Delay-Bounded Routing on Hybrid-Solar Vehicular Ad-Hoc Networks

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***Abstract*—Most of the researches pay attention to minimize the end-to-end delay rather than reduce the usage of radio. However, some information is not urgent and radio is a valuable and limited resource. Recently, delay-bounded routing protocol has become a popular issue, whose goal is to deliver messages to the destination within user-defined delay and minimize the usage of radio. To decrease the burden on the environment and save energy, the hybrid-solar vehicle is one of the most prominent solutions. The existing delay-bounded routing protocols do not consider the charge and the energy expenditure factors and only choose the path with the least forwarding times. To improve previous works, we propose a mechanism based on a cost function, which includes forwarding times and power gain, to choose a minimum cost path. Besides, we propose a novel mechanism to deliver message to the destination by the hybrid of data muling (carried by the vehicle) and forwarding (transmitted through radio). In the existing protocol, when the remaining time is not enough the vehicle should forward the message by radio and when the remaining time is enough the vehicle should carry the message by itself. However, forwarding message by radio consumes more energy and hence the energy factor should be added into the consideration. The proposed protocol contains two schemes: the greedy and centralized schemes. In the centralized scheme, the information such as the solar illumination, length of each road segment, and the average velocity of the vehicles on each road segment are collected and then the dynamic programming is used to find the least cost routing path. In the greedy scheme, it only has the knowledge of the average velocity, the solar illumination and the length of all the possible next road segments to choose the next road segment with the least cost. Simulation results illustrate that the proposed routing protocol can save more energy than existing protocols.**

I. INTRODUCTION

In vehicular ad hoc networks, routing protocols [1],[2] are emerging and important research issue in urban areas. Most of the researchers pay attention to minimize the end-to-end delay. However, the messages have different priorities and requirements for the end-to-end delay. Some messages need to be sent to the destination immediately, e.g. a car accidents or emergency information, while some messages can tolerate a longer delay time. Because radio is a valuable resource, reducing the end-to-end delay is not that important for lower-priority messages. The goal of delay-bounded routing protocol is to deliver messages to the destination within user-defined delay and reduce the usage of radio, so as to save more radio resource for other user who wants to transmit urgent messages. Delay-bounded routing protocols for vehicular ad hoc networks in urban areas have been proposed in [3], [4]. These protocols deliver message to the destination by two strategies including data muling (carried by the vehicle) and forwarding (transmitted through radio). The messages should be carried by the vehicles as long as the time is enough. Otherwise, the vehicle needs to find other vehicles to help to deliver the message to the destination in a bounded time by forwarding. Hence, the most important issue for the delay-bounded routing protocol is to decide when a vehicle should switch the delivery strategy.

Due to the imminent fuel shortage and the subsequent increase in fuel prices, there has been a notable market shift during the past few years towards more energy-efficient means of transport [5]. Transportation has a marked impact on noise and air pollution in urban areas, on fuels consumption, and on greenhouse effect [6]. Hybrid solar vehicles have emerged as one of the most effective and feasible alternatives to engine-driven vehicles. The use of solar energy promotes on-board renewable energy and hence reduces fuel consumption and emissions [7].

In the existing protocol, when the remaining time is not enough the vehicle should forward the message by radio and when the remaining time is enough the vehicle should carry the message by itself. However, forwarding message by radio consumes more energy and hence the energy factor should be added into the consideration. This paper focuses on designing a delay-bounded routing protocol for hybrid-solar VANETs in urban areas. 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. A vehicle can obtain the remaining time, the average velocity, the solar illumination, and the length of the next road segment from the road side unit (RSU) whenever it passed an intersection and then it uses these information and the previous sampling data to calculate the predicted line. Four possible cases are considered when deciding to mule or forward. Linear regression is used to predict the relationship between the available time, the travelling distance, and the accumulated power gain to select the appropriate delivery way.

The proposed protocol contains two schemes: the greedy and centralized schemes. Both of the schemes are based on liner regression. However, the greedy scheme uses the current sampling data to predict the available time, the power gain and to decide when to switch the delivery way, whereas the centralized scheme uses the global statistical information to choose a minimum-cost path. The greedy scheme has the average velocity, the solar illumination and the block length of the next road segments, which is between the current intersection and the next intersection, whereas the centralized scheme has the average velocity, the solar illumination and the block length of every road segment between every pair of neighboring intersections. Therefore, the Greedy strategy is used to choose the next road segment with the least cost, whereas the centralized scheme can apply dynamic programming to calculate the minimum-cost path.

The rest of this paper is organized as follows. Section II describes preliminaries. Section III describes the proposed delay-bounded routing protocol on hybrid-solar vehicular ad-hoc networks. Simulation results are presented in section IV. Section V concludes this paper.

II. PRELIMINARIES

A. System Model

Fig. 1 illustrates the system model of the hybrid solar-based vehicular ad-hoc network. Our protocol is designed for transferring large amounts of data, such as FTP. The packet, which is not urgent, is transmitted by the source vehicle (i.e. a hybrid solar vehicle) to the destination within user defined delay threshold (i.e.T_c). In the urban areas, the vehicle V_1 at the intersection $I_{1,1}$ generates a message to transmit to the access point located in intersection $I_{4,3}$. The destination can be any roadside unit with internet connection. Consider the solar illumination, the travelling distance and the average velocity; every hybrid solar vehicle can use muling or forwarding to transfer the packet. The decision of choosing muling or forwarding is depends on the predicted result derived from the linear regression. The recharge and energy expenditure factors are also considered so as to choose a route which gathers more solar energy to transfer the packet without increasing forwarding times. Because forwarding may consume more power, choosing the route which gathers more solar energy for the vehicles that carry the packet has less impact on their energy level. Each hybrid solar vehicle has the ability to communicate with each other in ad-hoc mode. The hybrid solar vehicle has a solar panel which can charge the battery under the solar illumination. The hybrid solar vehicle has a GPS receiver to obtain the geographical location, a digital map to be accessed by the on-board computer, the 802.11 transceiver to transmit and receive data, and sensors to measure the light and current battery voltage. The vehicles can communicate with neighbor vehicles or RSU within a transmission range of 250 meters. The vehicles can obtain local speed immediately and record the travelling distance in memory.

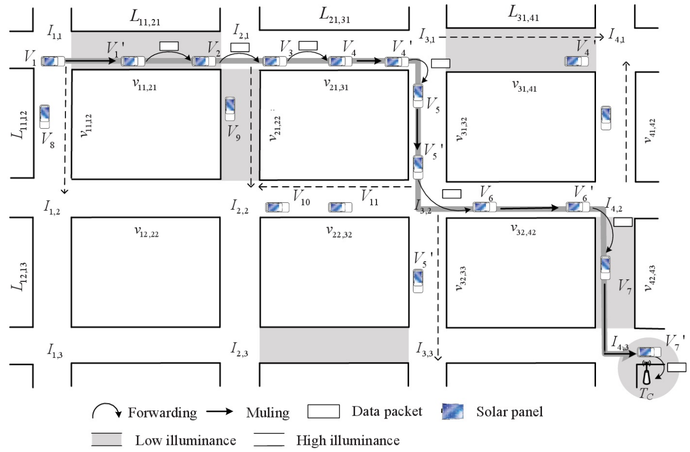


Fig. 1. System model.

B. Basic Idea

The basic idea of this work is to use two mechanisms to complete the routing request. First, the proposed protocol uses a mechanism based on a cost function, which includes forwarding times and power gain, to choose a minimum cost path. Second, the proposed protocol adds power factor into the consideration by using linear regression to predict the available time, the travelling distance, and the accumulated power gain and then uses the novel deliver mechanism to deliver message to the destination. The hybrid solar vehicle uses linear regression to predict the available time, the travelling distance, and the accumulated power gain.

$$\widehat{Y}_i = bx + a \tag{1}$$

$$\widehat{Y}_j = cx + d \tag{2}$$

, where $b = \frac{\sum_{i=1}^{n}(x_i-\overline{x})(y_i-\overline{y})}{\sum_{i=1}^{n}(x_i-\overline{x})^2}$, $a = \overline{y} - b\overline{x}$, x_i is the sampled travelling distance, y_i is the sampled travelling time, $c = \frac{\sum_{j=1}^{n}(x_j-\overline{x})(y_j-\overline{y})}{\sum_{j=1}^{n}(x_j-\overline{x})^2}$, $d = \overline{y} - c\overline{x}$, x_j is the sampled travelling distance, y_j is the sampled power gain, $\overline{x}$ is the average of all the sampled x, and $\overline{y}$ is the average of all the sampled y. Equation 1 is used to predict the available time and equation 2 is used to predict the accumulated power gain. The protocol uses the two equations to decide delivery mechanism (muling or forwarding).

In the proposed protocol, a hybrid solar vehicle may apply the linear regression model as follows: First, obtain the total path distance to calculate the time quota $T_{x_1y_1,x_2y_2}$ of each road segment and the road segment length $L_{x_1y_1,x_2y_2}$ to derive the criteria line. Second, the vehicle records the travelling road segment length, delivery time and the accumulated power gain periodically. Third, derive a new predicted line by the linear regression equations according to the recording data. Last, decide delivery mechanism according to the predicted line and the criteria line.

C. Contributions

The contributions of this paper are listed as follows: (1) Propose novel delay-bounded routing protocols for hybrid-solar vehicular ad-hoc networks. This paper aims to choose a path which can gather more energy to transmit the packets without increasing the forwarding times as far as possible. The hybrid solar vehicles obtaining more power can continue cruising with electric motor and thus can reduce the fuel consumption. (2) Propose a novel mechanism to deliver message to the destination by the hybrid of data muling and forwarding based on two predicted lines generated from delivery time and power gain. (3) Propose a path selection mechanism based on a novel cost function which includes forwarding times and power gain.

III. A DELAY-BOUNDED ROUTING ON HYBRID-SOLAR VEHICULAR AD-HOC NETWORKS

In this section, we will introduce the power consumption model of the hybrid solar vehicle, follows by the distributed greedy scheme of the linear regression-based delay bounded routing on hybrid solar vehicle (DH-Greedy) and the centralized scheme of the linear regression-based delay bounded routing on hybrid solar vehicle (DH-Centralized).

A. Power consumption model of the hybrid solar vehicle

To choose a minimum cost path, the cost of each possible road segment needs to be calculated beforehand. To calculate the cost of a road segment, the estimated forwarding time and power gain need to be calculated first. The allotted time quota (denoted as $T_{x_1y_1,x_2y_2}$), and the length of the road segment are used to estimate the forwarding times (denoted as $F_{x_1y_1,x_2y_2}$) in the next road segment. The forwarding times can be calculated by the length of the possible road segment, average velocity $v_{x_1y_1,x_2y_2}$, and the estimated time quota. The delay threshold of the road segment, which is between $I_{x_1y_1}$ and $I_{x_2y_2}$, is denoted as $T_{x_1y_1,x_2y_2}$. The remaining delay budget is denoted as T^c_{remain}. Each road segment on the routing path is assigned a delay budget that is proportional to its length. Let $L_{x_1y_1,x_2y_2}$ denotes the length of the road segment and L_{remain} denotes the length of the shortest path between the vehicle, which carries the message, and the destination. The equation to calculate $T_{x_1y_1,x_2y_2}$ is shown as follow:

$$T_{x_1y_1,x_2y_2} = \frac{L_{x_1y_1,x_2y_2}}{L_{remain}} \times T^c_{remain}$$

The estimated muling distance of the road segment is $v_{x_1y_1,x_2y_2} \times T_{x_1y_1,x_2y_2}$. The remaining distance which needs to be forwarded by radio is $L_{x_1y_1,x_2y_2} - v_{x_1y_1,x_2y_2} \times T_{x_1y_1,x_2y_2}$. Let R be the transmission range. The forwarding times $F_{x_1y_1,x_2y_2}$ of the road segment is derived as the following equation:

$$F_{x_1y_1,x_2y_2} = (L_{x_1y_1,x_2y_2} - v_{x_1y_1,x_2y_2} \times T_{x_1y_1,x_2y_2})/R$$

The energy charged by the solar panel is shown as the following equation

$$C(\beta_{x_1y_1,x_2y_2}, v_{x_1y_1,x_2y_2}) = \mathrm{W} \times Tran \times \beta_{x_1y_1,x_2y_2} \times \frac{L_{x_1y_1,x_2y_2}}{v_{x_1y_1,x_2y_2}}$$

where W is the energy in watts that the solar panel can produce in ideal way, $Tran$ is the transformation percentage from the sunlight to energy of the solar panel as the solar panel cannot totally transformed the sunlight into energy, $\beta_{x_1y_1,x_2y_2}$ is the solar illumination in the road segment, $L_{x_1y_1,x_2y_2}$ is the length of road segment, and $v_{x_1y_1,x_2y_2}$ is the average velocity to the hybrid solar vehicle on the road segment.

The energy consumption in transmission of a bit e_t is given by $e_t = \frac{P_{tc}}{D_r} = \frac{10W}{1\times10^6 bps} = 1 \times 10^{-5} j/bit$, where P_{tc} represents the total power consumed by the transmitter circuitry and D_r is the data rate. The total energy consumed for the transmission of a packet, whose packet size is P_{kt_size} and forwarding times is $F_{x_1y_1,x_2y_2}$, in the road segment is shown as follow:

$$E^t_{x_1y_1,x_2y_2} = \frac{P_{tc}}{D_r} \times P_{kt\_size} \times F_{x_1y_1,x_2y_2}$$

For a given hybrid solar vehicle, the required traction power can be calculated by multiplying the vehicle's driving force to the vehicle's speed. Assume that $P^{el}_{x_1y_1,x_2y_2}$ represents the vehicle's traction power requirement, η_t is the transmission efficiency, $v_{x_1y_1,x_2y_2}$ is the speed of the vehicle (km/h), m is the mass of the vehicle, f_r denotes the rolling resistance coefficient, C_d denotes the air resistance coefficient, g denotes the acceleration of gravity ($9.85m/s^2$), and A represents the frontal area. With no wind and 0% slope conditions, the equation of the vehicle's traction power requirement is shown as follow

$$P^{el}_{x_1y_1,x_2y_2} = \frac{1}{3600\eta_t} \times (mgf_r + \frac{C_d A v^2_{x_1y_1,x_2y_2}}{21.15}) \times v_{x_1y_1,x_2y_2}$$

Different speed causes different power gain and cost. Three different cruising speeds are considered, include: starting off/low speed cruising, medium speed cruising and high speed cruising. In the case of starting off/low speed cruising, the average speed is less than low speed threshold ($v_{x_1y_1,x_2y_2} < v_{lth}$), the hybrid solar vehicle is propelled by electric motor, the power is gained by solar panel and energy is consumed by forwarding messages and electric motor operation. The equations to calculate the charge $C_{x_1y_1,x_2y_2}$ and the energy expenditure $E^T_{x_1y_1,x_2y_2}$ during the starting off/low speed cruising are show as follows:

$$C_{x_1y_1,x_2y_2} = \mathrm{W} \times Tran \times \beta_{x_1y_1,x_2y_2} \times \frac{L_{x_1y_1,x_2y_2}}{v_{x_1y_1,x_2y_2}}$$

$$E^T_{x_1y_1,x_2y_2} = E^t_{x_1y_1,x_2y_2} + P^{el}_{x_1y_1,x_2y_2} \times \frac{L_{x_1y_1,x_2y_2}}{v_{x_1y_1,x_2y_2}}$$

When the vehicle cruises in medium speed, the average speed is greater or equal to the low speed threshold but less than the high speed threshold ($v_{lth} \leq v_{x_1y_1,x_2y_2} < v_{hth}$). During medium speed cruising, the hybrid solar vehicle utilizes both the fuel engine and electric motor to operate, when the engine energy output is more than the actual cruising requirement, excess energy would be utilized to charge the battery, and thus the power gains are via the solar panel and the recycled excess energy generated by the engine. The message forwarding and electric motor operation are main sources of power consumptions. The energy recovered by the fuel engine is $\frac{1}{2}mv^2_{x_1y_1,x_2y_2} \times \eta_e$, where η_e denotes the fuel engine energy recovery efficiency. The equations of the charge $C_{x_1y_1,x_2y_2}$ and the energy expenditure $E^T_{x_1y_1,x_2y_2}$ during the medium speed cruising are shown as follows:

$$C_{x_1y_1,x_2y_2} = \mathrm{W} \times Tran \times \beta_{x_1y_1,x_2y_2} \times \frac{L_{x_1y_1,x_2y_2}}{v_{x_1y_1,x_2y_2}} + \frac{1}{2}mv^2_{x_1y_1,x_2y_2} \times \eta_e$$

$$E^T_{x_1y_1,x_2y_2} = E^t_{x_1y_1,x_2y_2} + P^{el}_{x_1y_1,x_2y_2} \times \frac{L_{x_1y_1,x_2y_2}}{v_{x_1y_1,x_2y_2}}$$

When the vehicle cruises in high speed, the average speed is greater or equal to the high speed threshold ($v_{x_1y_1,x_2y_2} \geq v_{hth}$). The hybrid solar vehicle is mainly powered by the fuel engine with the electric motor as an aiding energy source. Therefore, the power gain is via the solar panel and the power is consumed by the message forwarding and electric motor operation. The equations of the charge $C_{x_1y_1,x_2y_2}$ and the energy expenditure $E^T_{x_1y_1,x_2y_2}$ during high speed cruising are shown as follows:

$$C_{x_1y_1,x_2y_2} = \mathrm{W} \times Tran \times \beta_{x_1y_1,x_2y_2} \times \frac{L_{x_1y_1,x_2y_2}}{v_{x_1y_1,x_2y_2}}$$

$$E^T_{x_1y_1,x_2y_2} = E^t_{x_1y_1,x_2y_2} + P^{el}_{x_1y_1,x_2y_2} \times \frac{L_{x_1y_1,x_2y_2}}{v_{x_1y_1,x_2y_2}}$$

When the vehicle is in the intersection, it can calculate the charging capacity and power consumption according to the cruising speed and the illumination at the road segment. The total recharge volume and total power consumption at the road segment can be used to estimate the total forwarding times and total power gain and then the total cost can be derived. Finally, the least cost next road segment can be chosen according to the cost function, which includes the normalized number of transmissions and power gain.

B. Distributed greedy scheme of linear regression-based delay bounded routing on hybrid solar vehicle (DH-Greedy)

In order to reduce the usage of wireless resource and the consumption of fuel as well as delivering the message to destination in delay-bounded time T_c. The DH-Greedy scheme formulates a cost function to choose the next road segment until the message reaches the destination. The decision of the delivery mechanism (muling or forwarding) is mainly based on the available time, the travelling distance and the accumulated power gain with linear regression. In DH-Greedy scheme, when the vehicle is in the intersection, the vehicle will compute the cost of all the possible next road segments to find the minimum-cost road segment until the message reaches the destination. The vehicle only has the knowledge of the local average velocity, solar illumination and the length of all the possible next road segments. The cost function is calculated by the normalized number of transmissions and the normalized power gain. The DH-Greedy scheme uses the predicted lines of delivery times and power gain to guide the switching of the delivery strategy at an appropriate time. When the vehicle is in the intersection, it calculates the cost for each of the possible next road segment. The cost function contains two tuples, the number of transmissions and the power gain. The equation of the power gain $P^G_{x_1y_1,x_2y_2}$ is shown as follow:

$$P^G_{x_1y_1,x_2y_2} = C_{x_1y_1,x_2y_2} - E^T_{x_1y_1,x_2y_2}$$

, where $C_{x_1y_1,x_2y_2}$ denotes the amount of energy charged between $I_{x_1y_1}$ and $I_{x_2y_2}$, and $E^T_{x_1y_1,x_2y_2}$ denotes the amount of energy consumed between $I_{x_1y_1}$ and $I_{x_2y_2}$.

For the fairness of the comparison, the forwarding times and power gain need to be normalized, that is to calculate the per unit length of forwarding times and power gain. The equation of normalized forwarding times F^{nor} is shown as follow:

$$F^{nor} = \frac{F_{x_1y_1,x_2y_2}}{L_{x_1y_1,x_2y_2}}$$

The equation of normalized power gain P^{Gnor} is shown as follow:

$$P^{Gnor} = \frac{P^G_{x_1y_1,x_2y_2}}{L_{x_1y_1,x_2y_2}}$$

The cost function is denoted as $\cos t_{x_1y_1,x_2y_2}(F^{nor}, P^{Gnor})$

For the ease of comparing two costs, assumes that $a_1 = F_1^{nor}, b_1 = -P_1^{Gnor}, a_2 = F_2^{nor}, b_2 = -P_2^{Gnor}$. If $(a_1 < a_2)$ or ($a_1 = a_2$ and $b_1 < b_2$) then $cost_1(F_1^{nor}, P_1^{Gnor}) < cost_2(F_2^{nor}, P_2^{Gnor})$. The road segment with the minimum cost is chosen as the next road segment.

To reduce the forwarding times, harvest more power and correspond to the user-defined delay, our protocol provides a distributed greedy algorithm with linear regression to decide delivery strategies. The vehicle V_i represents the current vehicle's location. Two equations $\widehat{Y}_i = bX + a$ and $\widehat{Y}_j = cX + d$, which are derived from recorded data by linear regression, are used to predict the lines of travelling time and power gain, respectively. As the message is delivered by the vehicle either through data muling or data forwarding, the vehicle records the delivery time (t_i), traveling road segment length (l_i) and the accumulated power gain (p_i) of the message periodically.

Fig. 2 shows the four possible cases of the predictions, where P_{cn} is the expected goal of power gain in the current road segment, P_p is the estimated power gain. In case 1, there is enough time but insufficient power gain; in case 2, there is not enough time but power gain is sufficient; in case 3, there is enough time and enough power gain; in case 4, there is not enough time and not enough power gain.

When $T_p < T_{x_1y_1,x_2y_2}$ (the time is enough) and $P_p < P_{cn}$ (the current power gain has not reached the expected goal), the message should be carried by the vehicle (muling) so as to reduce the usage of radio and save the energy consumed by forwarding. When $T_p \geq T_{x_1y_1,x_2y_2}$ (the time is not enough) and $P_p \geq P_{cn}$ (the power gained is higher than the expectation goal), there is extra power for forwarding and the remaining time is not enough, and hence forwarding is a better option as muling spends more time.

Case 3 can be further divided into two sub cases. When $F^{current}_{x_1y_1,x_2y_2} < F_{x_1y_1,x_2y_2}$ (the number of forwarding times must be less than the maximum expected forwarding times in

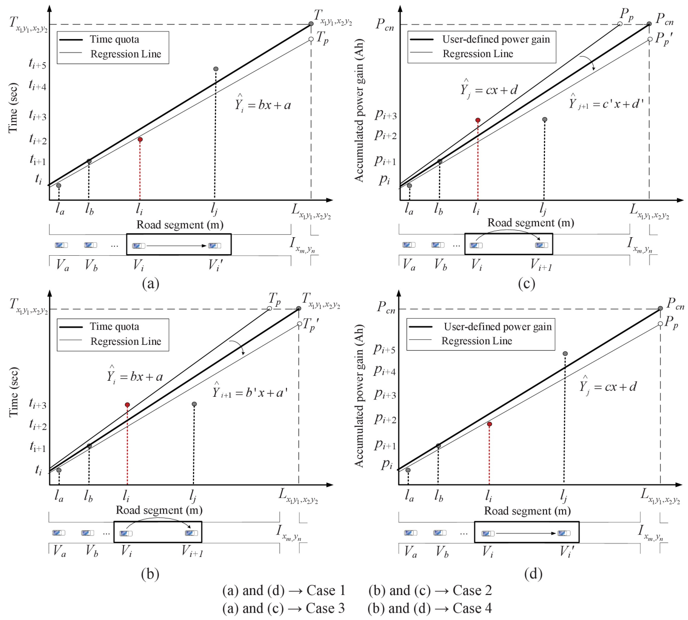


Fig. 2. Four cases to decide muling or forwarding. (a) The remaining time is enough. (b) The remaining time is not enough. (c) The power gain is enough. (d) The power gain is not enough.

the current road segment), $(T_{x_1y_1,x_2y_2} - T_{threshold}) < T_p < T_{x_1y_1,x_2y_2}$ (time is somewhat enough), and $P_p \geq P_{cn}$ (the current power gain is higher than the expected goal), there is extra time and power to accommodate forwarding. When $T_p < (T_{x_1y_1,x_2y_2} - T_{threshold})$ (current time is sufficient and less than $(T_{x_1y_1,x_2y_2} - T_{threshold})$) and $P_p \geq P_{cn}$ (current power gain is higher than the expecting goal), there is plenty of extra time to accommodate muling.

Case 4 can also be divided into two sub cases. A threshold is set above $T_{x_1y_1,x_2y_2}$, when $T_{x_1y_1,x_2y_2} < T_p < (T_{x_1y_1,x_2y_2} + T_{threshold})$ (the remaining time is somewhat not enough) and $P_p < P_{cn}$ (the current power gained has not reached the expecting goal), since the power gain is not enough, muling is used to conserve the power. When $T_p \geq (T_{x_1y_1,x_2y_2} + T_{threshold})$ (the current remaining time is in a great shortage which exceeds the threshold) and $P_p < P_{cn}$ (the current power gained has not reached the expecting goal), forwarding must be used even though the power gained is not sufficient and the number of forwarding times must not exceed the maximum forwarding times.

C. Centralized scheme of linear regression-based delay bounded routing on hybrid solar vehicle (DH-Centralized)

To predict the routing path accurately, we propose a centralized scheme. The DH-Centralized scheme utilizes the dynamic programming to find the minimum cost path. Assume that the vehicle locates at the intersection I_{x_i,y_j} and the destination is located at the intersection I_{x_m,y_n}. For the ease of explanation, assume that the destination is on the lower right corner (The cases that the destination is on the other directions are similar). There are two possible next intersections I_{x_{i+1},y_j} and $I_{x_i,y_{j+1}}$. The function that uses to calculate the minimum cost and discover the minimum cost path from intersection I_{x_i,y_j} to the intersection I_{x_m,y_n} is denoted as $f(x_i, y_j, x_m, y_n)$, which can be derived by the following recursive equation when I_{x_i,y_j} is more than one block away from I_{x_i,y_j},

$$f(x_i, y_j, x_m, y_n) = \min \begin{cases} \cos t_{x_i,y_j,x_{i+1},y_j} + f_{x_{i+1},y_j}(x_m, y_n) \\ \cos t_{x_i,y_j,x_i,y_{j+1}} + f_{x_i,y_{j+1}}(x_m, y_n) \end{cases}$$

,when $\begin{matrix} x_{i-1} \neq x_m \text{ and } y_j \neq y_n \\ x_i \neq x_m \text{ and } y_{j+1} \neq y_n \end{matrix}$

When I_{x_i,y_j} is one block away from I_{x_m,y_n}, $f(x_i, y_j, x_m, y_n)$ can be derived by the following equation.

$f(x_m, y_{n-1}, x_m, y_n) = \text{cost}_{x_m y_{n-1}, x_m y_n}$ or $f(x_{m-1}, y_n, x_m, y_n) = \text{cost}_{x_{m-1} y_n, x_m y_n}$

Recursive function $f(x_i, y_j, x_m, y_n)$ can be calculated by dynamic programming. When the minimum cost path has been discovered, the message is delivered along the minimum cost path. The delivery mechanism is the same as one in the distributed scheme.

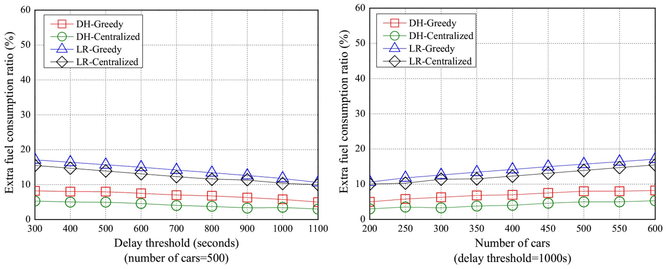
IV. SIMULATION RESULTS

This paper presents a delay-bounded routing protocol on hybrid-solar vehicular ad-hoc networks. To evaluate the performance of the proposed DH-greedy and DH-centralized schemes, we compare them with the LR-greedy and LR-centralized schemes [4] through NCTUns-6.0 [8] which is adopted as the simulation tool. The vehicles in the simulation are assumed to be rechargeable hybrid solar vehicles. The sampling cycle of our protocol is set as 0.5 sec (e.g. sampling rate = 2 samples/sec) . The performance metrics observed in the simulations are:

- The extra fuel consumption ratio (EFCR) is defined as $(F_{del} - F_{org})/F_{org}$, where F_{del} is the total fuel consumed by the vehicles which deliver the message and F_{org} is the total fuel consumed by the same vehicles but there is no delay bounded routing occurred in the networks.
- The average power gain (APG) is the total power gain of the vehicles which deliver the message divided by the number of the vehicles which deliver the message.

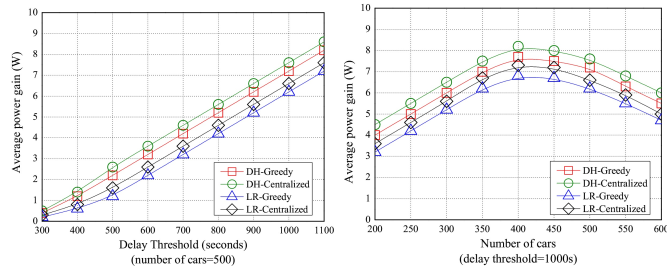
A. Extra Fuel Consumption Ratio (EFCR)

The simulation results of the extra fuel consumption ratio (EFCR) under the delay threshold and number of cars are shown in Fig. 3(a) and (b), respectively. We observed that the EFCR of DH-greedy and DH-centralized are lower than the LR-Greedy and LR-centralized as the delay threshold is high, as illustrated in Fig. 3(a). Fig. 3(a) shows the observed EFCR by tuning the delay threshold and fixing the number of cars on 500. The higher the delay threshold is, the lower the EFCR will be. As the delay threshold increases, the total transmitted bytes decreases because the vehicle has more available time to deliver the messages by muling and thus reduce energy and fuel consumption. Fig. 3(b) shows the observed ECFR by tuning the number of cars and fixing the delay threshold on 1000. The higher the number of cars is, the higher the EFCR will be. As the number of cars increases, the extra fuel consumption ratio increases because high density of cars may



(a) Impact of the delay threshold (b) Impact of the number of cars

Fig. 3. Extra fuel consumption ratio



(a) Impact of the delay threshold (b) Impact of the number of cars

Fig. 4. Average power gain

incur more candidates to relay the message and thus increases the extra fuel consumption ratio. Our protocol is better than LR routing protocol because LR routing protocol only consider the number of forwarding times without considering the power gain. Besides forwarding times, we consider power gain in our protocol as well, as the result two vehicles would choose different paths. The LR routing protocols do not consider power gain sand hence the remaining energy of the vehicle in the selected path may become relatively low because of data forwarding. On the other hand, the hybrid solar vehicle in the chosen path of our protocol will gather more electric energy and thus reduces extra fuel consumption.

B. Average Power Gain (APG)

The simulation results of the Average Power Gain (APG) under the delay threshold and number of cars are shown in Fig. 4(a) and (b), respectively. Fig. 4(a) shows the observed APG by tuning the delay threshold and fixing the number of cars on 500. The higher the delay threshold is, the higher the APG will be. As the delay threshold increases, the total transmitted bytes decreases because the vehicle has more available time to deliver the messages by muling and thus can save power. Our protocol is better than LR routing protocol because LR routing protocol does not consider the power gain. Fig. 4(b) shows the observed APG by tuning the number of cars and fixing the delay threshold on 1000. The higher the number of cars is, the lower the APG will be. As the number of cars increases, the average power gain decreases because high density of cars may incur low speed and more candidates to relay the message and thus increases energy consumption. When the number of cars is between 350 and 450, the number of cars is moderate, and thus the car speed can be maintained at a medium speed. When hybrid solar vehicle is in medium cruising speed, it can recover fuel engine energy, and thus the APG is the highest. When the number of cars is low, the car density also becomes low and the car speed becomes high, and thus the average power gain of the hybrid solar vehicle becomes lower.

V. CONCLUSIONS

This paper has discussed the delay-bounded routing on hybrid-solar vehicular ad-hoc networks. A path selection mechanism based on the cost function which includes forwarding times and power gain and a novel delivery mechanism which is based on the predicted line generated by delivery time and power gain are proposed. Two novel delay-bounded routing schemes for urban vehicular ad hoc networks have been presented (i.e. DH-Greedy and DH-Centralized). Both of the schemes use liner regression to predict the available time and the accumulated power gain. However, the DH-Greedy scheme uses only the current sampling data to predict the available time, the accumulated power gain and to decide when to switch the delivery strategy, whereas the DH-Centralized scheme uses the global statistical information to choose a minimum-cost path. The Greedy strategy is used to choose the least cost next road segment. Simulation results have shown that our schemes perform better than previous schemes in terms of extra fuel consumption ratio and average power gain.

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