Deadline-Aware Packet Routing Based on Optimal Charging Schedule in Electric Vehicular Networks

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***Abstract*—We present a deadline-aware packet routing based on optimal charging schedule in Electric Vehicular Ad Hoc Networks. It aims to propose an optimal charging schedule by incorporating EVs as packet carrier and its regular trajectory. Also, we aim to find out an energy efficient routing path by utilizing the EVs for delivering data packets from stationary nodes scattered over the network. We formulate the charging schedule problem into a binary integer program considering a packet deadline constraint. Along with this, we propose a routing protocol to forward data packets over a cost-effective route with the lowest packet transmission cost by fully exploiting EVs. We validate our optimal charging schedule in terms of acceptance ratio and service waiting time compared to a baseline counterpart. We also evaluate our routing protocol in terms of routing cost and on-time packet delivery ratio. We demonstrate that our algorithm increases the acceptance ratio of EVs in an overloaded situation, while decreasing the overall routing cost for forwarding data over the EV network.**

I. Introduction

As an important component of Intelligent Transportation Systems (ITS), Vehicular Ad Hoc Networks (VANET) is a promising technology for improving data delivery efficiency. By connecting mobile nodes to the deployed stationary networks, it significantly contributes to enhancing the routing performance of real-time data and emergency traffic information [7]. Nowadays, new emerging wireless technologies with Electric Vehicle (EV) bring out Electric Vehicular Ad-hoc Networks (EVANETs) where EVs can be operated as mobile relays. Using the EVANETs, urgent local information on roads and streets can be more effectively shared throughout the networks [6].

However, these EVs may suffer from battery outage, and require frequent battery charging to keep performing their routing jobs [5]. Charging Stations (CSs) can be constructed to provide charging service only to a fixed number of EVs at the same time. Due to only a limited number of charging stations, their limited capacity, charging time, and simultaneous charging requests, designing a more efficient charging schedule is a challenging research problem.

We consider the role of EVs as packet carriers for delivering data packets over stationary networks. The challenges are 1) to solve the charging schedule problem with optimization, and 2) to find out an efficient route that mixes mobile routes of EVs and stationary routes. This approach can greatly reduce the number of transmissions required to the packet destination, and lengthen network lifetime.

Recently, many researches have studied the charging scheduling problem considering EVs. In [1], [2], [5], researchers propose a charging schedule that minimizes waiting time at charging stations by taking an optimization approach. However, they focus on alleviating stress in the power grid and reducing charging cost by taking into account power grid constraints of voltage and power. A theoretical study [4] tries to minimize the charging waiting time by scheduling charging activities in time and space. In [10], two heuristic algorithms, namely Earlier Start Time (EST) and Earlier Finish Time (EFT), have been proposed for scheduling EVs into nearest charging stations for schedule.

The problem of efficient data delivery using mobile nodes has been studied in [3], [8], [9]. In [9], a message ferrying approach is proposed for delivering data in the network without exploiting the prior knowledge of physical movements of mobile nodes. Using the idea of *carry-and-forward*, the vehicle assisted data delivery (VADD) is proposed in [8]. Vehicles carry packets in the absence of route and forward the packets only to a new receiver that comes into its vicinity. However, it suffers from low packet delivery ratio and high packet transmission delay. In [3], a greedy data transportation approach is proposed such that an intermediate node decides whether a data packet should be relayed either to a stationary node close to the destination or a mobile node moving toward it along the predefined trajectory.

This paper presents a cost-effective routing protocol by exploiting mobile EVs in ad-hoc networks. Motivated by the technique in [3] for using mobile nodes for energy-efficient routing, we embed EVs as packet carriers by taking a practically crucial charging problem into this domain.

In this paper, we aim to answer the following questions of 1) how to select a suitable charging station for battery charging of EVs under a hard packet deadline constraint, and 2) how to leverage EVs for designing a cost-effective data delivery that minimizes total packet routing cost, while guaranteeing on-time packet delivery.

We formulate the charging schedule problem into an optimization problem of binary integer program. With the constraints of available charging outlets and the minimum packet deadline, we find the optimal EV-CS assignment for all concurrently requesting EVs that accommodates as many

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EVs as possible into a limited number of CSs. Along with our underlying charging schedule, we propose an detailed routing step of packet loading to EV, packet carrying by EV, and packet drop-off from EV, significantly improving routing efficiency within a packet deadline.

The rest of the paper is organized as follows: After describing system model in Sec. II, our proposed charging schedule algorithm and routing protocol are presented in Sec. III. We discuss evaluation results in Sec. IV, and finally conclude this paper in Sec. V.

II. System Model

This paper considers the problem of energy-efficient packet routing in stationary ad-hoc networks where electric vehicles are roaming over and continuously get connected to parts of them within their radio range as in Fig. 1. We consider a realistic scenario such that electric vehicles (EVs) are powered by a limited amount of battery and need to be charged at one of nearby charging stations when they are running out of battery.

The first goal of this paper is to find the optimal charging scheduling of multiple EVs only with a limited number of charging stations over the networks. We want to lengthen the lifetime of EVs and allow them to contribute to routing in the networks as packet carriers. The second goal is to design a cost-effective routing mechanism. We aim to leverage EVs as mobile relays to help to reduce the number of stationary hops, eventually lessening the routing cost, under a packet deadline constraint.

We assume that EVs move along predefined regular trajectories in the network, e.g., city buses, shuttles. A stationary node can relay packets either to an EV within its radio range (and vice versa) or to a nearby stationary node. It is also assumed that a centralized charging scheduling server receives charging requests from EVs along with EV's current position and battery status in the network. Then the server determines where to be charged per each EV depending on the location of charging stations relative to EVs and the load status of charging stations. The communication between EVs and the scheduling server for sending charging requests from EVs and for assigning to a charging station for each relies on an existing infrastructure network for control. All of data are transferred throughout EVANETs along with stationary ad-hoc nodes. In this paper, we do not take into account real-time road traffic situation that can lead to unexpected travel delay of EVs.

III. Deadline-Aware Routing using EVs

Given only a limited number of charging stations in the network, a number of EVs need to get charged while moving over streets. When an EV reaches a certain battery threshold level, it would send a charging request to a centralized server that determines the overall charging request by permitting an EV to a specific charging station or refusing to be charged at that time. This scheduling decision is made based on the charging request load, the current load status of already scheduling EVs at charging stations, and the relative position between a EV and a candidate charging station.

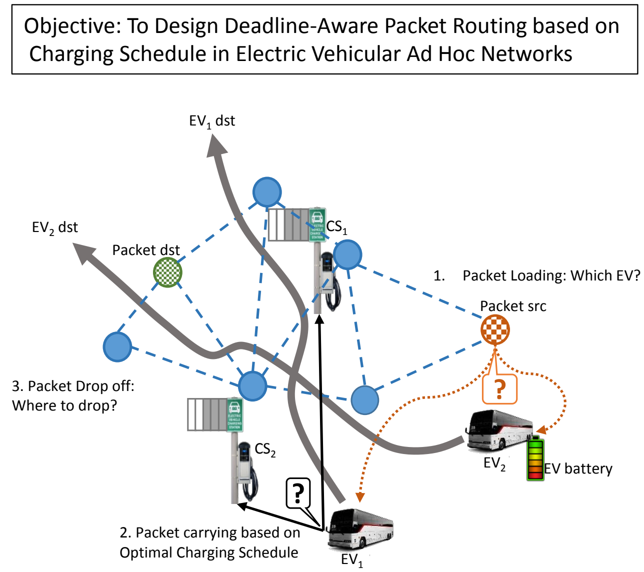


Fig. 1. Overall scenario of packet loading, packet carrying based on optimal charging schedule, and packet drop off in Electric Vehicular Ad Hoc Network.

We propose an scheduling optimization algorithm for accepting EVs upon charging requests into charging stations in an overloaded scenario where the number of EVs is significantly larger than that of charging stations. We maximize the acceptance ratio by fully distributing the request overload over charging stations. Also, by exploiting the proposed charging schedule, we propose a data delivery scheme that utilizes electric vehicles as packet carriers, significantly reducing routing cost compared to stationary node-based routing.

In the next three sub-sections, we describe the procedure of how the overall system operates in the protocol level (Sec. III-A), and then formulate the problem of charging schedule into a binary integer program (Sec. III-B). We propose a cost-effective data delivery scheme based on EVs (Sec. III-C).

A. Protocol

We provide an overview of the necessary steps to take in our proposed system as follows.

1) Packet Loading to EV: Stationary nodes are deployed over the network. A stationary node that has a packet to deliver looks for any EVs moving toward the packet destination. While EVs move along their predefined trajectory, they send hello packets together with their future trajectory information toward each corresponding travel destination. If a nearby stationary node receives it, the stationary node needs to determine whether to load data to this EV or not. First, the stationary data source checks whether the EV has an available buffer space to carry a packet. Then, it calculates the estimated routing cost incurred over stationary routes from the estimated drop-off node on the trajectory to the packet destination after travel. If the estimated routing cost is less than the stationary routing cost without using any EVs, and the estimated travel time is within the packet deadline, the stationary node considers that

EV as a useful packet carrier, reducing total routing cost. The data source creates a sorted list of all possible estimated drop-off nodes based on the above-defined conditions. Finally, it picks up the stationary drop-off node with the lowest routing cost in the sorted list and loads its data packet to the EV. A detailed flowchart is illustrated in Fig. 2(a).

2) Sending Charging Request: While moving along the trajectory, an EV reaches the battery threshold level, and sends a charging request with the current battery level to a centralized scheduling server as in Fig. 2(b). Under an overload situation where a number of EVs send charging requests in the network, the scheduling server collects all the charging requests throughout the network.

3) Charging Station Assignment: Since the server knows all the necessary information of the current battery level of EVs under charging requests, their future trajectories, and charging stations accessible within their battery level, it attempts to accept as many EVs as possible by running a globally optimal scheduling that assigns a subset of EVs to each suitable charging station. A more detailed algorithm is described in Sec. III-B.

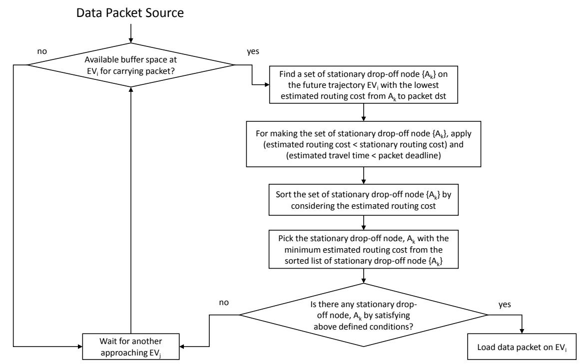
4) Packet Drop-off: While EVs move along their own trajectories toward their travel destination with packets loaded from several stationary nodes, they should determine where to drop a packet considering packet deadline and EVs' battery status. The detailed procedure of packet drop-off is illustrated in Fig. 2(b) and described in Sec. III-C2. Once a data packet is dropped from the EV at a stationary node, it waits to be loaded by another approaching EV, or would be routed over stationary networks otherwise.

B. Charging Schedule

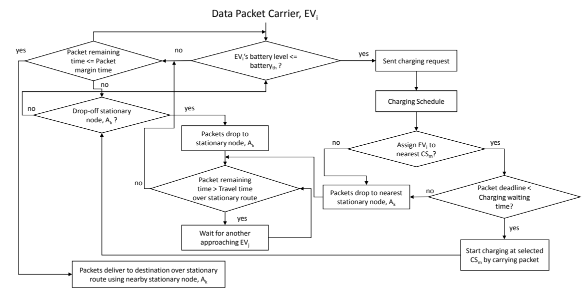
Our charging schedule scheme uses the status information of the currently waiting and scheduled EVs, and the packet deadline information of the currently requesting EVs as the input. Our schedule finds out a set of EV-to-CS assignment for all the requesting EVs that can maximize the number of successfully assigned EVs at one of charging stations.

We formulate the problem of charging station selection of EVs into a binary integer program. The proposed scheme finds the optimal charging station which each EV should be connected to. A centralized scheduler computes the solution given the nearest charging station list that has an available slot, the current waiting time at each charging station, and also the minimum packet deadline among packets carried by a requesting EV.

To set up a binary integer program, we first define indicator functions I_{EV_i,CS_j} indicating whether EV i should be assigned to charging station j. When an EV reaches the battery threshold level, $battery_{th}$ (e.g., 30%), it sends a charging request to the centralized scheduler. The scheduler lists up all the nearest charging stations reachable under the current battery level for each requesting EV. We assume that an EV gets charging service from one of the nearest charging stations located in the future trajectory. For EV i, the nearest charging station list is denoted by $CSlist_{EV_i} = \{CS_{i_1}, CS_{i_2}, CS_{i_3}, \ldots, CS_{i_n}\}$



(a) At data packet source



(b) At data packet carrier

Fig. 2. Control flowcharts of our proposed protocol.

where $i \in \{1, 2, 3, ..., N\}$, and N is the total number of EVs. We introduce additional indicator function J_i indicating whether EV i is assigned to any charging station.

Based on this definition, we write the objective function as $f = \sum J_i$ to maximize the total number of EVs successfully assigned to one of available charging stations. Thus, the optimal charging station selection problem is formulated as a binary integer program as follows:

$$\text{maximize} \quad \sum_{i=1}^{N} J_i \tag{1}$$

$$\text{subject to} \quad N_{CS_k} + \sum_{i} I_{EV_i,CS_k} \leq Q_{CS_k} \qquad \forall k \tag{2}$$

$$(N_{CS_k} + \sum_{i} I_{EV_i,CS_k}) \cdot \Delta t \leq \min_{i} \{ P_{deadline}^{(EV_i)} \} \qquad \forall k \tag{3}$$

$$\sum_{j} I_{EV_i,CS_j} = J_i \leq 1 \qquad \forall i \tag{4}$$

where N_{CS_k} is the total number of currently waiting and already scheduled EVs at CS k, Δt is the service duration to fully charge one EV, $P_{deadline}^{(EV_i)}$ is the earliest packet deadline among packets carried by EV i, and Q_{CS_k} is the maximum queue size to accommodate at CS k.

We want the objective function (1) to maximize the total number of assigned EVs to any charging stations out of all the requested EVs. Constraint (2) ensures that the number of newly scheduled EVs should be within the available space at each charging station. Constraint (3) makes the total waiting time at each charging station fit to the smallest packet deadline among earliest packets of EVs. Finally, constraint (4) enforces one EV to be connected to at most one charging station at a time.

A centralized server solves this binary integer program to obtain I_{EV_i,CS_j} and J_i values as the output of this optimization problem using the MATLAB bintprog solver. From this output, we find the optimal charging station selection for EVs.

C. Cost Effective Data Delivery

Our routing algorithm starts from an assumption the regular predefined movement of EVs as city buses and shuttles. We assume that N electric vehicles $EV_1, EV_2, EV_3, ..., EV_N$ regularly pass over stationary ad hoc nodes along their predefined trajectories. The trajectory information is broadcasted to accessible stationary nodes within radio range. Let us define the trajectory of EV i as $T_{EV_i} = \{A_{i_1}, A_{i_2}, A_{i_3}, ..., A_{i_n}\}$ where A_i is an ad-hoc stationary node.

Our routing protocol provides a detailed procedure of selecting an EV for a stationary data source node to load a data packet, and dropping off the loaded packet from the EV to a stationary relay node.

1) Packet Loading to EV: As described in Sec. III-A, a data source receives the presence alert message and the future trajectory information from a visiting EV. Given this information, the data source determines whether to load its data packet to that EV by estimating the amount of benefit compared to just stationary routing over the longer hop length, costing too much.

The stationary node calculates the estimated routing cost in case of loading to the EV i as

$$RC_{mobileEV_i} = \min_j \{RC_{mobile} + RC_{stationary}(A_{i_j}, A_{dst})\}$$

where $RC_{mobileEV_i}$ is the routing cost in case of carrying on EV i, RC_{mobile} is the routing cost from a stationary node to EV i or from EV i to a stationary node, and $RC_{stationary}(A_{i_j}, A_{dst})$ is the total routing cost over the shortest path from A_{i_j} to A_{dst} in the stationary network.

Further, we estimate the routing delay as travel time of EV and stationary routing delay. We use the underlying delay estimate from our previous work [3].

Based on the above two criteria, the data source determines to load this EV with the drop-off node A_{i_j} with the lowest routing cost among possible candidates that satisfy the packet deadline constraint. However, if two conditions are not held for EV i, the data source waits until another EV approaches, and continues this procedure.

To prevent never-ending waiting at its own data source, we define a packet margin time such that if the remaining packet deadline of a packet reaches the fixed packet margin time, our routing starts using not any mobile route, but stationary route from that time. This can guarantee on-time packet delivery performance with the sacrifice of increased routing cost as a trade-off.

2) Packet Drop-off: After finding out a cost-effective mobile route path based on EV, the stationary source node delivers a packet to the selected EV to carry until reaching the estimated drop-off node. We present detailed packet drop-off cases as follows.

a) Normal Packet Drop-off: We consider a scenario where an EV carries several packets with different packet deadline. While moving on the trajectory, the remaining packet deadline becomes decreasing due to travel time. If the EV reaches the original drop-off node for a packet before the packet margin time, the EV drops off the packet to the drop-off node of which the relevant information is marked in the packet header (shown in Fig. 2(b)). Once a packet is at the drop-off stationary node, it continues to exploit another EV by running the packet loading procedure in Sec. III-C1.

b) Packet Drop-off due to Battery Outage: Our routing protocol considers another packet drop-off case due to battery outage. As an EV moves around the network, the battery level becomes deducted. When an EV will reach the $battery_{th}$ level, it will ask for charging by sending out a charging request. In case that the charging request is continuously refused by the centralized scheduler due to the overload or no nearby charging stations, the EV will run out of its battery at some point. Thus, it is inevitable to drop-off the carried packets at a near stationary node (shown in Fig. 2(b)). The stationary node continues the routing procedure by following Sec. III-C1.

c) Packet Drop-Off due to Charging: The last packet drop-off case occurs when a charging schedule is being performed. If an EV reaches the $battery_{th}$ level, it will seek to be charged at a nearby charging station. After sending the charging request to the centralized scheduler at the position of $battery_{th}$ level, our scheduler tries to find out a suitable charging station per a requested EV. When an EV finally reaches its scheduled charging station, now it can know how many number of EVs are waiting and estimate the start servicing time. If some packets are supposed to run out of deadline until that time, the EV would rather release them to a stationary node to guarantee the on-time arrival of them using another EV or over the stationary networks (shown in Fig. 2(b)). Once packets are dropped off from the EV to a stationary node, it continues the remaining routing procedure in Sec. III-C1.

IV. Evaluation

We validate our proposed scheme using the dataset from [3] where 716 stationary nodes are distributed over 830 $\times$ 790 m^2 area with 20 unique vehicle trajectories. During the movement of EVs along their predefined trajectories, they get connected to a part of stationary nodes within radio range. In our experiment, we randomly select 100 stationary nodes as packet sources, and the maximum buffer size of EVs for carrying packets is 10. For our evaluation, 9 charging stations are located in a simulated network, while reducing it to 6 charging stations to make a more overloaded charging scenario.

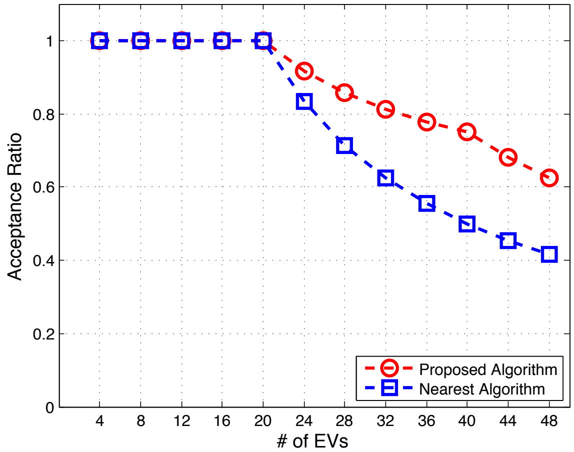


Fig. 3. Acceptance ratio with respect to the number of requested EVs (where packet deadline = 20,000 sec and # of CSs = 6).

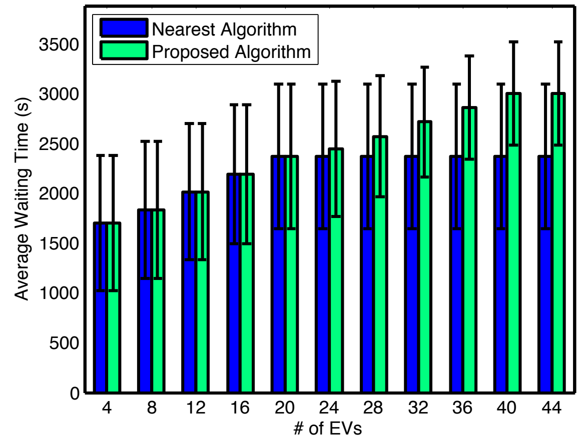


Fig. 4. Service waiting time with respect to the number of requested EVs (where packet deadline = 20,000 sec and # of CSs = 6).

We evaluate our proposed charging schedule algorithm compared to the Nearest algorithm that schedules into the nearest charging station, in terms of acceptance ratio and average waiting time as the number of EVs increases. Then, we validate how our routing algorithm improves routing cost and on-time packet delivery ratio as the number of EVs increases, and the packet deadline becomes more relaxed.

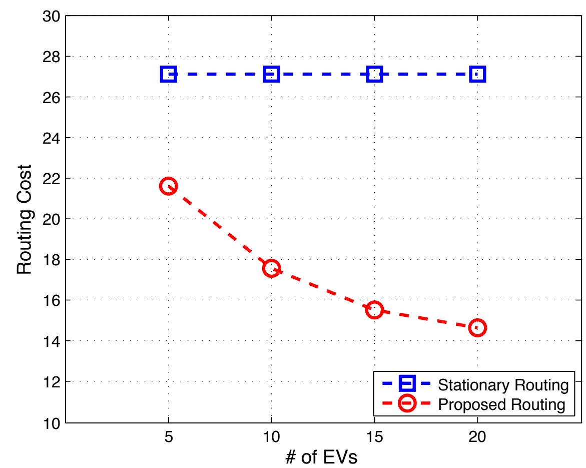
A. *Charging Schedule*

We investigate charging schedule performance with respect to the number of EVs. In this simulation, 6 charging stations and 4 unique vehicle trajectories are used. As in Fig. 3, both our proposed schedule and the Nearest schedule have accommodated all of EV charging requests up to 24 EVs. However, as the number of EV increases further beyond it, it is inevitable that both algorithms deteriorate acceptance ratio. Whereas the Nearest algorithm steeply gets worse, our schedule algorithm keeps the acceptance ratio still relatively high. This means that our schedule algorithm works well in the overload situation by fully distributing charging requests over possible nearby charging stations as far as it can.

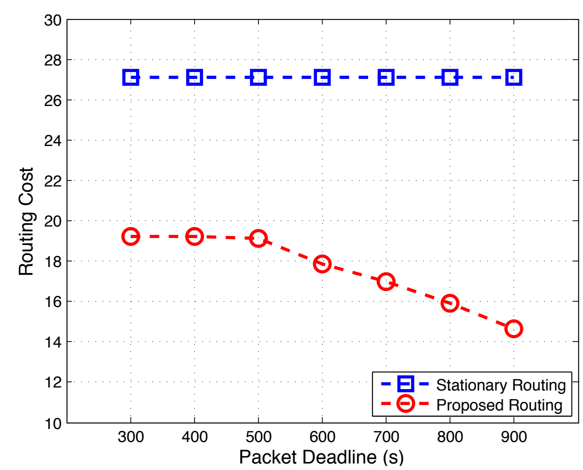
We measure service waiting time at charging stations after running a scheduling algorithm in Fig. 4. We plot the average waiting time with the standard deviation with error bar between our proposed schedule and the Nearest schedule. In an overloaded situation where the number of EVs is beyond 20, our algorithm has a slightly larger waiting time because our algorithm has accommodated a larger number of EVs at charging stations, showing a trade-off relationship between acceptance ratio and service waiting time.

B. *Cost Effective Data Delivery*

We validate our proposed routing scheme based on our MATLAB-based packet-level simulator. We evaluate network performance in terms of routing cost and on-time packet delivery ratio. We examine how performance metrics vary with respect to packet deadline and the number of EVs.



(a) Routing cost with respect to the number of EVs (where packet deadline = 900 sec).



(b) Routing cost with respect to packet deadline (where # of EVs = 10).

Fig. 5. Routing cost comparison between the shortest stationary route and the mixed route of stationary nodes and EVs.

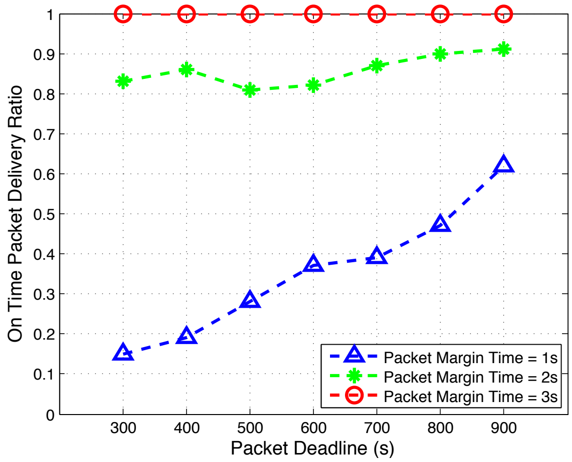


Fig. 6. Packet delivery ratio with respect to packet deadline (where # of EVs = 10).

We quantify routing cost as the summation of per-link ETX (the expected number of transmissions) over the shortest path from a packet source to a packet destination in Fig. 5, We measure routing cost with respect to the number of EVs and packet deadline. In Fig. 5(a), as the network utilizes a larger number of EVs as packet carriers, our routing finds out a greatly cost-effective mobile route together with stationary route, and reduces routing cost with a factor of over 1.8. Our routing scheme significantly outperforms the shortest path routing over only stationary nodes.

We examine how the packet deadline constraint dependent of application type affects routing cost in Fig. 5(b). The shortest path routing based only on stationary nodes does not change its routing decision even if a packet deadline is given longer. However, our routing adaptively changes the routing mode by utilizing more partial routes based on EVs, reducing routing cost. This implies that a larger packet deadline provides a more chance to meet more EVs to carry data packets toward the packet destination.

Finally, we evaluate on-time packet delivery ratio from source to destination to verify how our routing achieves on-time delivery performance within its given packet deadline. As in Fig. 6, the on-time packet delivery ratio increases as the packet deadline is relaxed. When the remaining packet deadline reaches a given packet margin time, our routing protocol relies only on stationary routes by dropping off packets from EVs and forwarding them only over stationary networks. If a suitable packet margin time is tuned, our routing starts leaning toward more stationary routes, achieving on-time packet delivery performance.

V. Conclusion

We have presented a deadline-aware routing protocol in ad hoc networks consisting of stationary nodes as well as EVs serving as mobile relays. By taking the practically critical issue of battery outage in this problem, we have presented an efficient charging schedule algorithm for the routing. By formulating it into an optimization problem, we have significantly improved acceptance ratio and service waiting time for a number of EVs under an overload scenario. Together with efficient charging schedule for EVs, we have designed an intertwined routing strategy that decides to deliver either to a stationary node or to an approaching EV depending on battery status and packet deadline. As a packet deadline constraint becomes more relaxed, our protocol has successfully lessened routing cost, while improving on-time packet delivery rate.

For future work, we would devise a routing algorithm based on a distributed charging schedule algorithm. Also, by designing an adaptive schedule algorithm considering real road traffic situation, we may obtain a more practical routing solution in vehicular ad hoc networks.

Acknowledgment

This work was supported by Basic Science Research Program through the National Research Foundation of Korea(NRF) funded by the Ministry of Education(NRF-2015R1D1A1A01057902), and by the Ministry of Science, ICT, and Future Planning(NRF-2013R1A2A2A04014772).

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