP collects the mobility information (e.g., GPS position, moving speed, and direction) of vehicles within one-hop communication range. After collecting the mobility information of the neighboring vehicles, the AP announces the timing frame telling the vehicles when they can access the channel in the contention-free period.

Nowadays, cloud computing has been realized and popularly used for a variety of Internet services. Cloud computing makes companies process their batch-oriented tasks through servers interconnected via networks in the scalable and elastic way[11]. As one of leading solution companies for cloud computing systems, VMware allows companies to run their own private cloud systems through the product of vCloud Suite[22]. Amazon runs Amazon Web Services (AWS) cloud service[23]. AWS provides cloud infrastructure for small businesses or persons according to the load of tasks with the corresponding charge for temporary lease of computing and storage resources. Mobile devices (e.g., smartphones and tablets) are used as main terminals for information retrieval and business transactions through the cloud. Google and Apple support various mobile services for mobile devices via their own cloud[24][25].

The advent of mobile cloud computing is due to the popularity of mobile devices. Now mobile devices can run not only cloud client Apps, but also cloud servers or proxies for other mobile devices as mobile cloud[13]. The boundary of cloud clients and servers has broken down. As service models of mobile cloud computing, mobile devices play a role of (i) Mobile as a service consumer (MaaSC), (ii) Mobile as a service provider (MaaSP), and (iii) Mobile as a service broker (MaaSB). By being aware of user patterns and environment contexts, mobile devices can change their role dynamically to maximize the satisfaction of mobile users. Mobile devices can offload the task load of the cloud systems for other mobile devices as an intermediate cloud. This new paradigm will open new fascinating services in various networks, such as home networks, personal & body networks, social networks, cellular networks, mobile ad hoc networks, vehicular networks, and mission critical networks. In this paper, we focus on the mobile cloud computing in vehicular networks.

In this paper, with the emergence of mobile cloud computing and vehicular networks, we will design the architecture of vehicular networks for VCPS and the smart road services through VCPS. For the vehicular networks for VCPS, we will propose an organization of network systems consisting of TCC, RSUs, and RNs with appropriate V2I, I2V, and V2V data forwarding schemes. For the smart road services, we will suggest a feasible design of an interactive navigation service and a pedestrian protection service through the interaction between mobile devices and the vehicular cloud.

Ⅲ. Problem Formulation

In this section, for Vehicular Cyber-Physical Systems (VCPS), we describe our vehicular network architecture and then list up assumptions for our VCPS.

Ⅲ.1. Vehicular Network Architecture

Vehicular networks consist of the following system components, as shown in Fig. 2:

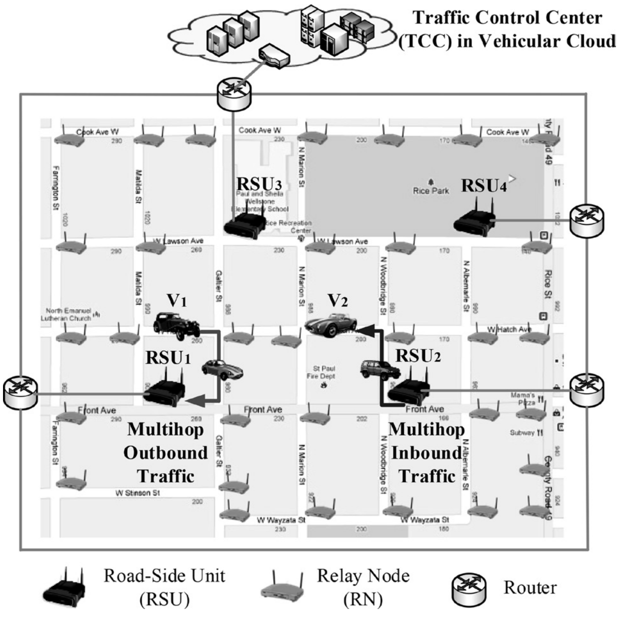


Fig. 2. Vehicular Network Architecture for VCPS

- Traffic Control Center (TCC)[14] is a management node for vehicular cloud systems. As a trusted entity, TCC maintains the trajectories of vehicles for the location management for the data delivery toward the vehicles. These vehicle trajectories are not exposed to other vehicles for privacy concerns. In I2V data delivery, TCC determines which RSU will be the packet source node to deliver the packets to moving destination vehicle(s) as shown in Fig. 2. It is assumed that TCC and RSUs are interconnected with each other through a wired network such as the Internet.
- Road-Side Unit (RSU)[15] is a wireless node interconnecting vehicular ad hoc networks and a wired network. RSU has the DSRC communications, storage, and processing capability to forward packets from TCC to packet destination vehicles, as shown in Fig. 2. For the cost effectiveness, RSUs are sparsely deployed into the road network and are interconnected with each other through the wired network or wirelessly (as Mesh Network)[26][27]. Each RSU installation with power and wired network connectivity can cost as high as US$5,000[28].
- Relay Node (RN)[16] is a wireless stand-alone node as a temporary packet holder for the store-and-forward of packets toward an intended direction in the road network. RN has the capability of DSRC communication, storage, and processing capability, but does not have the wired network connectivity for the cost saving, as shown in Fig. 2. This means that RNs do not have the direct, wired connectivity to either RSUs or TCC to save deployment cost. Also, it is assumed that RNs are not wirelessly connected to each other. However, in the case where RNs are wirelessly connected, we can regard the road segments among them as wirelessly covered by a Mesh Network consisting of those RNs. With a small number of RSUs, RNs are used to perform the reliable data delivery from RSU to the other RNs corresponding to the target points (i.e., packet destinations) by using intermediate vehicles as packet carriers, moving on road networks. One RN is assumed to be deployed at each intersection for the reliable forwarding, but we can handle the case where some intersections do not have their own RNs, as discussed in TSF[16]. Of course, RNs can be deployed for the Quality-of-Service (QoS) data delivery in the middle of road segments for a Mesh Network consisting of RNs.

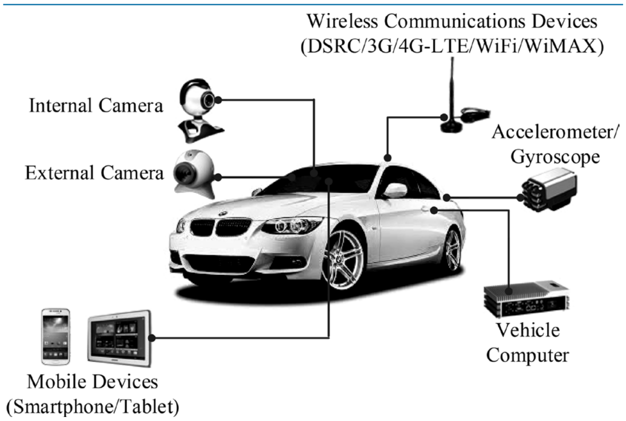


Fig. 3. Smart Vehicle

- Vehicles have mobile devices (such as smartphones and tablets) or their dedicated on-board computers. As mobile sensors, vehicles can measure travel delay for each road segment along their travel path. For VANET, vehicles have DSRC device[3] along with other wireless communication devices, such as WiFi, WiMAX, 3G, and 4G-LTE[12]. Fig. 3 shows a smart vehicle with various devices for smart road services, such as mobile devices (e.g., smartphone and tablet), internal and external cameras, wireless communication devices (e.g., DSRC, 3G, 4G-LTE, WiFi, and WiMAX), accelerometer, gyroscope, and vehicle computer. It is announced that major vehicle vendors (such as GM and Toyota) are planning to release vehicles with DSRC devices[29][30]. These DSRC vehicles play a role of packet forwarders and packet carriers until they can forward packets to a relay node or packet destination vehicle.

Ⅲ.2. Assumptions

We have the following assumptions:

- Mobile devices (e.g., smartphones and tablets), TCC, RSUs, and RNs are installed with GPS-based navigation systems including digital road maps for location-based services (such as data forwarding or retrieval)[31]. Road traffic statistics, such as vehicle arrival rate and average vehicle speed per road segment, are measured through mobile devices or loop-detectors. These traffic statistics can be used to produce metrics (e.g., packet link delivery delay in Section IV.3) for the data forwarding in road segments for smart road services.
- For smart road services, drivers or pedestrians voluntarily input their travel destination into their GPS-based navigation systems before their travel. This makes it possible for the vehicles to compute their future trajectory based on their current location and their final destination. Mobile devices (e.g., smartphones and tablets) in vehicles or in pockets regularly report their trajectory information and their current location to TCC through RSUs. This reporting can be performed, using the existing unicast forwarding schemes, such as TSF[16] and SADV[32].

Ⅲ.3. The Concept of Vehicular Cyber-Physical Systems

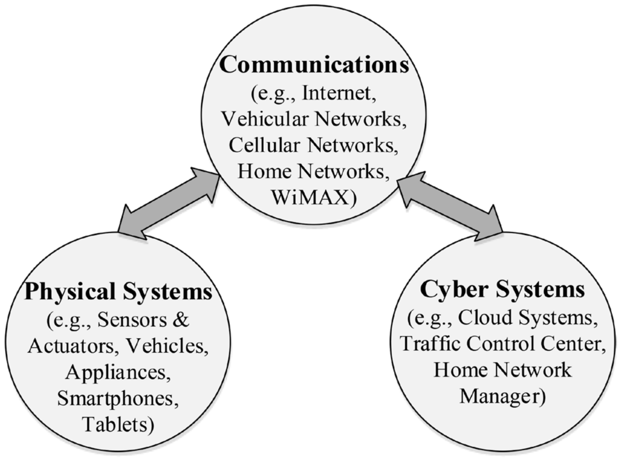
In this subsection, at first, we formally define Cyber-Physical Systems (CPS) and Vehicular Cyber-Physical Systems (VCPS) and then specify the target applications in VCPS.

We define CPS and VCPS in this paper as follows:

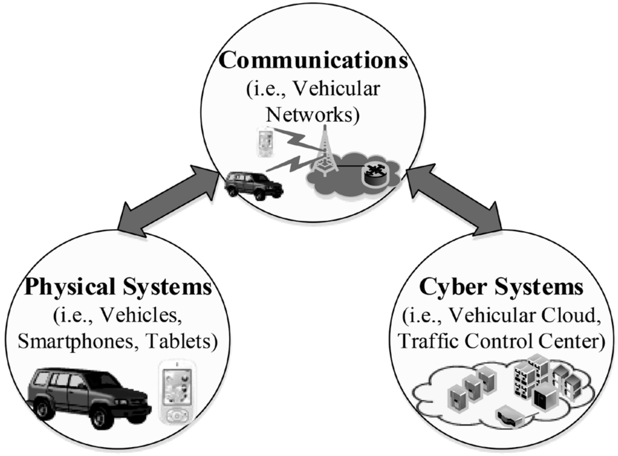
- Cyber-Physical Systems (CPS): Let CPS be the systems that are integrated by Physical Systems (following physical laws in continuous time domain) and Cyber Systems (following discrete mathematics in discrete time domain) via Communications.
- Vehicular Cyber-Physical Systems (VCPS): Let VCPS be the systems that are integrated by Physical Systems in Road Networks and Cyber Systems in Vehicular Cloud via Wireless and Wired Communications, as a subset of CPS.

Fig. 4 illustrates the concept of CPS and VCPS using the interaction among system components, such as Physical systems, Cyber Systems, and Communications. Fig. 4(a) describes the CPS consisting of Physical Systems (e.g., Sensors & Actuators, Vehicles, Appliances, Smartphones, and Tablets), Cyber Systems (e.g., Cloud Systems, Traffic Control Center, and Home Network Manager), and Communications (e.g., Internet, Vehicular Networks, Cellular Networks, Home Networks, and WiMAX). Fig.

4(b) describes the VCPS consisting of Physical Systems (e.g., Vehicles, Smartphones, and Tablets), Cyber Systems (e.g., Vehicular Cloud and Traffic Control Center), and Communications (e.g., Vehicular Networks).



(a) Cyber-Physical Systems



(b) Vehicular Cyber-Physical Systems

Fig. 4. Cyber-Physical Systems and Vehicular Cyber-Physical Systems

The VCPS takes advantages of the characteristics of road networks to design vehicular networks and services[32], such as (i) Predictable vehicle mobility, (ii) Road network layout, (iii) Vehicular traffic statistics, and (iv) Vehicle Trajectory. First, for Predictable vehicle mobility, vehicle moves along roadways with bounded speed. Second, for Road network layout, road network layout can be represented as a road map that can be reduced to a road network graph. Third, for Vehicular traffic statistics, vehicle inter-arrival time and average vehicle speed can be measured per road segment and average waiting time for traffic signal can be measured per intersection. Last, for Vehicle trajectory, vehicles follow the routes provided by GPS-based navigation systems for the efficient driving. These characteristics are very important assets to design the vehicular networks (e.g., data forwarding schemes and media-access control protocols) and the vehicular services (e.g., interactive navigation and pedestrian protection). In the following sections, considering these characteristics, we will show the delay modeling for event prediction and data delivery and also the design of VCPS services.

Ⅳ. Delay Modeling

In this section, we model the travel delay of a vehicle or pedestrian on a road segment and an End-to-End (E2E) travel path in a target road network. Also, we model the delivery delay of a packet on a road segment and an E2E forwarding path in the target road network. Note that these delay models in this section originate from our early work TSF[16].

Ⅳ.1. Link Travel Delay on Road Segment

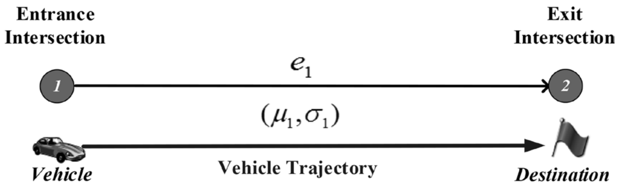


Fig. 5. Link Travel Delay on Road Segment

In this subsection, we model the travel delay of a vehicle on a road segment from the entrance intersection to the exit intersection. This travel delay modeling can be extended to the travel delay on an E2E path from a source position to a destination position in a target road network.

Let $G = (V,E)$ be a road network graph where V is the set of intersections (as vertices) and E is the set of directed road segments (as edges). It is proved that the travel delay of one vehicle over a fixed distance in light-traffic vehicular networks follows the Gamma distribution[16][34]. Thus, the travel delay through a road segment i (denoted as e_i) in the road network is defined as *link travel delay* d_i such that $d_i \sim \Gamma(\kappa_i, \theta_i)$ where κ_i is a shape parameter and θ_i is a scale parameter[35].

To calculate the parameters κ_i and θ_i, the mean μ_i and the variance σ_i^2 can be used for the link travel delay d_i [35] on the given road segment $e_i \in E$. The traffic statistics of μ_i and σ_i^2 are available from commercial navigation service providers (e.g., Garmin[31]). Fig. 5 shows the statistics (μ_1, σ_1) for the link travel delay on road segment e_1. Let the mean of d_i be $E[d_i] = \mu_i$ and the variance of d_i be $Var[d_i] = \sigma_i^2$. Thus, the formulas for κ_i and θ_i are as follows[35]:

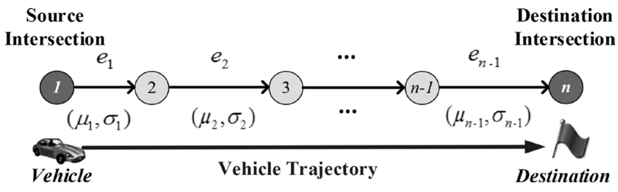
$$\theta_i = \frac{Var[d_i]}{E[d_i]} = \frac{\sigma_i}{\mu_i}. \quad (1)$$

$$\kappa_i = \frac{E[d_i]}{\theta_i} = \frac{\mu_i^2}{\sigma_i}. \quad (2)$$

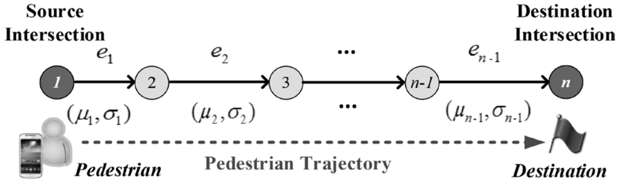
In addition to the above mathematical model for link delay distribution on a road segment, our delay modeling can accommodate empirical measurements for the distribution of link delay. These empirical measurements can be performed by the periodical reports of mobile devices of vehicles or pedestrians (passing through the road segment or walking in a street) to the RSU taking charge of the road segment. Thus, a more accurate link travel delay distribution will allow for a more accurate E2E travel delay distribution in the following subsection.

Ⅳ.2. Path Travel Delay on End-to-End Path

The End-to-End (E2E) travel delay in a road network can be modeled with the link delay model in Section IV.1[16]. As the link travel delay is modeled as the Gamma distribution of $d_i \sim \Gamma(\kappa_i, \theta_i)$ for road segment i, the E2E travel delay can be modeled with a sum of Gamma distributions of the link delays. Assume that as shown in Figs. 6(a) and 6(b), for two contiguous edges (e.g., e_1 and e_2) in a given E2E travel path, the intersection waiting delay from the first edge (e.g., e_1) to the second edge (e.g., e_2) is included in the first link travel delay (e.g., d_1).



(a) Vehicle Travel Delay for Vehicle Trajectory



(b) Pedestrian Travel Delay for Pedestrian Trajectory

Fig. 6. Path Travel Delay on End-to-End Path

Given an E2E travel path, it is assumed that the link travel delays of different road segments for the path are independent. With this assumption, the mean (or variance) of the E2E travel delay is approximately calculated as the sum of the means (or variances) of the link travel delays for the links along the E2E path. Assuming that as shown in Figs. 6(a) and 6(b), the travel path consists of $n - 1$ road segments, the mean and variance of the E2E travel delay are computed as follows:

$$E[D] = \sum_{i=1}^{n-1} E[d_i] = \sum_{i=1}^{n-1} \mu_i. \quad (3)$$

$$Var[D] = \sum_{i=1}^{n-1} Var[d_i] = \sum_{i=1}^{n-1} \sigma_i^2. \quad (4)$$

With (3) and (4), the E2E travel delay D is approximately modeled as a Gamma distribution as follows: $D \sim \Gamma(\kappa_D, \theta_D)$ where κ_D and θ_D are calculated using $E[D]$ and $Var[D]$ using the formulas of (1) and (2). Note that if a more accurate distribution for the E2E path is available from the measurements or another mathematical model, our travel delay model can use this distribution for the E2E travel delay estimation.

Let's discuss the relationship between the arrival time of vehicle V_a at a target intersection n_k and the E2E travel delay (denoted as $D_{a,jk}$) from V_a's current position n_j to the target intersection n_k. Let be T^* the current time. Let $T_{a,jk}$ be the arrival time at n_k for vehicle V_a's E2E travel from the current position n_j to the target intersection n_k. The arrival time $T_{a,jk}$ can be modeled as a Gamma distribution with Equations (3) and (4) such that $T_{a,jk} = D_{a,jk} + T^*$. This is because $T_{a,jk}$ is a linear combination of a Gamma random variable $D_{a,jk}$ and a constant value T^*.

For an application for our travel delay modeling, we can develop a smartphone App for the pedestrian protection, as shown in Fig. 11. We can compute the travel delay distribution of a vehicle and that of a pedestrian. With these delay distributions, we can predict a possible collision between a vehicle and a pedestrian, which will be discussed in Section V.2.

Ⅳ.3. Link Delivery Delay on Road Segment

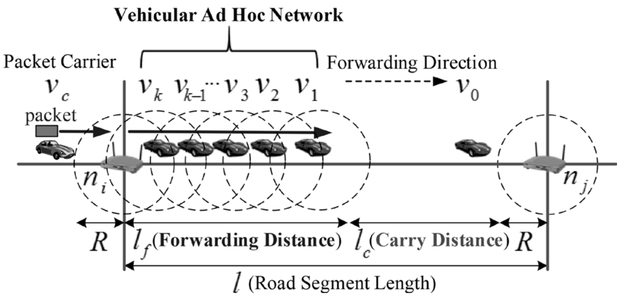


Fig. 7. Link Delivery Delay on Road Segment

This subsection shows the modeling of the link delivery delay (called link delay) from our early work TSF[16]. It is assumed that one road segment with one-way vehicular traffic has the road length (l), the vehicle arrival rate (λ), the vehicle speed (v), and the communication range (R). It is also supposed that for packet store-and-forward, one relay node is placed at each end-point (i.e., intersection) of the road segment. The link delay for a two-way vehicular traffic is left as future work. In VANET scenarios, carry delay is the dominant delay factor since the communication delay caused by the wireless communication is negligible in comparison to the carry delay incurred by vehicles carrying the packets. Therefore, in our analytical model for the link delay, only the carry delay is considered for the sake of clarity, though the small communication delay does exist in our design.

The link delay for one road segment is computed considering the following two cases for the communication range of the relay node at intersection n_i in Fig. 7, such as (i) Immediate Forward at entrance intersection n_i toward exit intersection n_j and (ii) Wait and Carry at entrance intersection n_i.

- Case 1: Immediate Forward: The packet carrier V_c forwards its packet to the relay node at entrance intersection n_i. The relay node then forwards the packet toward the head v_1 by Forwarding Distance l_f for the VANET consisting of vehicles v_h for $h = 1..k$. The head v_1 carries the packet with itself by Carry Distance l_c to the communication range R of the relay node at the exit intersection n_j.
- Case 2: Wait and Carry, the packet carrier V_c forwards its packet to the relay node at entrance intersection n_i. Since there is no vehicle moving toward the exit intersection n_j, the relay node will wait until a vehicle shows up and moves toward the exit intersection n_j as a packet carrier. Such a packet carrier will carry the packet received from the relay node at the entrance intersection n_i to the communication range R of the relay node at the exit intersection n_j by Carry Distance $l - R$.

Considering these two cases, we can compute the mean μ_i and variance σ_i^2 of the link delay d_i on a road segment e_i. Refer to TSF[16] for the detailed derivation of μ_i and σ_i^2.

Let $G = (V, E)$ be road network graph where V is the set of intersections and E is the matrix of road segments. With the mean $E[d_i]$ and variance $Var[d_i]$ of the link delay d_i, we model the link delay d_i as the Gamma distribution. Note that the Gamma distribution is usually used to model the positive continuous random variable, such as the waiting time and lifetime[35]. Thus, the distribution of the link delay d_i for edge $e_i \in E$ is $d_i \sim \Gamma(\kappa_i, \theta_i)$ such that $E[d_i] = \kappa_i\theta_i$ and $Var[d_i] = \kappa_i\theta_i^2$ for $d_i, \kappa_i, \theta_i > 0$ [35]. Since we have the mean and variance of the link delay, that is, $E[d_i] = \mu_i$ and $Var[di] = \sigma_i^2$, we can compute the parameters θ_i and κ_i of the Gamma distribution[35] in the same way with Link Travel Delay in Section Ⅳ.1.

Note that our design can accommodate an empirical link delay distribution if available through measurement. For this empirical distribution of link delay, adjacent relay nodes can periodically exchange probe packets with each other to obtain link delay samples. Therefore, with the link delay model for a directed edge corresponding to a road segment, next subsection will model the End–to–End packet delay.

Ⅳ.4. Path Delivery Delay on End–to–End Path

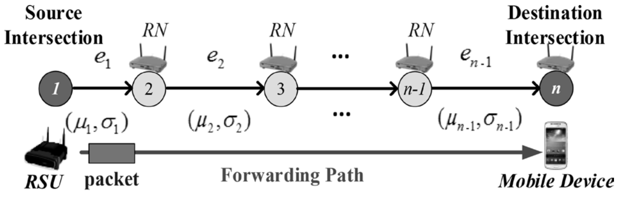


Fig. 8. Path Delivery Delay on Forwarding Path

This subsection models the End–to–End (E2E) Packet Delay from one intersection to another intersection in a given road network[16]. As discussed in Section Ⅳ.3, the link delivery delay (i.e., link delay) is modeled as the Gamma distribution of $d_i \sim \Gamma(\kappa_i, \theta_i)$ for edge $e_i \in E$ in the road network graph G.

Given a forwarding path from an RSU to a target point, we assume that the link delays of edges constructing the path are independent. From this assumption, the mean and variance of the E2E delivery delay (P) are computed as the sum of the means ($E[P]$) and the sum of the variances ($Var[P]$) of the link delays along the E2E path, respectively. Fig. 8 shows the E2E delivery delay model for the forwarding path from RSU to mobile device. In the similar way with the E2E travel delay in Section Ⅳ.2, the E2E delivery delay distribution can be modeled as $P \sim \Gamma(\kappa_P, \theta_P)$ such that $E[P] = \kappa_P \theta_P$ and $Var[P] = \kappa_P \theta_P^2$ for $P, \kappa_P, \theta_P > 0$ [35].

So far, we have explained our delay models for mobile node's travel delay and packet's delivery delay on both a road segment and an E2E path. In next section, we will design two smart road services using the delay models discussed in this section.

Ⅴ. VCPS Applications

In this section, we explain two applications as smart road services based on VCPS, such as (i) Interactive Navigation Service and (ii) Pedestrian Protection Service.

Ⅴ.1. Interactive Navigation Service

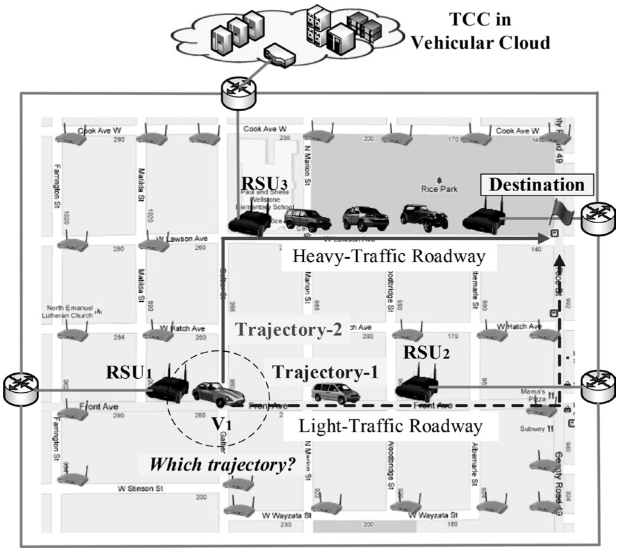


Fig. 9. Interactive Navigation through VCPS

With vehicular cloud, we can design an interactive navigation service for the more efficient driving for vehicles in road networks. The state–of–the–art navigation services[4~10] are based on real–time road traffic, but they do not perform traffic load balancing for the efficient road traffic flowing. For a better navigation service considering the traffic load balancing, the trajectories of the vehicles can be maintained by TCC in the vehicular cloud (as shown in Fig. 9), so TCC will be able to predict which road segments will be highly congested in the near future. By this prediction, TCC can guide vehicles to take better alternative paths as their vehicle trajectories for the navigation.

Fig. 9 shows interactive navigation through the communication between vehicle V_1 and road–side unit RSU_1. Since RSU_1 is connected to TCC via the Internet, TCC can guide V_1 via RSU_1 to choose the best trajectory for its destination, considering both the current road traffic conditions and the future congestion in road segments.

Now we clarify the interaction between the vehicle and the vehicular cloud. It is assumed that Navigation Client is running on the vehicle as a smartphone App and Navigation Server is running on the vehicular cloud as a cloud server. The procedure for the interactive navigation service is as follows:

1) As Navigation Client, a vehicle with navigator contacts Navigation Server in TCC via adjacent RSUs for navigating from its source to its destination. The navigation route request is performed by V2I data delivery scheme, such as TBD[17]. In the case where RSUs are not available for DSRC, the vehicle can use other wireless links, such as 3G/4G-LTE and WiMAX.

2) Navigation Server maintains road traffic matrices for a target road network graph to estimate both link travel delay and traffic congestion level per road segment in the graph.

3) With these matrices, Navigation Server computes an optimal route for the Navigation Client to experience the minimal travel delay, considering the future traffic conditions (i.e., traffic congestion levels) on the road segments in the target road network.

4) Navigation Server gives the optimal route to Navigation Client for navigation. The data delivery from Navigation Server to Navigation Client is performed by I2V data delivery scheme, such as TSF[16]. This I2V data delivery toward a moving destination vehicle is possible because TCC maintains the trajectory of the vehicle as Navigation Client for the location management.

5) When receiving the route from Navigation Server, Navigation Client starts its travel along the guided route.

6) If Navigation Client goes out of the guided route, it repeats Steps 1 through 5 to get a new route from Navigation Server.

The research issue is how to construct and maintain the road traffic matrices for the estimation of link travel delay and traffic congestion level per road segment.

V.2. Pedestrian Protection Service

Pedestrian protection is very important to reduce the fatality around school zones and downtown streets. Nowadays most of people are carrying a smartphone as either a pedestrian or a driver every day. Fig. 10 shows the pedestrian protection through the communication between the smartphones of the pedestrian and the driver in the vehicle approaching the pedestrian. If two smartphones share their trajectories and motion vectors, it is feasible to tell the possibility that the pedestrian and the vehicle will collide by some mistake caused by either the pedestrian or the driver. When the vehicle is going to hit the pedestrian just in a couple of seconds, the smartphone of the driver will be able to notify the pedestrian of such a dangerous situation in the form of either voice or vibration.

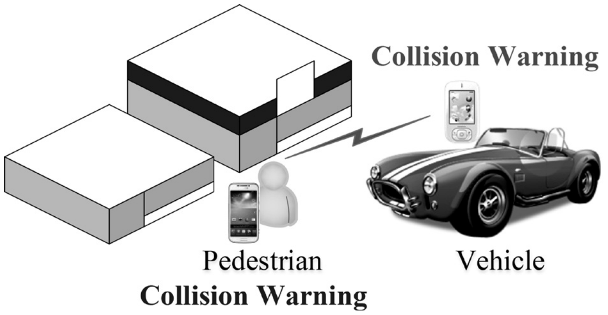


Fig. 10. Pedestrian Protection through VCPS

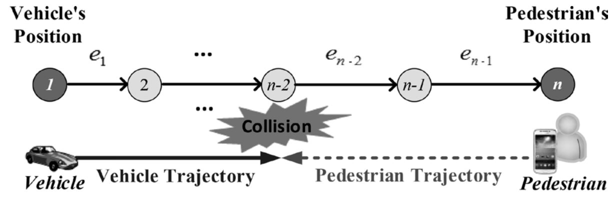


Fig. 11. Collision Prediction between Vehicle and Pedestrian

Fig. 11 shows collision prediction between a vehicle and a pedestrian with the vehicle trajectory and the pedestrian trajectory. This collision prediction can be done through the modeling of the vehicle travel delay and the pedestrian travel delay, as discussed in Section IV.

Now we articulate the interaction between the pedestrian's smartphone and the vehicle's smartphone through the vehicular cloud. It is assumed that one Navigation Client is running on the pedestrian's smartphone and the vehicle's smartphone as a smartphone App, respectively and that Navigation Server is running on the vehicular cloud as a cloud server. Also, Navigation Agent is running on an RSU nearby the pedestrian for the sake of the effective information exchange among Navigation Clients along with Navigation Server as middle cloud[11][13]. The procedure for the pedestrian protection service is as follows:

1) As Navigation Client, a smartphone with navigator periodically reports its location, direction, and speed to Navigation Server in TCC via adjacent RSUs during its travel from its source to its destination. The delivery of this location update message is performed by V2I data delivery scheme (such as TBD[17]) by using the smartphones of the neighboring vehicles or pedestrians as intermediate packet forwarders or carriers. In the case where RSUs are not available for DSRC, the smartphone can use other wireless links to communicate with Navigation Server, such as 3G/4G-LTE and WiMAX.

2) Navigation Server maintains location and motion vector matrices for the smartphones of the pedestrians and vehicles in a target road network graph to predict the possible collision in the graph.

3) With these matrices, Navigation Server computes the collision probability for a pair of pedestrian and vehicle, considering the pedestrian trajectory and the vehicle trajectory along the road segments in the target road network.

4) For each pair with a high collision probability above the predefined threshold for accident avoidance, Navigation Server delivers the emergency message to both the vehicle and the pedestrian in one pair with a possible collision in the form of voice or vibration. This emergency message delivery must be performed within some short threshold (e.g., 0.1 second) by the cellular link through 4G-LTE/3G or I2V data delivery scheme (such as TSF[16]).

5) When receiving this notification from Navigation Server, Navigation Client immediately reacts to it by generating a special voice message or sound along with a special vibration to let the relevant pedestrian and the driver react to the dangerous situation promptly.

6) If Navigation Client goes out of the dangerous situation, it repeats Steps 1 through 5 for the pedestrian protection with Navigation Server.

In this pedestrian protection, it is important to minimize false negative and false positive for the collision between a vehicle and a pedestrian. Otherwise, the walking and driving will disturb pedestrians and drivers by the misleading guidance for the pedestrian protection service.

As other VCPS applications, we can envision Vehicle Collision Avoidance and Road Condition Sharing among only vehicles for the driving safety. Therefore, we will increase our welfare in road networks through VCPS based on vehicular cloud.

Ⅵ. Research Issues

In this section, we discuss further research issues for VCPS. We have the following research issues for VCPS:

- To realize the VCPS, we need to consider system-level design of vehicular cloud systems. For example, for the interactive navigation service, we decompose the tasks and roles of Navigation Client and Navigation Server in the viewpoint of the cloud systems.

- In VCPS, mobile devices promptly need to select wireless link(s) among the available wireless links, such as DSRC, 3G, 4G-LTE, WiFi, and WiMAX. A switching mechanism among the multi-links is required as a vertical handover. Also, a horizontal handover for the same wireless links should be supported in a seamless way.

- For the interactive navigation service, we need to measure vehicular traffic statistics with mobile devices. Thus, we need to design the measurement functions for vehicle's average speed and speed deviation per road segment by using GPS navigation systems in the mobile devices.

- For the pedestrian protection, we need to track the mobility of the mobile nodes (i.e., vehicle and pedestrian). To track the pedestrian, we can implement the motion prediction using the accelerometer and gyroscope in smartphones. Since the accurate motion prediction is important to prevent a possible collision between the vehicle and the pedestrian, the algorithm of the mobile node tracking should be well-designed and implemented in a solid way.

- Autonomous dynamic system reconfiguration for VCPS is required to self-adapt the VCPS according to the change of task loads and the available resources in cloud clients and cloud servers, such as (i) the computing power and storage capacity in the cloud servers and (ii) the battery consumption rate or battery budget in mobile devices. For these scalable and elastic cloud services, the VCPS should be self-adaptive systems under highly dynamic environments in the real world, such as road networks and streets.
- Networking and connectivity mechanisms should be self-adaptive for the effective battery consumption for mobile devices. Since the mobile devices (e.g., smartphones) have high energy drain rate for interactive cloud services (e.g., interactive navigation and pedestrian protection) due to the frequent communications with the vehicular cloud infrastructure nodes, such as RSUs and RNs. For these interactive cloud services, service processes can be decomposed into multiple modules that are collaboratively performed in mobile devices, RNs, RSUs, and TCC in order to minimize the energy consumption in the mobile devices, while guaranteeing a certain level of Quality of Service.

Ⅶ. Conclusion

In this paper, we proposed our design of Vehicular Cyber-Physical Systems (VCPS) based on vehicular cloud for smart road networks. For the communications among mobile devices in VCPS, vehicular networks in VCPS need to support multiple wireless communications, such as DSRC, 3G, 4G-LTE, WiFi, and WiMAX. With these multiple wireless links, the vehicular networks consist of Traffic Control Center (TCC), Road-Side Units (RSUs), Relay Nodes (RNs), and Mobile Devices (e.g., vehicles, smartphones, and tablets). To design smart road services, we first described our delay modeling for a mobile node's travel delay. We then explained two smart road services for the driving efficiency and safety, that is, interactive navigation and pedestrian protection, respectively. As future work, we will investigate the design and implementation of the vehicular cloud computing considering the efficient smartphone battery consumption. That is, we will research on how to design and implement vehicular cloud applications to minimize the energy consumption of smartphones by using the infrastructure of vehicular networks, such as RSUs.

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