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Transmission Control Method to Realize Efficient Data Retention in Low Vehicle Density Environments

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Abstract With the development and spread of Internet of Things (IoT) technology, various kinds of data are now being generated from IoT devices, and the number of such data is expected to increase significantly in the future. Data that depends on geographical location and time is commonly referred to as spatio-temporal data (STD). Since the "locally produced and consumed" paradigm of STD use is effective for location-dependent applications, the authors have previously proposed using a STD retention system for high mobility vehicles equipped with high-capacity storage modules, high-performance computing resources, and short-range wireless communication equipment. In this system, each vehicle controls its data transmission probability based on the neighboring vehicle density in order to achieve not only high coverage but also reduction of the number of data transmissions. In this paper, we propose a data transmission control method for STD retention in low vehicle density environments. The results of simulations conducted in this study show that our proposed scheme can improve data retention performance while limiting the number of data transmissions to the lowest level possible.

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1 Introduction

With the development and spread of Machine-to-Machine (M2M) and Internet of Things (IoT) technologies, various kinds of data are now being generated from IoT devices. In the current era, the data generated from IoT devices are mostly collected and analyzed by Internet cloud servers that then provide useful data to applications. According to Cisco Systems, Inc., the number of M2M connections can be expected to grow from 6.1 billion in 2017 to 14.6 billion by 2022 [1]. Therefore, a considerable traffic volume increase will result because of the increasingly enormous amounts of data flowing into the Internet. In order to cope with this, it will be necessary to increase link bandwidth and improve router performance levels to prevent the burden on network infrastructure from skyrocketing due to unrestrained growth.

From the viewpoint of data content, some data generated from IoT devices, such as traffic, weather, and disaster-related information, are highly dependent on location and time. We define such information as "spatio-temporal data (STD)." The most effective way to use STD is to provide it directly to the users who are in the vicinity of the STD generation location. However, since servers connected to the Internet collect IoT device data, users often receive data from servers located far away. Therefore, to facilitate the "local production and consumption of data", a network infrastructure that can retain data within a specific area is crucial.

Previously, we proposed a novel Geo-Centric Network (GCN) as an infrastructure that can facilitate collection, analysis, and provision of STD based on geographical proximity. We have also proposed a vehicle-based STD retention system equipped with large capacity storage modules, high-performance computing resources, and short-range wireless communication equipment, as a means of distributing STD based on geographical proximity [2]. In this system, vehicles capable of wireless communication are defined as regional information hub (InfoHub), and the purpose of this system is to retain STD within a specific area. STD management by InfoHub vehicles has three particular advantages. First, the user can acquire the most up-to-date date in real-time since the data is retained in the vehicle network around the information source. The second is its ability to improve fault tolerance by distributing the data to each vehicle because all other vehicles will retain the data received even if one vehicle fails. Third, it allows data to be collected, analyzed, and distributed by each vehicle without using the server, which leads to improved server load distribution.

However, since all vehicles use the same communication channel, channel competition occurs when the number of vehicles increases, which in turn leads to deterioration in communication quality. In order to solve this problem, we have proposed a method for controlling vehicle data transmission probabilities based on the density of neighboring vehicles [2]. However, since vehicle density levels are always changing due to the mobility of the vehicles participating in the network, areas where the vehicle density levels become low may occur. In such case, this method may not be able to retain data effectively.

In this paper, we proposed a transmission control method for low vehicle density environments. In such environments, since the area that can be covered only by the own vehicle increase, the importance per transmission increases. Therefore, it is necessary to increase the transmission frequency. Accordingly, in this system, each vehicle adjusts its transmission period based on the degree of contribution to the coverage rate improvement. The effectiveness of this method is shown in our simulation results.

The rest of this paper is organized as follows. In Section 2, we describe studies related to data retention, while we outline our previous STD retention system and discuss the problems to be addressed in Section 3. In Section 4, we describe our proposed method to achieve efficient data retention in low vehicle density environments, while simulation models and evaluation results are provided in Section 5. Finally, we give our conclusions in Section 6.

2 Related Works

For data utilization using vehicular networks, Maihofer et al. proposed the method in which all vehicles in the retention area hold the data and position information of all other vehicles [3]. This method, which have been the subject of many previous studies, is suitable for vehicles that have a wide range of practical uses because no outside infrastructure is required. In a separate study, Maio et al. proposed a method using a software-defined network (SDN) as a technique for setting an optimum retention area range [4]. In that method, the server also operates an SDN controller that collects and analyzes mobility information such as speed and position from the vehicles, and then calculates the maximum radius of the retention area. Additionally, Rizzo et al. proposed an application for exchanging information between vehicles based on the assumption that infrastructure would become unusable in a disaster [5], while Leontiadis et al. proposed a method in which navigation information is exchanged to facilitate prediction of a vehicle heading into a retention area and in which data is delivered efficiently [6]. In the Floating Content [7] and Locus [8] system, each vehicle has a data list and exchanges it with passing vehicles. Next, each vehicle determines their data transmission probability based on their distance to the center where the data was generated. As the distance from the center increases, data acquisition probabilities decline. On the other hand, when there are numerous vehicles in the vicinity of the center, channel contention occurs, and the communication quality deteriorates because all vehicles transmit data with high transmission probabilities. Furthermore, even if data can be stored in the vicinity of the place where it was generated, there is an overhead in the data acquisition process because the users acquire data by query/response type information distribution such as query transmission, data discovery, and transfer to user. With these points in mind, we propose a novel network base capable of passively acquiring data as part of efforts to improve overhead and promote local production and consumption of data.

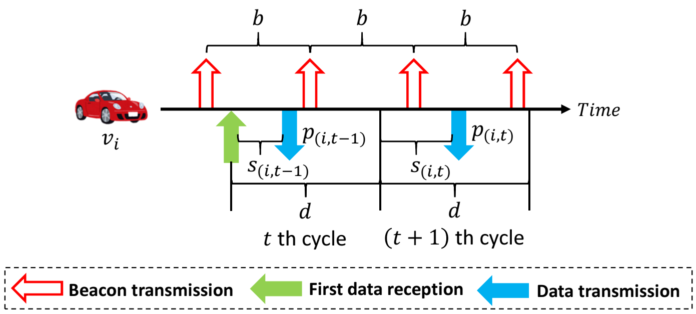


Fig. 1 Data transmission procedure

3 STD Retention System

In this section, we describe the assumptions, requirements, and outline of the retention system [2], and then discuss the related problems.

3.1 Assumption

In this system, STD includes not only data for an application but also area information such as the center coordinates, radius R of the retention area, length r of an auxiliary area, and frame period d. Each vehicle can obtain location information using a Global Positioning System (GPS) receiver and broadcasts a beacon that includes a unique identifier (ID). Furthermore, all vehicles are equipped with the same antenna and transmit at equal power levels.

3.2 System Requirements

In this paper, we defined coverage rate as an indicator of the data retention state. The coverage rate formula is as follows:

$$Coverage\ Rate = \frac{S_{DT}}{S_{TA}} \tag{1}$$

where S_{TA} is the size of retention area and S_{DT} is the size of the total area where a user can obtain the data transmitted from InfoHub vehicles within the one cycle. A high coverage rate means that users can automatically receive STD from anywhere within the retention area, so it is important to maintain a high coverage rate within the retention system.

3.3 Previous Work

In this section, we will provide an outline of our previous work [2] in which we proposed a method to control data transmission probability. This method uses simple information, such as the number of neighboring vehicles and the data reception number in order to improve the overhead of processing location information [9]. We begin by defining the data transmission area. When each vehicle v_i transmitted data, it confirms the retention area center coordinates from the received data and then calculates its distance y from the center. Data transmission areas are classified into the following two categories by y

$$\begin{cases} 0 < y \leq R + r: & data\ transmission\ area \\ otherwise: & out\ of\ area \end{cases} \tag{2}$$

where R is the retention area radius, and r is the auxiliary area length. The vehicles within the auxiliary area also transmit data to improve the coverage rate. Next, we will describe the data transmission timing. Fig.1 shows the data transmission procedure. When each vehicle v_i receives data from other vehicles for the first time, it first checks the frame period d included in the received data. Then, the vehicle randomly determines the next transmission time $s_{(i,t)}$ within d in order to avoid data transmission collisions. Furthermore, $s_{(i,t)}$ is calculated at the beginning of the cycle t.

The actual data transmission probability is controlled according to the neighboring vehicle density. Each vehicle detects the number of neighboring vehicles $n_{(i,t)}$ from the number of beacons transmitted by those vehicles. When the number of neighboring vehicles is more than four, the vehicle's transmission range has the potential to completely cover all the neighboring vehicles. For example, if the neighboring four vehicles are located to a vehicle's north, south, west, and east, they can cover the vehicle's transmission range. Therefore, the data transmission probability $p_{(i,t)}$ is determined based on the number of neighboring vehicles $n_{(i,t)}$ as described below.

case1 $n_{(i,t-1)} \leq 3$:
Since the vehicle's transmission area cannot be completely covered by that of the neighboring vehicles, the vehicle has to set its transmission probability individually $p_{(i,t)}$ to 1.

case2 $n_{(i,t-1)} \geq 4$:
In high vehicle density environment, since the potential for data transmission collisions increases with increases in the number of data transmissions, it is necessary to use the minimum number of vehicles to maintain high coverage rate. On the other hand, if the neighboring vehicles are clustered in some directions, coverage within the vehicle's transmission range may be spotty even if there are a large number of neighboring vehicles. To solve these problems, we defined $m_{(i,t)}$ as the estimated value of the number of received data during t-th cycle and adjusted the transmission probability $p_{(i,t)}$ based on the $m_{(i,t)}$. The predicted value $m_{(i,t)}$ is given as following equation:

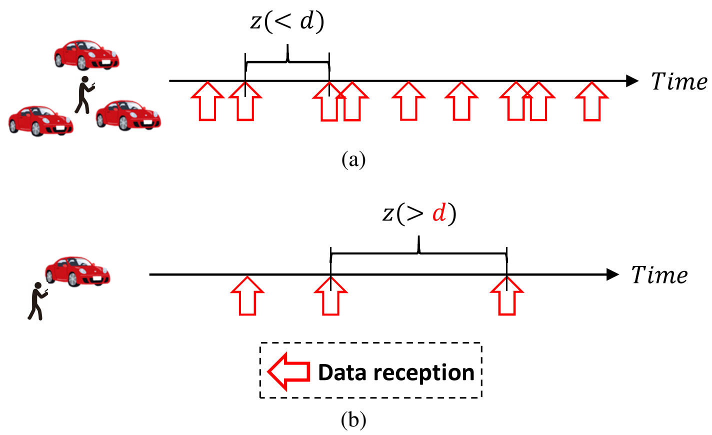


Fig. 2 Problems with the previous method: (a) high vehicle density, (b) low vehicle density

$$m_{(i,t)} = \alpha * l_{(i,t-1)} + (1-\alpha) * m_{(i,t-1)} \tag{3}$$

where $m_{(i,t-1)}$ is the predicted value of the previous cycle, $l_{(i,t-1)}$ is the number of received data during the previous cycle, and α is the moving average coefficient. The vehicle adjusts the data transmission probability by the following equation so that the number of received data becomes β in the t-th cycle.

$$p_{(i,t)} = \begin{cases} p_{(i,t-1)} + \frac{\beta - l_{(i,t-1)}}{n_{(i,t-1)}+1} & (0 < m_{(i,t)} < \beta) \\ p_{(i,t-1)} & (m_{(i,t)} = \beta) \\ p_{(i,t-1)} - \frac{l_{(i,t-1)} - \beta}{n_{(i,t-1)}+1} & (m_{(i,t)} > \beta) \end{cases} \tag{4}$$

Here, the transmission probability in the first cycle (initial value of transmission probability) is set to $\frac{\beta}{n_{(i,t-1)}+1}$. This means that the average value is set in order to control the number of received data from all vehicles (not only the number of neighboring vehicles, but also its own) to β. If $m_{(i,t)}$ is less than β, the vehicle increases the data transmission probability by $\frac{\beta - l_{(i,t-1)}}{n_{(i,t-1)}+1}$ in order to compensate for the shortage $\beta - l_{(i,t-1)}$ created by all $n+1$ vehicles. On the other hand, if $m_{(i,t)}$ is more than β, the vehicle decreases the data transmission probability by $\frac{l_{(i,t-1)} - \beta}{n_{(i,t-1)}+1}$ in order to reduce the excess amount $l_{(i,t-1)} - \beta$ produced by all $n+1$ vehicles. If $m_{(i,t)}$ is equal to β, $p_{(i,t)}$ is set to $p_{(i,t-1)}$ because the current data transmission probability is appropriate. If the value of $\frac{\beta - l_{(i,t-1)}}{n_{(i,t-1)}+1}$ or $\frac{l_{(i,t-1)} - \beta}{n_{(i,t-1)}+1}$ is negative, $p_{(i,t)}$ is set to $p_{(i,t-1)}$.

3.4 Problems with the Previous Method

As shown in Fig.2(a), if the vehicle density is high, the user's data reception interval z rarely exceeds the frame period d because the number of data transmissions is large. However, as shown in fig.2(b), if the vehicle density is low, z can exceed d. This is because the transmission interval within two consecutive cycles can exceed d due to the randomness of the transmission timing determination and the influence per vehicle can become especially large in low vehicle density environments. Therefore, since z can exceed d, method that is suitable for such environments is necessary.

4 Proposed Method

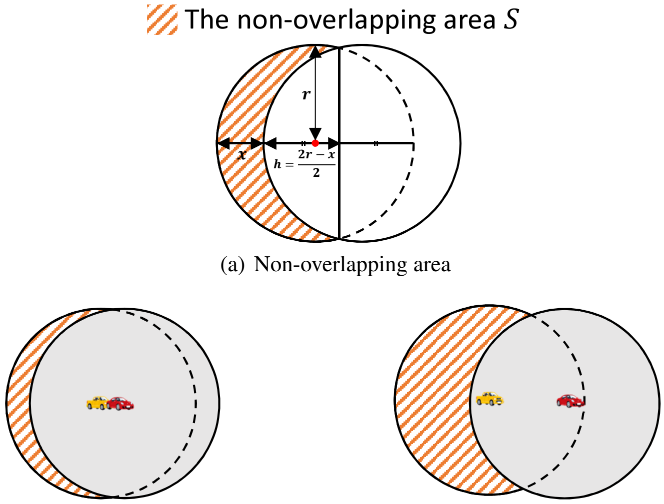
In this section, we describe a method for facilitating efficient data retention in low vehicle density environments. We first present a setting the minimum transmission period and then introduce the data transmission period control.

In order to solve the problems related to the previous method, it is necessary to make the maximum transmission interval randomly determined smaller than d. Hence, the frame period must be set to half of d. This frame period d_{min} is then defined as the minimum data transmission period.

By setting the frame period to d_{min}, the data transmission interval can be prevented from exceeding d. However, the number of data transmissions increases drastically. In order to suppress an increase in the number of data transmissions, our proposed method controls each vehicle's data transmission period according to its degree of contribution to the coverage rate improvement. The degree of contribution is calculated based on the size of the area S in which the communications range does not overlap with the nearest vehicle (Fig.3). This area cannot be covered by other vehicles in the retention area. Therefore, the larger S is, the larger the influence on the coverage rate improvement becomes. Then, based on the results of our previous study, a case where the number of neighboring vehicles n is three or less is defined as a low vehicle density environment, and the data transmission period is calculated according to the size of the non-overlapping area S using the following equation:

$$d_{ctl} = d - d_{min} * \frac{S}{S_{max}} \tag{5}$$

where d_{ctl} is the frame period set in a low vehicle density environment and S_{max} is the maximum value of the non-overlapping area, which is the value achieved when the distance between vehicles x equals the maximum communication distance. As the distance between vehicles increases from this equation, that is, as the non-overlapping area increases, the data transmission period is controlled to approach the minimum data transmission period. The area S is calculated by the following equation:



(a) Non-overlapping area

(b) Distance between vehicles is small

(c) Distance between vehicles is large

Fig. 3 Difference in non-overlapping area with the change in the distance between vehicles

$$S = \pi r^2 - 2\left\{ r^2 \cos^{-1}(1 - \frac{h}{r}) - (r-h)\sqrt{h(2r-h)} \right\} \tag{6}$$

where r is the communication range radius and h is the height of two identical arcs appearing at the overlap area.

For the distance calculation between vehicles, if the transmission power and antennas of all vehicles are the same, the distance between vehicles is calculated by measuring the loss power from the received radio wave strength of the receiving side. Loss L is calculated by the free space propagation loss and is given by the following equation:

$$L = 20\log(\frac{4\pi f l}{c}) \tag{7}$$

where f is the frequency, l is the distance, and c is the wave velocity. By solving this equation for l, we can calculate the distance. Since signals can be blocked by objects (such as buildings) in real environments, the calculated distance may be different from the theoretical value. When the received radio wave strength from neighboring vehicles is smaller than the theoretical value, the proposed method calculates the distance between vehicles as larger than the actual value so that the data transmission period becomes shorter and the data transmission frequency becomes higher. However, this increase compensates for areas where radio waves do not reach certain vehicles due to the decrease in signal strength from neighboring vehicles within communication range. Consequently, our proposed method can realize effective data retention by calculating distances between vehicles from their measured power losses even when a real environment is assumed.

5 Simulation

In this section, we evaluate the performance of our proposed method using a simulation.

5.1 Simulation Model

We evaluated our proposed method using the Veins [12] simulation framework, which simultaneously implements both the IEEE 802.11p specification for wireless communications and the vehicular ad-hoc network (VANET) mobility model. Veins also includes a Two-Ray interference model and a simple obstacle shadowing model that has been calibrated and validated against real world measurements. Veins can combine the Objective Modular Network Testbed in C++ (OMNeT++) [10] network simulator with the Simulation of Urban MObility (SUMO) road traffic simulator [11].

In our simulations, which are based on our previous work [2], the frame period d and the beacon interval b were set to 5 s, the moving average coefficient α was set to 0.5, and the target value of the number of received data β was set to 4.

For comparison purposes, three methods, naive (2.5s), naive (5s), and our previous method [2] were used. The naive method always set the transmission probability $p_{(i,t)}$ of all vehicles to 1. The numbers 2.5 and 5 indicate the transmission interval d. Since the naive (2.5s) method's transmission interval is set to d_{min}, the naive (2.5s) method can achieve the maximum coverage rate discussed in this study.

To show the effectiveness of our proposed method, we used random topology (Fig.4) in which vehicles with randomly generated starting and end points ran on a road grid at a spacing of 50 m. A traffic signal that switches short time (in 5 second intervals) in order to focus on the change in the coverage rate due to the movement of the vehicle was installed at the intersection. Furthermore, in order to create vehicle density differences, we made routes through all areas (A, B, C, and D), the left area (B and C), bottom area (C and D), and combined them. This made it possible to create environments in which the density of vehicles in area A is low. We then created and evaluated 10 kinds of movement models. The communication range of the vehicle was set to 300 m, and the speed was set to 40 km/h. In addition, the retention area radius R was set to 750 m, and the auxiliary area length r was set to 250 m. In this simulation, the vehicle numbers were set to 20, 40, and 60, and the simulation time was set to 300 s.

5.2 Performance Evaluation

Figure 5 shows the average coverage rate, by area, for each number of vehicles. The horizontal axis represents the area, the vertical axis represents the coverage rate,

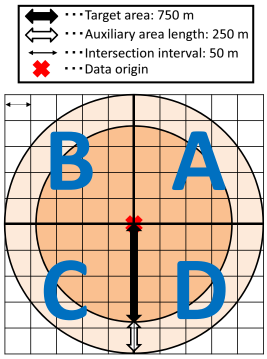
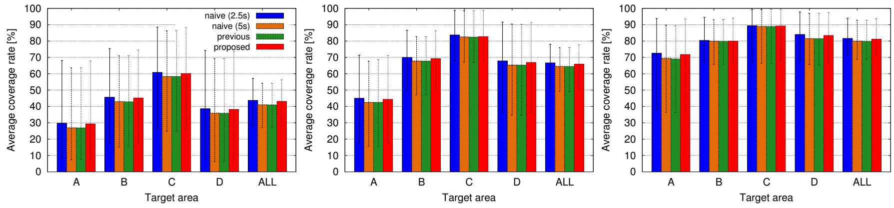


Fig. 4 Simulation Model

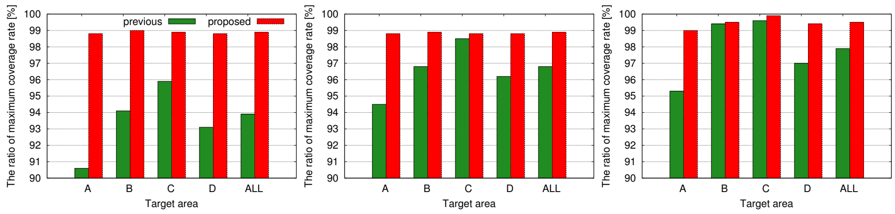
and the error bar represents the maximum and minimum values of 10 simulation trials. The average coverage rate of the naive (5s) method and the previous method is lower than of the naive (2.5s) method, especially in the environment where the vehicle density is low (area A). This result indicates that the maximum coverage rate cannot be achieved using the current transmission period setting in low vehicle density environment. In contrast, our proposed method can achieve a coverage rate close to the naive (2.5s) method regardless of the vehicle density. To show the coverage rate in detail, Fig.6 provides the ratio of the coverage rate of our previous and proposed methods to the naive (2.5s) method. Here, the coverage rate of the naive (2.5s) method is presented as 100. In our previous method, the ratio decreases as the vehicle density decrease (area A). However, in our proposed method, the ratio approaches 99% at any vehicle density. Thus, we can conclude that our proposed method can achieve data retention close to that of the naive (2.5s) method, regardless of vehicle density.

Next, we evaluated the number of data transmissions, the average number of which is shown Fig.7. Here, it can be seen that the naive (2.5s) method has significantly increased the number of data transmissions compared with the previous method. However, we see also that our proposed method can suppress the increase in the number of data transmissions. To evaluate the increase in the number of data transmissions in detail, Fig.8 shows the increase rate in the number of data transmissions for the naive (2.5s) and proposed methods over the previous method. It shows that the number of data transmissions produced by the naive (2.5s) method has increased approximately twice, while the proposed method can suppress that increase up to approximately 40%. Therefore, we can conclude that the proposed method can suppress the increase in the number of data transmissions up to about 40% while achieving a the coverage rate of approximately 99% against the naive (2.5s) method.



(a) 20 vehicles (b) 40 vehicles (c) 60 vehicles

Fig. 5 Coverage rate



(a) 20 vehicles (b) 40 vehicles (c) 60 vehicles

Fig. 6 The ratio of maximum coverage rate

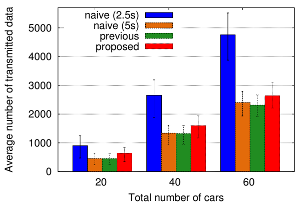


Fig. 7 The number of data transmissions

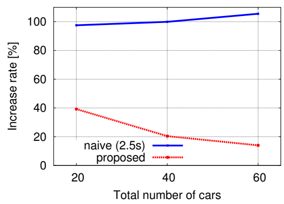


Fig. 8 Increase rate

6 Conclusions

In this paper, we proposed a system that facilitates the retention of STD in a specific area by using an ad-hoc network constructed solely by InfoHub vehicles. Additionally, our proposed STD retention system improves coverage rates in low vehicle density environments by controlling data transmission periods based on the size of the area in which the communications range of one vehicle does not overlap with the nearest vehicle (practically, the vehicle with the highest beacon intensity). Through simulations, we clarified that the proposed method could suppress the increase in the number of data transmissions up to approximately 40% and achieve a coverage rate of approximately 99% against the maximum coverage rate. In our future work, as part of efforts for further coverage rate improvements, we will verify a novel STD retention system that cooperates with Mobile Edge Computing (MEC).

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