RESEARCH ARTICLE

Linear regression-based delay-bounded routing protocols for VANETs

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ABSTRACT

Routing protocols for vehicular ad hoc networks (VANETs) have attracted a lot of attention recently. Most of the researches emphasize on minimizing the end-to-end delay without paying attention to reducing the usage of radio. This paper focuses on delay-bounded routing, whose goal is to deliver messages to the destination within user-defined delay and to minimize the usage of radio because radio spectrum is a limited resource. The messages can be delivered to the destination by the hybrid of data muling (carried by the vehicle) and forwarding (transmitted through radio). In the existing protocol, a vehicle may only switch the delivery strategy (muling or forwarding) at an intersection according to the available time of the next road segment, which is between the current intersection and the next intersection. To improve previous works, our protocol uses linear regression to predict the available time and the traveling distance, and thus, the vehicle can switch to a proper delivery strategy at a proper moment and can reduce the number of relays by radio. Our protocol contains two schemes: the greedy and centralized schemes. The greedy scheme uses only the current sampling data to predict the available time and decide when to switch the delivery strategy, whereas the centralized scheme uses the global statistical information to choose a minimum-cost path. Simulation results justify the efficiency of the proposed protocol. Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS
VANET; vehicular network; inter-vehicle communication; routing; delay-bounded; linear regression

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1. INTRODUCTION

The advancement of the wireless communication technology has brought a cheaper and portable wireless communication device, and hence, it is possible that every vehicle will be equipped with a wireless communication device in the near future. With the idea of mobile ad hoc networks (MANETs) [1], vehicles equipped with wireless communication devices may also form an ad hoc network named as the vehicular ad hoc network (VANET). It differs from MANET in that each vehicle on a VANET can only move along the road and should obey the traffic law. Vehicles on VANETs may communicate through inter-vehicle communication (IVC) or roadside-to-vehicle communication (RVC). IVC is for vehicle-to-vehicle communication, which is similar to the ad hoc mode communication of MANETs, whereas RVC is for vehicle-to-roadside unit communication, which is similar to the infrastructure mode communication of MANETs. Through IVC and RVC, a vehicle in a VANET would be able to get the information of real-time traffic and emergent notification and thus improves road safety.

Routing protocols for VANETs have attracted a lot of attention recently [2–9]. Most of the researches emphasize on minimizing the end-to-end delay. However, different applications have different requirements for end-to-end delay. The notification of car accident and emergency is urgent and needs to be sent to the destination immediately, whereas file transfer and e-mail can tolerate longer delay time and thus can be considered as lower-priority messages.

Because radio is a precious resource, minimizing the end-to-end delay is not that important for lower-priority messages. Delivering messages to the destination within the threshold of user-defined delay and minimizing the usage of radio are more important issues for lower-priority messages.
messages. Therefore, in this paper, we focus on designing an efficient delay-bounded routing protocol for VANETs in urban areas. The goal of delay-bounded routing protocol is to deliver messages to the destination within user-defined delay and minimize the usage of radio so as to save more radio resource for other user who wants to transmit urgent messages. The destination is assumed to be an access point (or a roadside unit). The vehicle may pass message to the access point so as to upload data to the Internet.

The delay-bounded routing protocol is first proposed in [10]. Because a vehicle moves much faster than a pedestrian, it assumes that the messages can be delivered to the destination by the hybrid of data muling (carried by the vehicle) and forwarding (transmitted through radio). To minimize the usage of radio resource, the messages should be carried by the vehicles as long as the time is enough. Two delay-bounded routing schemes have been proposed in [10], the greedy and centralized schemes. In the greedy scheme, messages are delivered along the shortest path, whereas in the centralized scheme, messages are delivered along the minimum-cost path, where cost stands for the total number of relays by radio. The greedy scheme has only the average speed of the next road segment, which is between the current intersection and the next intersection, whereas the centralized scheme has the average speed of every road segment between every pair of neighboring intersections. Therefore, the centralized scheme can apply dynamic programming to calculate the minimum-cost path. However, in both of the schemes, a vehicle may only switch the delivery way (muling or forwarding) of messages at an intersection according to the available time of the next road segment and thus cannot switch to a proper delivery way at a proper moment.

To improve previous works, we proposed a novel delay-bounded routing protocol, which uses linear regression to predict the available time and the traveling distance at every sampling moment. Each time after sampling, the predicting line is calculated and the vehicle may switch its delivery way according to the predicting line. If the available time is not enough, the delivery way can be switched to forwarding; otherwise, the delivery way can be switched to muling. This way, a vehicle can switch to a proper delivery way at a proper moment. Therefore, our protocol can make a better usage of the available time, reduce the frequency of data forwarding, and thus reduces the usage of radio.

Our protocol also contains two schemes: the greedy and centralized schemes. Both of the schemes are based on liner regression. However, the greedy scheme uses only the current sampling data to predict the available time and to decide when to switch the delivery way, whereas the centralized scheme uses the global statistical information to choose a minimum-cost path. Simulation results show that our protocol greatly reduces the usage of radio, makes a better usage of the available time, and achieves higher delivery ratio than those of the existing protocol.

The rest of this paper is organized as follows. Section 2 discusses related works. Preliminaries are given in Section 3. Section 4 presents the proposed linear regression-based delay-bounded routing protocol. Section 5 evaluates the performance of the proposed protocol. Section 6 concludes this paper.

2. RELATED WORKS

2.1. Routing protocols of VANETs

The survey of the routing protocols for VANETs is proposed in [11]. VANETs are different from traditional MANETs because a vehicle should move along the road and may move with a very high speed [12]. Therefore, the routing protocols of MANETs cannot be directly applied to VANETs [13,14]. Some routing protocols for VANETs [3,4,15] are improved from the geographical routing protocol of MANETs [16]. Greedy Perimeter Coordinator Routing (GPCR) [15] is a position-based routing protocol, which takes advantage of the fact that streets and junctions form a natural planar graph and hence does not require a graph planarization algorithm. GPCR consists of two parts: a restricted greedy forwarding procedure and a repair strategy. GpsrJ+ [3] improves GPCR by predicting on which road segment its neighboring junction node will forward packets to. Hence, junction nodes need not to decide which road segment to turn. GpsrJ+ uses the natural planar feature of urban maps to reduce the hop count used in the perimeter mode and allow faster switching back of the routing scheme to the greedy mode. Movement Aware Greedy Forwarding (MAGF) [4] uses the information of the vehicle’s position, velocity, and direction to select a suitable next hop toward the destination. The link lifetime is evaluated to avoid sending data through an unstable link.

Network fragmentation may occur in VANETs because of the driver’s behaviors or low vehicle density. Wisitpongphan et al. [17] develop a statistical traffic model to study the key performance metrics in disconnected VANETs, such as network restoration time. Epidemic Routing [18] is proposed to deliver messages when a connected path from the source to the destination is rarely available. A random pair-wise exchange of messages among mobile hosts ensures eventual message delivery. The flooding-like transmission may achieve high delivery rates and very low latency at the cost of high bandwidth utilization. Opportunistic exchange of messages [19] explores an opportunistic approach for resource discovery, in which a vehicle obtains information about resources from encountered vehicles. The vehicles sort the resources and save only the most relevant ones, which use a spatiotemporal relevance function, and exchange only the most relevant resources. Lightweight Information Dissemination protocol [20] specifies routing behavior using a propagation function that conveys information about both target areas and preferred routes. It disseminates information to a set of target zones without specific destination nodes. They use a propagation function whose value is minimized over the target zones.
MOtion VEctor (MOVE) [8] considers a scenario where the moving vehicle knows its own position through the Global Positioning System. The destination node is static, and its position is known globally. The location-based algorithm makes use of the relative position between vehicles and destinations to make a forwarding decision, while MOVE-vector and MOVE-look ahead take account of the relative velocities of the vehicles. This protocol is not feasible for vehicular scenario that a vehicle usually changes its moving vector and is unforeseeable before reaching a destination. Connectivity-Aware Routing (CAR) [21] is designed for IVC. It can locate positions of destinations and find connected paths between source and destination pairs. ‘Guards’ can help the tracking of the current position of a destination so that the path between the source and the destination can be auto-adjusted. Mobility-centric data dissemination algorithm for vehicular network (MDDV) [22] is designed to address the data dissemination problem. Messages are forwarded along a predefined trajectory that minimizes the sum of weights on that graph between the source vehicle and the destination region. Intermediate vehicles must buffer and forward messages opportunistically. The main weakness of MDDV is the restriction of the predefined forwarding trajectory. Vehicle-assisted data delivery (VADD) [9] adopts the idea of carrying and forwarding, where a moving vehicle carries the packet until a new vehicle moves into its vicinity and forwards the packet. Vehicles find the next road to forward the packet to reduce the delay. VADD’s goal is to find the lowest-delay delivery paths, whereas our goal is to deliver packets within user defined delay threshold with the minimum communication cost. GeoDTN+Nav [5] incorporates both geo-routing and delay-tolerant network (DTN) forwarding. For sparse or partitioned networks, GeoDTN+Nav exploits the vehicular mobility and uses DTN forwarding to carry packets between partitions so as to improve the packet delivery rate of delay-tolerant applications. For dense or connected networks, GeoDTN+Nav uses geo-routing to deliver packets through radio forwarding.

The delay-bounded routing protocol [10] focus on delivering packets within the user-defined delay threshold and minimizing the communication cost. Two novel forwarding schemes for urban vehicular networks are proposed in the delay-bounded routing protocol. D-Greedy uses local information to determine whether the data muling strategy or multihop forwarding strategy should be adopted when vehicles get into the next segment. Vehicles adopt the data muling strategy when the budget is greater than the expected time. On the contrary, vehicles adopt the multihop forwarding strategy when the budget is smaller than the expected time. D-MinCost uses global traffic statistics to find the minimum-cost path and accurately calculate the segment of the path, which should be muling or forwarding. The shortcoming is that it can only switch the delivery strategy (muling or forwarding) at an intersection.

Most of the existing routing protocols emphasize on how to reduce end-to-end delay without considering high channel overhead. Therefore, they are not suitable for the situation which can tolerate long delay.

2.2. Forecasting methods

The forecasting methods based on statistical analysis can be categorized as time series and linear regression. Time series refer to the phenomenon of a number of changes taken place in chronological order. The law of the development of the phenomenon is used to forecast the direction and quantity. Trend line represents a time-series data of the long-term trend. It tells us a specific set of data (such as GDP, oil prices, and stock prices) over a period in the growth or decline. Regression analysis is aimed at understanding the relation between two or more variables. The establishment of the mathematical model is to observe the specific variable to predict the variable that the researchers are interested in. Regression analysis [6] can be used to predict the relationship between variables. If the goal is to forecast or predict, linear regression can be used for the appropriate forecasting model of observational data sets a and b. After developing the regression model of a and b, with the value of a, the model can be used to predict its accompanying value b. Although we can observe the data points in the coordinate system, a more appropriate method is to use a linear regression trend line to calculate the location and slope. Time series can be used to predict the trend of a period in the future, whereas linear regression can be used to predict the trend of the line in the future. Therefore, we adopt linear regression to predict the delivery time of the proposed protocol. In our protocol, we consider the relation of the traveling distance and the delivery time of the intended packet.

3. PRELIMINARIES

This section describes the system model and assumptions first, followed by the description of the motivation and basic idea.

3.1. System model and assumptions

The proposed delay-bounded routing protocol is modified from D-Greedy and D-MinCost [10] and is designed for urban area. Because of the limitation of the budget, only a few access points can be deployed in the urban area and these access points cannot cover the whole area. Therefore, a vehicle may need to send messages to the access point via multihop communications if it cannot communicate with the access point directly. In our protocol, vehicles are equipped with on-board computers, wireless communication devices, GPS, and digital maps so as to get geographical locations. Access points can only be installed in the intersection and their locations are known by vehicles. Our protocols assume that vehicles can acquire the travel time and distance from an odometer and record them in the
memory of the on-board computers. Vehicles can obtain traffic statistic information when they can contact with access point. When a message is generated by a vehicle, that message is involved with a time-to-live value (TTL). The TTL value is considered as a threshold to restrict the message from reaching the destination before expiration. The goal of our protocol is to make the best usage of the available time and reduce the usage of radio. There are two strategies to deliver messages: data muling (carried by the vehicle) and forwarding (transmitted through radio) as shown in Figure 1. Switching between the two strategies is a tradeoff between transmission delay and communication cost. Data forwarding increases communication cost but saves delivery time, whereas data muling increases delivery time but saves communication cost.

For the ease of describing the proposed protocol, the system model is formalized as Figure 2 and the definition of nations are shown in Table I. The gray line denotes the selected path to deliver the data. The routing path can be stretched to a straight line as shown in Figure 3 so that it would be easier to generate the regression line and make the prediction.
Linear regression-based delay-bounded routing
Y-S. Chen, C-S. Hsu and Y-G. Siao

Figure 3. Stretch a route to a straight line.

### Table I. Notations of the system model.

<table>
<thead>
<tr>
<th>Notation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{x,y}$</td>
<td>The intersection of the $i$th row and the $j$th column</td>
</tr>
<tr>
<td>$V_k$</td>
<td>The $k$th vehicle</td>
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</tbody>
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### Table II. Notations of the regression scheme.

<table>
<thead>
<tr>
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<tr>
<td>$Y$</td>
<td>Dependent variable</td>
</tr>
<tr>
<td>$X_i$</td>
<td>Independent variables</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Random term</td>
</tr>
<tr>
<td>$\beta_i$</td>
<td>The respective parameter of the independent variable $X_i$</td>
</tr>
<tr>
<td>$p$</td>
<td>The number of parameters to be estimated in the linear regression</td>
</tr>
<tr>
<td>$x_i$</td>
<td>The $i$th sampling data of the traveling distance</td>
</tr>
<tr>
<td>$y_i$</td>
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</tr>
<tr>
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<td>The average of all recorded $x$</td>
</tr>
<tr>
<td>$y$</td>
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### 3.2. Motivation and basic idea

The major drawback of the existing delay-bounded routing protocol [10] is that it can only switch the delivery strategy at the intersection and thus cannot switch to an appropriate delivery strategy at the appropriate moment. For example, if a vehicle determines to forward the message by radio in the road segment but the speed of the vehicle becomes high in the middle of the road segment (or it determines to carry the message by itself, but the speed of the vehicle becomes low in the middle of the road segment), the vehicle should switch its delivery strategy in the middle of the road segment. Therefore, our goal is to design a delay-bounded routing protocol that can select an appropriate delivery strategy at the appropriate moment and make the best usage of the available time. To achieve our goal, we use linear regression to guide the switching of delivery strategy.

In statistics, linear regression is a regression scheme that models the relationship between a dependent variable $Y$, independent variables $X_i$, and a random term $\varepsilon$. The notations used in the regression scheme are defined in Table II. The model can be written as Equation (1):

$$Y = \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_p X_p + \varepsilon \quad (1)$$

Since our protocol uses only one independent variable, the linear regression formula is simplified as Equation (2).

$$\hat{Y} = bX + a = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n} (x_i - \bar{x})^2}, \quad a = \bar{y} - b\bar{x} \quad (2)$$

In the proposed protocol, a vehicle may apply the linear regression model as follows:

- Form a criteria line according to the path length $D$ and delay threshold $T_c$.
- Record traveling distance ($x_i$) and delivery time ($y_i$) periodically.
- Compute the linear regression equation according to all the recorded data to form a predicted line periodically.
- If the slope of the predicted line is greater than that of the criteria line (e.g., the predicted time is greater than the delay threshold), forward the message by radio; otherwise, carry the message by the vehicle.

An example is shown in Figure 4, where $T_c$ is the TTL of the message, $T_p$ is the predicted time calculated by the equation of linear regression (e.g., $T_p = bD + a$). Vehicle $V_1$ starts at intersection $I_{1,1}$ and uses data mul-ing strategy to deliver message. As the vehicle has arrived $V_1'$, $T_p$ becomes greater than $T_c$. Vehicle $V_1$ forwards the message immediately to the next vehicle $V_2$ by radio. The predicted time $T_p$ is decreased because the traveling distance increases greatly in a very short period, so vehicle $V_2$ can carry the message by itself for a while. When $V_2$ has arrived $V_2'$, $T_p$ is greater than $T_c$. The message is forwarded to vehicle $V_3$ by radio, but $T_p$ is still greater than $T_c$, so vehicle $V_3$ forwards the message to vehicle $V_4$ by radio. Then, $T_p$ becomes smaller than $T_c$, and vehicle $V_4$ carries the message until $T_p$ is greater than $T_c$. 

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4. LINEAR REGRESSION-BASED DELAY-BOUNDED ROUTING PROTOCOLS

We describe our delay-bounded routing protocol in this section. First, we present how to reduce the size of control packets, followed by the description of the LR-Greedy and LR-Centralized schemes.

4.1. Reduce the size of control packets

To make an accurate estimation, the regression line needs to be regenerated periodically according to the latest sampling data. However, as time goes by, the amount of the sampling data will become too large and too costly to be passed to the next vehicle. To reduce the size of the control packet, which can be used to generate the regression line, a vehicle needs not to transmit all the sampling data. It only needs to transmit data that are essential.

As mentioned in Section 3.2, the formula of linear regression is \( \hat{Y} = bX + a \), as shown in Equation (2). By expanding \( b \), we have Equation (3).

\[
\hat{b} = \frac{(x_1y_1 + x_2y_2 + \cdots + x_ny_n) - \bar{y}(x_1 + x_2 + \cdots + x_n) - \bar{x}(y_1 + y_2 + \cdots + y_n) + n\bar{x}\bar{y}}{(x_1^2 + x_2^2 + \cdots + x_n^2) - 2\bar{x}(x_1 + x_2 + \cdots + x_n) + n\bar{x}^2}
\]

Because \( x_1 + x_2 + \cdots + x_n = \bar{x}n \) and \( y_1 + y_2 + \cdots + y_n = \bar{y}n \), \( x_1 + x_2 + \cdots + x_n \) and \( y_1 + y_2 + \cdots + y_n \) can be derived from \( \bar{x} \) and \( \bar{y} \), respectively. \( \sum_{i=1}^{n} x_iy_i \) can be derived from \( x_1y_1 + x_2y_2 + \cdots + x_ny_n \) and the new sampling data \( (x_{n+1}, y_{n+1}) \), whereas \( \sum_{i=1}^{n} x_i^2 \) can be derived from \( x_1^2 + x_2^2 + \cdots + x_n^2 \) and the new sampling data \( x_{n+1} \). Therefore, a vehicle only needs to keep (or pass) five numbers: \( \bar{x}, \bar{y}, n, \sum_{i=1}^{n} x_iy_i, \) and \( \sum_{i=1}^{n} x_i^2 \). By combining the new sampling data \( (x_{n+1}, y_{n+1}) \), a vehicle will be able to generate the new regression line.

4.2. Greedy forwarding scheme (LR-Greedy)

The LR-Greedy scheme uses only the current sampling data and digital map to make prediction. At the beginning, the LR-Greedy scheme uses Dijkstra’s algorithm to find the shortest path, and then, the message is delivered along the shortest path to the destination access point. Assume that the length of the shortest path is \( D \) and the delay threshold is \( T_c \). A criteria line, whose slope is \( \frac{D}{T_c} \), can be derived.

As the message is delivered by the vehicle either through data muling or data forwarding strategies, the vehicle will record the delivery time \( t_i \) and traveling distance \( d_i \) of the message periodically. After each sampling, the vehicle can use Equation (2) to calculate the regression line according to all the sampling data and then the vehicle will switch the delivery strategy according to the predicted time \( T_p = \frac{bD + a}{T_c} \) calculated by the equation of the regression line. As shown in Figure 5, if \( T_p < T_c \), which indicates that the remaining time is enough, the vehicle will carry the message by itself. On the other hand, if \( T_p > T_c \), which indicates that the remaining time is not enough, the vehicle will forward the message by radio as shown in Figure 6.

4.3. Centralized forwarding scheme (LR-Centralized)

The problem of the LR-Greedy scheme is that it is short-sighted. It can only make the prediction according to the current information. It may reserve too much time if the traffic jam occurs in the following road segment such that the vehicle moves too slowly to carry the message. On the other hand, it may reserve too little time if there are too few vehicles in the following road segment that the vehicle cannot find any vehicle to forward its message by radio. In order to predict the delivery time more accurately,
LR-Centralized scheme is proposed. The LR-Centralized scheme assumes that each vehicle has the global information, such as the average velocity and traffic records of each road segment. With the global information, the source vehicle can allot a proper quota of available time to each road segment, generate a criteria line for each road segment according to the quota and the length of the road segment, and use dynamic programming to find a minimum-cost path, where the cost is defined as the total number of relays by radio.

To find a minimum-cost path, the source vehicle will compute the cost of each road segment. For the ease of describing the computation, notations are defined in Table III. The possible muling distance of the road segment is $V_{x_{i}y_{i},x_{i+1}y_{i}} \times t_{x_{i}y_{i},x_{i+1}y_{i}}$. The remaining distance which needs to be forwarded by radio is $BL - V_{x_{i}y_{i},x_{i+1}y_{i}} \times t_{x_{i}y_{i},x_{i+1}y_{i}}$. The cost of the road segment between intersections $I_{x_{i}y_{i}}$ and $I_{x_{i+1}y_{i}}$ is shown in Equation (4).

$$\text{cost}_{x_{i}y_{i},x_{i+1}y_{i}} = \frac{(BL - V_{x_{i}y_{i},x_{i+1}y_{i}} \times t_{x_{i}y_{i},x_{i+1}y_{i}})}{T_{r}}$$

If $\text{cost}_{x_{i}y_{i},x_{i+1}y_{i}} < 0$, $\text{cost}_{x_{i}y_{i},x_{i+1}y_{i}}$ will be set as 0. When the source vehicle is located on intersection $I_{x_{i}y_{i}}$, the possible next intersections are $I_{x_{i+1}y_{i}}$ and $I_{x_{i}y_{i+1}}$. Figure 5. When $T_{p} < T_{c}$, vehicle carries data by itself.

Figure 6. When $T_{p} > T_{c}$, vehicle forwards data by radio.
Table III. Notations of the LR-Centralized scheme.

<table>
<thead>
<tr>
<th>Notation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>BL</td>
<td>The length of the road segment</td>
</tr>
<tr>
<td>T_r</td>
<td>The transmission range</td>
</tr>
<tr>
<td>V_{x,y}, V_{x+1,y}</td>
<td>The average velocity between intersections I_{x,y} and I_{x+1,y}</td>
</tr>
<tr>
<td>t_{x,y}, t_{x+1,y}</td>
<td>The available delivery time from I_{x,y} to I_{x+1,y}</td>
</tr>
<tr>
<td>I_{x,y}</td>
<td>The intersection where the source vehicle is located</td>
</tr>
<tr>
<td>I_{x+m,y}</td>
<td>The intersection where the destination access point is located</td>
</tr>
</tbody>
</table>

The recursive function to find the minimum-cost path can be defined as Equations (5)–(7).

\[
f(x_i, y_j, x_m, y_n) = \min \left\{ \begin{array}{l}
\text{cost}_{x_iy_j, x_{i+1}y_j} + f(x_{i+1}, y_j, x_m, y_n) \\
\text{cost}_{x_iy_j, x_{i+1}y_j+1} + f(x_i, y_{j+1}, x_m, y_n)
\end{array} \right\}
\]  \hspace{1cm} (5)

\[
f(x_m, y_{n-1}, x_m, y_n) = \text{cost}_{x_my_{n-1}, x_my_n}
\]  \hspace{1cm} (6)

\[
f(x_m-1, y_n, x_m, y_n) = \text{cost}_{x_{m-1}y_n, x_my_n}
\]  \hspace{1cm} (7)

Dynamic programming can be used to solve the aforementioned recursive function and derive the minimum-cost path. The message is then delivered along the minimum-cost path. Similar to LR-Greedy scheme, as the message is delivered by the vehicle, the vehicle also needs to record the delivery time and traveling distance of the message periodically. After each sampling, the vehicle also needs to recalculate the new regression line and compare its slope with that of the criteria line of the road segment. The result can guide the switch of the delivery strategy. The major difference is that each road segment has its own criteria line which is derived from the length of the road segment and the allotted quota of the available time. The allotted time quota of a road segment is proportional to the length and average velocity of the road segment so that a road segment with high average velocity will have more time to deliver messages by muling and a road segment with low average velocity will be more likely to deliver messages by forwarding.

An example of LR-Centralized scheme is shown in Figure 7: V_{i,j,i+1,j} denotes the average velocity between intersections I_{i,j} and I_{i+1,j}, t_{i,j,i+1,j} denotes the available delivery time from I_{i,j} to I_{i+1,j} in traffic records. Because vehicle V_1 has the knowledge of the average velocity and traffic records of each road segment, vehicle V_1 uses history records to estimate the available delivery time of each road segment, and then vehicle V_1 can use dynamic programming to compute the minimum-cost path.

The minimum-cost path is I_{1,1}, I_{2,1}, I_{2,2}, I_{3,2}, whose cost is 9.

Table IV. Simulation parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation area</td>
<td>8 km x 8 km</td>
</tr>
<tr>
<td>Number of lanes</td>
<td>4</td>
</tr>
<tr>
<td>Transmission range</td>
<td>250 m</td>
</tr>
<tr>
<td>Number of vehicles</td>
<td>200–600</td>
</tr>
<tr>
<td>Beacon period</td>
<td>5 s</td>
</tr>
<tr>
<td>Delay threshold</td>
<td>200–1100 s</td>
</tr>
<tr>
<td>Number of generated messages</td>
<td>10</td>
</tr>
<tr>
<td>Message size</td>
<td>100 KB</td>
</tr>
<tr>
<td>Bitrate</td>
<td>1000 Kbps</td>
</tr>
<tr>
<td>Sampling cycle</td>
<td>0.5 s</td>
</tr>
</tbody>
</table>

Figure 7. An example of LR-Centralized scheme.
5. SIMULATION RESULTS

To evaluate the performance of the proposed LR-Greedy and LR-Centralized schemes, we compare them with D-Greedy and D-MinCost schemes [10]. NCTUns-5.0 [23] is adopted as the simulation tools. The simulation parameters are shown in Table IV. Each vehicle moves according to the average velocity of the road segment. Figure 8 shows the impact of sampling cycle to average delivery delay. As the sampling cycle decreases (e.g., the sampling rate increases), the difference between the average delivery delay and the delay threshold decreases because lower sampling cycle incurs higher sampling rate and thus brings on a more accurate prediction and can make a better usage of the available time. The sampling cycle of our protocol is set as 0.5 s (e.g., sampling rate = 2 samples/s) because we cannot make a much better usage of the available time even when the sampling cycle is smaller than 0.5 s.

The performance metrics observed in the simulations are the following:

- Total transmitted bytes: the total amount of control and data messages that have been transmitted by radio during the routing process.
- Average delivery delay: the average of the delivery delay of all successfully delivered messages within the delay threshold.
- Delivery ratio: the total number of packets that have reached the destination in time divided by the total number of packets that have been delivered by the source vehicle.

![Figure 8. Sampling cycle versus average delivery delay.](image)

![Figure 9. Total bytes transmitted versus (a) number of cars, (b) delay threshold, and (c) correlation coefficient.](image)
The correlation coefficient used in our simulation is defined as a value that indicates the correlation between traffic records and current traffic states. In the simulations, the correlation coefficient is tuned between 0.5 and 1. The greater the correlation coefficient is, the more accurate the traffic records are.

5.1. Total transmitted bytes

Figure 9(a), (b), and (c) show the impacts of the number of cars, delay threshold, and correlation coefficient to total transmitted bytes, respectively. The total transmitted bytes of the LR-Centralized scheme is the lowest followed by the D-MinCost, LR-Greedy, and D-Greedy schemes. The proposed LR-Centralized and LR-Greedy schemes perform better than the D-MinCost and D-Greedy schemes respectively, because our schemes can switch the delivery strategy whenever the regression line is moving from the upper side to the lower side of the criteria line (or vice versa). Hence, our schemes can switch to proper delivery strategy at proper moment and thus can reduce the number of relays by radio. The LR-Greedy scheme reduces the radio usage of the D-Greedy scheme by 30%, whereas the LR-Centralized scheme reduces the radio usage of the D-MinCost scheme by 20%.

As the number of car increases, the total transmitted bytes also increases because higher density of cars will slow down the moving speed of vehicles and thus increases the number of relays by radio. As the delay threshold increases, the total transmitted bytes decreases because the vehicle has more available time to deliver the messages by muling. Higher correlation coefficient brings lower total transmitted bytes because higher correlation coefficient indicates more accurate traffic records and predictions.

5.2. Average delivery delay

Figure 10(a), (b), and (c) show the impacts of the number of cars, delay threshold, and correlation coefficient to average delivery delay, respectively. The average delivery delay of the LR-Centralized scheme is the highest followed by LR-Greedy, D-MinCost, and D-Greedy schemes. The average delivery delays of the proposed LR-Centralized and LR-Greedy schemes are much closer to the delay threshold than those of the D-MinCost and D-Greedy schemes, which indicates that our schemes can make a better usage of the available time. As the number of car increases, the average delivery delay decreases because higher density of cars will slow down the moving speed of vehicles and thus reduces the chance to deliver the message by muling. As

![Graphs showing impacts of number of cars, delay threshold, and correlation coefficient to total transmitted bytes and average delivery delay.](image)
the delay threshold increases, the average delivery delay increases because the vehicle has more available time to deliver the messages by muling and thus can make a better usage of the available time. Higher correlation coefficient brings higher average delivery delay because higher correlation coefficient indicates more accurate traffic records and thus can make a better usage of the available time.

5.3. Delivery ratio

Figure 11(a), (b), and (c) show the impacts of the number of cars, delay threshold, and correlation coefficient to delivery ratio, respectively. The delivery ratio of the LR-Centralized scheme is the highest, whereas the delivery ratio of the D-Greedy scheme is the lowest. The LR-Centralized and LR-Greedy schemes perform better than the D-MinCost and D-Greedy schemes, respectively, because our schemes can make a better usage of the available time and switch to a proper delivery strategy at a proper moment and thus improves the delivery ratio. As the number of cars increases, the delivery ratio also increases because a higher density of cars may incur more candidates to relay the message and thus increases the delivery ratio. As the delay threshold increases, the delivery ratio also increases because the vehicle has more available time to deliver the messages. Higher correlation coefficient brings higher delivery ratio because higher correlation coefficient indicates more accurate traffic records and predictions.

5.4. Reserved time

As shown in Figure 11(b), when the delay threshold decreases, the delivery ratio also becomes lower. When achieving high delivery ratio is more important than reducing the usage of radio, we may reserve some time to ensure that the message can be delivered in time. The reserved time can be set as \( T_c \times p \), where \( T_c \) is the delay threshold and \( p \) is the percentage of delay threshold being reserved. Figure 12 shows the impact of the percentage of the time being reserved to delivery ratio. As the percentage of time being reserved increases, the delivery ratio also becomes higher because more available time is reserved for the later road segments and thus the message is more likely to be delivered in time.

6. CONCLUSIONS

In this paper, we have presented a delay-bounded routing protocol for VANETs. Our protocol contains two schemes:
the LR-Greedy and LR-Centralized schemes. Both of the schemes use linear regression to predict the available time. However, the LR-Greedy scheme uses only the current sampling data to predict the available time and to decide when to switch the delivery strategy, whereas the LR-Centralized scheme uses the global statistical information to choose a minimum-cost path. Simulation results show that both of the proposed schemes can greatly reduce the usage of radio, make a better usage of the available time, and achieve higher delivery ratio than those of the D-Greedy and D-MinCost schemes. The LR-Centralized scheme possesses more information and thus can make a more accurate prediction. Hence, the LR-Centralized scheme performs the best, but it needs to gather more information, while the LR-Greedy scheme can be applied easily.

To make the proposed protocol more suitable for the real urban traffic environment, we will consider the effect of traffic lights and provide solution for a mobile destination in the future.

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