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Vehicle Assisted Data Update for Temporal Information Service in Vehicular Networks

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***Abstract*—Vehicular networks blueprint the bright future of transportation systems in safety, efficiency and sustainability. Highly dynamic traffic information is one of the most important features in vehicular networks, which makes data services very challenging, as the data quality drops over time dramatically and timely data update is expected to maintain the service quality. In this paper, we consider the system architecture, in which vehicles coming from different directions are able to sense and carry up-to-date location-based information along their trajectories and upload fresh information to the roadside unit (RSU) when passing through. Meanwhile, vehicles may request information from the RSU for other routes. To enable efficient data services in such a scenario, firstly, we characterize the freshness of temporal data. Then, based on the general form of data quality function, we propose a heuristic algorithm called priority-based scheduling (PBS), which synthesizes the data quality, the broadcast effect and the real-time service requirement in making scheduling decisions. A comprehensive performance evaluation demonstrates the superiorty of PBS under a variety of scenarios.**

I. Introduction

Vehicular networks are envisioned as a promising way to enhance the transportation system in safety, efficiency and sustainability [1]. Advantages in wireless communications make real-time applications in vehicular networks possible, such as autonomous intersection control [2], road reservation [3] and in-vehicle infotainment [4], to name but a few. In these applications, there are stringent timing requirements on data services, including both the timely data dissemination to serve real-time requests and the timely data update to ensure information quality. Nevertheless, it is non-trivial to satisfy both requirements simultaneously, as they have to compete for common resources (i.e. processors or wireless bandwidth) and therefore it is imperative to strike a balance between serving real-time requests and updating temporal data items to achieve the best system performance.

In this work, we consider a common information service scenario in vehicular networks where the RSU is installed at the road intersection to provide information services to the passing vehicles via infrastructure-to-vehicle (I2V) communication [5, 6]. Specifically, we consider that the fresh information is sensed and carried by vehicles, such as value-added advertisements, real-time traffic conditions and parking information, etc. Therefore, passing vehicles can upload the up-to-date information to the RSU. Then, the RSU can broadcast fresh data items to other vehicles, via an on-demand manner. This type of data update architecture enables a flexible and practical way to provide temporal data services. This paper presents a novel information service architecture and investigates the temporal data service problems in details.

In vehicular networks, location-based applications usually impose strict temporal and spatial requirements on data services. When the value of the requested data item is outdated, the quality of service cannot be promised. Even worse, it may cause dangerous consequences when retrieving outdated information in safety-critical applications. Some relevant studies have investigated the data dissemination problem assuming internet-based data update [7, 8], where RSUs are assumed to be connected to a backbone network, and the data update is guaranteed by the powerful backbone network. Nevertheless, these studies did not consider the overhead of data update when passing vehicles are supposed to upload fresh information to the RSU. Zhang et.al [9] has paid attention to vehicle-assisted data update. They focused on enhancing the ratio of fresh data maintained at the RSU. Nevertheless, they only considered the freshness of data in binary states, namely valid or invalid. In many applications, the values of data items change over time and hence, the binary state cannot reflect the magnitude of information freshness efficiently. In this paper, we analyze the property of data value in detail by modeling the data quality and investigate the information service problem by synthesizing both the data quality and the real-time service requirement.

The main contributions of this paper are outlined as follows. First, we present a temporal information service system in vehicular networks, which involves both vehicle-based data update (uploading) and RSU-based data dissemination (down-

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loading). The upload of fresh data items and the download of requested data items compete for the same bandwidth resource. Second, we investigate the property of data quality in vehicular networks and formulate the problem by deriving a general form of the data quality function. Third, considering the key factors including data quality, broadcast effect and real-time requests, we propose a heuristic scheduling algorithm called priority-based schedule (PBS), which aims at enhancing both the quality of service and the service ratio. Fourth, we build the simulation model and implement the proposed algorithm. The comprehensive simulation results demonstrate the effectiveness of the proposed algorithm under a variety of circumstances.

The rest of this paper is organized as follows. Section II presents the system architecture. In Section III, we analyze the property of data quality and formulate the problem. In Section IV, we propose a heuristic scheduling algorithm. In Section V, we build the simulation model and evaluate the algorithm performance. Section VI concludes the work and discusses future research directions.

II. SYSTEM MODEL

We consider a typical temporal data service scenario in vehicular networks via I2V communication [9]. The RSU is installed at the road intersection and provides data services to passing vehicles. In particular, we focus on location-based temporal data services such as real-time traffic information in vicinity, or current available parking slots nearby, etc [9, 10]. The value of such information varies over time and it requires timely update to make information useful. Furthermore, we consider that passing vehicles from different directions will be able to collect such location-based information along their trajectories, and then they can update the database by uploading the up-to-date information to the RSU. The RSU will periodically broadcast available services to all the vehicles and hence, vehicles can request information of interest (e.g. traffic conditions where they are heading to). According to the pending requests and certain scheduling policy, the RSU selects corresponding data items from the database and broadcasts them to serve vehicles.

The system architecture is shown in Fig.1. Once entering RSU's coverage, the vehicle monitors the control channel and retrieves the service information broadcast from the RSU. Then, the vehicle sends the notification message to the RSU, which contains two parts: cache message and request message. The cache message contains a list of up-to-date data items collected by vehicles. The set of data items cached by vehicles provides a chance for RSU to update its stale data items during the dwelling time of vehicles. The request message includes a list of data items required by the vehicle, which have to be received before the vehicle leaves RSU's coverage.

The RSU maintains two lists: upload list and request list. The upload list contains each data item associated with the set of vehicles which are capable of upload the corresponding data item. The RSU is able to assign an upload task to a specified vehicle and allocate corresponding time slots for data uploading. The request list contains the requested data items and the corresponding vehicle IDs. Due to the broadcast nature of wireless communication, RSU can broadcast one data item to satisfy all the vehicles requesting for it. In this model, the RSU can process either data update or service request at a time. As shown in Fig.1, RSU alternatively updates (denoted by U) and disseminates data (denoted by D) in different time slots. Clearly, how to effectively utilize the shared bandwidth to strike a balance between keeping data freshness and serving time-constrained requests is critical to enhance the overall system performance. The detailed formulation of the problem is elaborated in the following section.

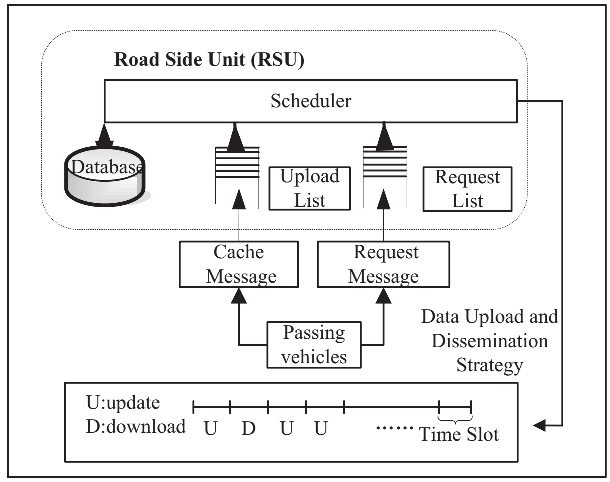

Figure 1. System architecture of temporal information service in vehicular networks

III. PROBLEM FORMULATION

A. Notations

In order to concentrate on the investigation of the temporal information service problem, we make several reasonable assumptions to simplify the vehicular environment without loss of the essentials of the concerned problem:

- The vehicle caches the up-to-date information along its own trajectory when it enters RSU's coverage. Assume that vehicles coming from different directions sense and carry different location-based information.
- The temporal data items are assumed to be in uniform size, and the time unit for uploading/downloading a data item is referred to as a time slot.

The set of data items in the database is denoted by $D = \{d_1, d_2, ..., d_{||D||}\}$. We use τ to denote the time for uploading or disseminating one data item (i.e. a time slot). $U_{d_i}(t)$ represents the last update time of d_i at t and $E_{d_i}(t)$ represents the expiration time of d_i at t. The valid period of d_i is denoted by l_{d_i}. Accordingly, $E_{d_i}(t) = U(d_i, t) + l_{d_i}$. Then, we define the quality function $Q_{d_i}(t)$ to indicate the magnitude of freshness of d_i. Specifically, we use $Q^R_{d_i}(t)$ and $Q^{v_j}_{d_i}(t)$ to represent the data quality of d_i cached by RSU and vehicle v_j, respectively.

The set of vehicles in the service range of RSU is denoted by $V = \{v_1, v_2, ..., v_{||V||}\}$. For each vehicle v_j, ET_{v_j} and LT_{v_j} represent the entering time and leaving time, respectively. $H(v_j)$ is the set of data items cached by vehicle v_j. The direction of v_j is denoted by O_{v_j}. Two vehicles v_i and v_j coming from two different directions carry different information. That is, if $O_{v_i} \neq O_{v_j}$, then $H(v_i) \cap H(v_j) = \emptyset$. $R(v_j)$ is the set of data items requested by v_j. Likewise, if $O_{v_i} \neq O_{v_j}$, then $R(v_i) \cap R(v_j) = \emptyset$.

B. Data quality model

In this section, we quantitatively model the data quality for location-based temporal information services. For comparison, we normalize the range of data quality to [0,1], where 1 means the data item has no loss of quality and 0 means the data item is invalid. Accordingly, we have $0 \leq Q_{d_i}(t) \leq 1, \forall d_i \in D$. We summarize the general property of the data quality as follows:

- $Q_{d_i}(t)$ degrades over time if it has not been updated in due course. For the information with longer valid period l_{d_i}, $Q_{d_i}(t)$ decreases slower.
- $Q_{d_i}(t)$ is related to the last update time $U_{d_i}(t)$. At time t, the larger value of $U_{d_i}(t)$ indicates that the data is updated more recently, and therefore the quality of $Q_{d_i}(t)$ is better.
- As vehicle carries the up-to-date information when it enters the coverage of RSU, $Q_{d_i}(t)$ of d_i cached by v_j at ET_{v_j} is set as $Q_{d_i}^{v_j}(ET_{v_j}) = 1$ where $U_{d_i}(t) = ET_{v_j}$.
- If the RSU schedules a vehicle v_j to upload d_i at time t, the upload is completed at $t + \tau$. Then $Q_{d_i}^{R}(t + \tau)$ of d_i maintained at the RSU is updated to $Q_{d_i}^{v_j}(t + \tau)$.

The degradation of data quality depends on the specific application. Hence, the formulation of the data quality function can be various according to different applications. To emphasize the generality of our analysis, in this paper, we model the quality function in a general form to be defined later.

C. Temporal Data Management

RSU is responsible for scheduling update and service tasks by selecting the corresponding upload/download data item in each time slot. RSU maintains two lists: upload list and request list, which are denoted by $UD = \{ud_1, ud_2, ..., ud_{||UD||}\}$ and $RD = \{rd_1, rd_2, ..., rd_{||RD||}\}$, respectively. Due to the dynamics of vehicular mobility, several timing requirements are imposed on data update and dissemination, which are described as follows.

When $Q_{d_i}^{R}(t)$ degrades over time, the RSU schedules a vehicle v_i which has cached the latest version of d_i for updating to enhance the data quality of d_i. As the limited dwelling time of v_i, the uploading has to be completed before v_i leaves:

$$t_{d_i}^{U} + \tau \leq LT_{v_j} \tag{1}$$

where $t_{d_i}^{U}$ is the upload start time for d_i and LT_{v_j} is the leaving time for v_j.

When the RSU schedules to broadcast d_i, if the vehicle v_j is able to receive d_i, it should satisfy the following condition:

$$t_{d_i}^{D} + \tau \leq LT_{v_j} \tag{2}$$

where $t_{d_i}^{D}$ is the broadcast start time of d_i. Then, the set of vehicles which are able to receive d_i at time t is represented as follows:

$$\gamma_{d_i}(t) = \{v_j | t + \tau \leq LT_j, d_i \in R(v_j)\} \tag{3}$$

We define the broadcast productivity in order to evaluate the broadcast effect.

Definition III.1. *broadcast productivity:* the broadcast productivity of d_i at time t, represented by $\|\gamma_{d_i}(t)\|$, is defined as the number of vehicles which have received d_i before leaving the coverage of RSU.

In order to effectively evaluate the utility of data broadcast, we define the broadcast performance for broadcasting d_i at t as follows:

Definition III.2. *broadcast performance:* The broadcast performance of d_i is defined as the product of data quality and its broadcast productivity, which is computed by

$$\Phi_{d_i}(t) = Q_{d_i}^{R}(t) \cdot \|\gamma_{d_i}(t)\| \tag{4}$$

This metric considers both the data quality and broadcast productivity. On one hand, to improve $\Phi_{d_i}(t)$, RSU can allocate a time slot to update d_i and enhance $Q_{d_i}(t)$. On the other hand, RSU can broadcast the data item with higher broadcast productivity. Based on Eq.4, we define the overall system performance during the time interval [0, T] as follows:

Definition III.3. *system performance:* it is defined as the ratio of the broadcast performance summation of all broadcast data items to the total number of service requests in [0,T].

$$\Phi_s(T) = \frac{\sum\limits_{\forall t_j + \tau \leq T} \Phi_{td_j}}{\sum\limits_{\forall d_i \in D}^{||D||} rq_{d_i}} = \frac{\sum\limits_{\forall t_j + \tau \leq T} Q_{td_j}^{R}(t_j) \cdot \left\|\gamma_{td_j}(t_j)\right\|}{\sum\limits_{\forall d_i \in D}^{||D||} rq_{d_i}} \tag{5}$$

where $\Phi_S(T)$ is the overall system performance during time interval [0,T]. td_j refers to the data item broadcast by RSU at time t_j and rq_{d_i} refers to the total number of requests pending for d_i. From the system point of view, the RSU desires both high quality of data items and high service ratio of requests. However, as the limited bandwidth and dynamics of vehicular topology, it is challenging to achieve both of the goals. Therefore, it is imperative to design a scheduling mechanism to enhance system performance by striking a balance between the data quality and the service ratio.

IV. Algorithm Design

In this section, we propose a priority-based schedule (PBS) algorithm. For each data item d_i, it is associated with a set of vehicles capable of accomplishing the upload, which is defined as the available upload set:

Definition IV.1. *available upload set:* At time t, the available upload set of d_i, denoted by $HS_{d_i}(t)$, is defined as the set of vehicles which are able to completely upload d_i before leaving RSU*:*

$$HS_{d_i}(t) = \{v_j | t + \tau \leq LT_j, d_i \in H(v_j)\}, \forall d_i \in UD \quad (6)$$

At time t, d_i may be cached by multiple vehicles. The data quality of d_i varies with ET_{v_j} of v_j. To improve system performance, RSU chooses the best data quality of d_i cached by vehicles in $HS_{d_i}(t)$. Therefore, we define upload quality as follows:

Definition IV.2. *upload quality:* At time t, if the RSU schedules to update d_i, then the data quality of d_i cached by RSU after updating is computed by:

$$Q_{d_i}^U(t+\tau) = \max_{v_j \in HS_{d_i}(t)} \left\{ Q_{d_i}^{v_j}(t+\tau) \right\} \quad (7)$$

where $Q_{d_i}^U(t+\tau)$ represents the best quality of d_i after data update at $t+\tau$. Then, the vehicle for uploading d_i can be determined by:

$$v_{d_i} = \arg \max_{v_j \in HS_{d_i}(t)} \left\{ Q_{d_i}^{v_j}(t+\tau) \right\} \quad (8)$$

For a data item demanded by multiple requests, we define a service deadline to indicate the urgency of broadcasting a data item:

Definition IV.3. *service deadline:* The service deadline of broadcasting d_i at time t is defined as the closest deadline of those pending requests asking for d_i, which is computed as follows:

$$s_{d_i}(t) = \min_{v_j \in \gamma_{d_i}(t)} \left\{ LT_{v_j} - t | d_i \in R(v_j) \right\} \quad (9)$$

Based on the above analysis, the algorithm is designed based on the following observations. First, to enhance system performance, the algorithm gives a higher priority to the data item associated with a higher value of broadcast performance. Second, to improve the service ratio, the algorithm gives a higher priority to the data item with closer service deadline. Third, to enhance the data quality, the algorithm gives a higher priority to the data item whose broadcast performance would be improved if the update was scheduled. To sum up, the schedule priority is defined as follows:

$$P(d_i,t) = \max \left\{ \frac{Q_{d_i}^R(t+\tau) \cdot \gamma_{d_i}(t+\tau)}{\tau \times s_{d_i}(t+\tau)}, \frac{Q_{d_i}^U(t+2\tau) \cdot \gamma_{d_i}(t+2\tau)}{2\tau \times s_{d_i}(t+2\tau)} \right\} \quad (10)$$

The left term in the Max function indicates the gain of directly broadcasting d_i and the right term indicates the gain of updating d_i before broadcasting. According to Eq.10, it shows that only if the update of d_i can improve system performance, the RSU decides to update d_i. Otherwise, the RSU broadcasts d_i directly.

PBS consists of three steps. In step 1, the RSU traverses the upload list and the request list to update the information of data items in the database, including adding the cache message and the request message of new arrival vehicles and removing the cache message and the request message of vehicles which have left the coverage. In step 2, the RSU computes the priority of each data item in RD and finds the one with the highest $P(d_i,t)$. In step 3, RSU determines whether to update d_i before broadcasting and makes final scheduling decisions.

V. Performance Evaluation

A. Setup

The simulation model is built based on the system architecture illustrated in Section II and it is implemented by CSIM19 [11]. We simulate a four-way intersection, where the arrival pattern of vehicles in each direction follows the Poisson process. Hence, the inter-arrival time of vehicles in each direction follows the Exponential distribution with mean value of $1/\lambda$. The traffic characteristics are simulated according to the Greenshield's model [12], which is widely adopted in macroscopic traffic models [13]. Accordingly, the relationship between speed (v) and traffic density (k) is represented by $v = v^f - \frac{v^f}{k^j} \cdot k$, where v^f is the free-flow speed and k^j is the traffic jam density. In the simulation, we set $v^f = 100km/h$ and $k^j = 100veh/km$. For each vehicle, it will randomly cache $10 \sim 15$ fresh data items and the number of requested data items are uniformly generated in the range of rs. The data access pattern follows the Zipf distribution [14] with a skew parameter θ and the valid period of each data item is generated in the range ep. The number of data items in the database is 4×100, where the number of data items for each direction is 100. The time slot (i.e. the time for uploading or broadcasting one data item) is set as $\tau = 0.2s$, which is reasonable because according to Dedicated Short Range Communication (DSRC) [15], the data rate of DSRC using BPSK modulation is about 3 Mbps and it consumes 0.2s to complete the transmission of one data item with 0.6Mb. The range of the RSU's coverage is 500m. To quantitatively evaluate the data quality, a commonly-used linear function [16] is adopted, which is a typical setting for evaluating data quality in vehicular networks. The formulation is expressed as follows:

$$Q_{d_i}(t) = \begin{cases} 1 - \frac{t - U_{d_i}(t)}{l_{d_i}}, & U_{d_i}(t) \leq t \leq E_{d_i}(t) \\ 0, & t > E_{d_i}(t) \end{cases} \quad (11)$$

The defaults parameter settings are summarized in Table I. Unless stated otherwise, the simulation is conducted under the default setting. For performance comparison, we have implemented a well-known algorithm called Two-Step [9], which is one of the most competing alternatives in the literature. For performance evaluation, we collect the following statistics from the simulation: the broadcast productivity $\|\gamma_{td_i}(t_i)\|$, the data quality $Q_{td_i}^R(t_i)$ of td_i and the total requested number rq_{d_i} of d_i. On this basis, the following metrics are evaluated.

1) Service Ratio (SR): the ratio of the number of satisfied requests to the total number of service requests, which is

Table I
DEFAULT SETTINGS

Param	Default	Description
$\|D\|$	100*4	Size of database
λ	0.3	The arrival rate of vehicles
L	1000m	The diameter of coverage of RSU
rs	[10,15]	Request size (Uniform distribution)
ep	[200s, 300s]	Valid period of data items
τ	0.2s	The time slot
θ	0.8	Zipf distribution parameter

computed by:

$$SR = \frac{\sum_{\forall t_i+\tau \leq T} \gamma_{td_i}(t_i)}{\sum_{\forall d_i \in D} rq_{d_i}} \quad (12)$$

2) Average Data Quality (ADQ): it is defined as the mean value of data quality of the satisfied requests, which is computed by:

$$ADQ = \frac{\sum_{\forall t_i+\tau \leq T} \Phi_{td_i}}{\sum_{\forall t_i+\tau \leq T} \|\gamma_{td_i}(t_i)\|} \quad (13)$$

3) System Performance (SP): it has been defined in Definition III.3. A higher value of SP indicates better performance of the scheduling algorithm in improving overall system performance.

B. Experimental Results and Analysis

1) Effect of vehicle arrival rate: Fig. 2 shows the SP of the two algorithms under different vehicle arrival rates. A higher vehicle arrival rate results in a heavier traffic workload, indicating that the service workload is getting higher. According to Fig.2, PBS achieves better SP than Two-Step. Specifically, the gap between the two algorithms decreases with an increasing of vehicle arrival rates. We explain such a result by analyzing SR and ADQ in Figs. 3 and 4, respectively. When the vehicle arrival rate increases, the SR of the two algorithms decreases dramatically at the beginning due to the higher service workload. Then, the SR maintains a stable level as vehicle dwell time is getting much longer due to the heavy traffic workload, and the long dwell time dominates the service performance. In Fig.4, ADQ of Two-Step is very low at low arrival rates. This is because Two-Step considers both service deadline and broadcast productivity, and when the traffic workload is light, the service deadline dominates scheduling decisions. Therefore, Two-Step gives much higher priority to update data items associated with closer deadlines, resulting in low data quality of data items associated with more broadcast productivity.

2) Effect of data valid period: Fig.5 shows the system performance (SP) of the two algorithms under different data valid periods. The shorter data valid period indicates that the data quality degrades more dramatically. In Fig.5, PBS shows better SP than Two-Step over the entire range. Especially, PBS shows greater advantage in improving overall system performance when the data valid period is getting shorter.

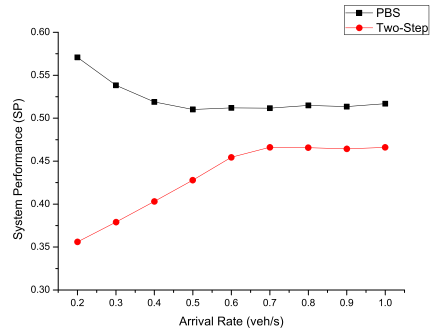

Figure 2. System performance under different vehicles arrival rates

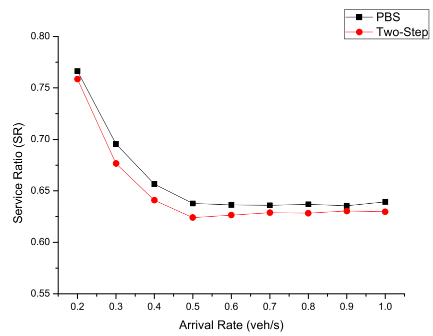

Figure 3. Service ratio under different vehicle arrival rates

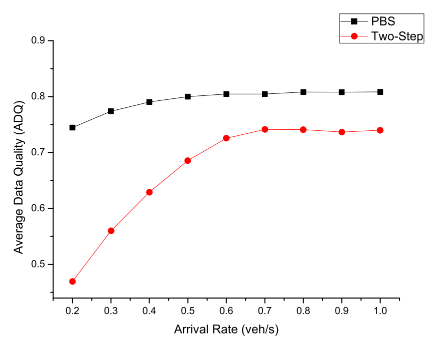

Figure 4. Average data quality under different vehicle arrival rates

The results in Fig.6 and Fig.7 explain more details, in which the service ratio (SR) and the average data quality (ADQ) of the two algorithms under different data valid periods are investigated, respectively. In Fig. 6, we note that the SR of PBS decreases dramatically and it is even lower than that of Two-Step when the data valid period is very short. This is because PBS allocates much more bandwidth to enhance the data quality when the data valid period is short. Therefore, although Two-Step achieves higher SR in such scenarios, it sacrifices the data quality severely. PBS maintains the value of ADQ at a preferable level across all the cases. Synthesizing both the service ratio and data quality factors, PBS outperforms Two-Step significantly under different data valid periods.

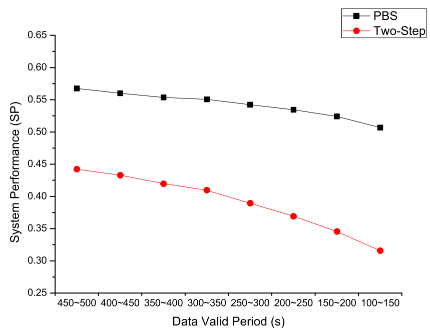

Figure 5. System performance under different data valid periods

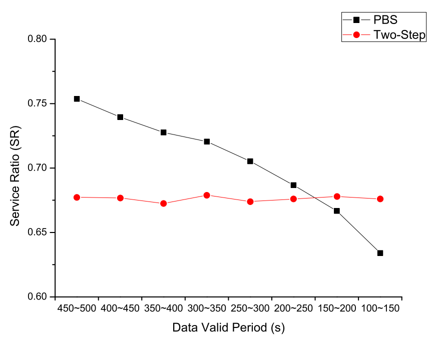

Figure 6. Service ratio under different data valid periods

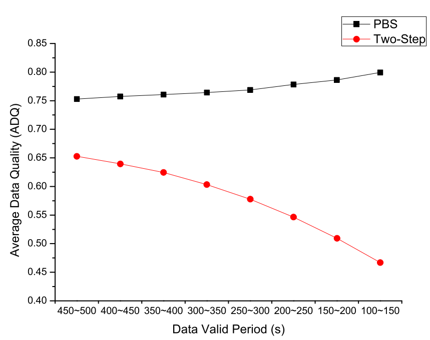

Figure 7. Average data quality under different data valid periods

VI. Conclusion and Future Work

In this paper, we focus on location-based temporal information services in vehicular networks and present a service architecture where the data items maintained in the RSU is refreshed by vehicle uploading. Then, we analyze key factors of data quality, including data valid period and update time. To enhance both the service quality and the service ratio, we propose a scheduling algorithm called PBS, which combines the data quality, broadcast productivity and request urgency in scheduling to maximize the system performance. Last, we build the simulation model and design three metrics for performance evaluation, including system performance, service ratio and average data quality. The results demonstrate that PBS achieves better performance over Two-Step under a variety of environments.

In our future work, we will extend the service to multiple RSUs and exploit the benefit of RSUs' cooperation as well as V2V communication to further enhance system performance.

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