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V2G-combined Tour Scheduler for Electric Vehicles

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Abstract

This paper designs a tour scheduler for electric vehicles (EVs) which want to visit multiple places including V2G (Vehicle-to-Grid)-enabled buildings. During a tour, an EV consumes energy, has its battery charged, and even provides (or sell) redundant electricity to a microgrid, which can avoid consuming expensive peak-rate energy from the power vendor. To find an efficient schedule for a set of user-selected destinations, relevant criteria on tour length, waiting time, and earned reward are calculated to evaluate the fitness of each schedule. Moving EVs can achieve temporal and spatial load shift, necessarily allowing collaboration between independent microgrids separated mainly due to security reasons and technical problems. With the definition of fitness functions, our scheme traverses the search space consisting of feasible tour schedules. The performance measurement result shows that the sales amount maximization improves the amount of electricity sold to a grid by up to 85.6 %, compared with the waiting time minimization scheme. Additionally, tour length minimization generally achieves reasonable performance due to the reduced tour length and battery consumption.

Keywords: *Vehicle-to-grid, tour schedule, electric vehicle, surplus energy, temporal and spatial load shift*

1. Introduction

Smart grid tries to achieve energy efficiency from power generation to consumption by means of intelligently planning, monitoring, and controlling involved facilities and entities [1]. It is built upon sophisticated computer algorithms and real-time two-way communication [2]. Meantime, with the deployment of EVs (Electric Vehicles), which are powered by battery-stored electricity, even the transportation system becomes a part of the power grid. Besides avoiding burning fossil fuels, EVs provide a large reserve of electricity batteries, while connected to the grid. With a large storage, it is possible to shift load by charging batteries during the low-demand night time and giving back to the gird during the peak-demand hours. Moreover, they can participate in frequency regulation, reacting to the real-time signal for their charge and discharge. Here, V2G (Vehicle-to-Grid) is the technology of sending active power from EVs to the grid [3].

Actually, the primary role of EVs is driving, and some EVs want to visit multiple destinations during their trips. The battery-stored electricity is consumed while they are driving except the case of regenerative brakes. On the contrary, the battery can be charged if

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the place has charging facilities, while drivers are doing their work, for example, shopping, taking tours, dining, and the like. The energy not used for driving can be sold in exchange for cost-benefit incentives to a microgrid. It can cut down the consumption of contracted power extremely expensive during the peak-rate interval. Practically, the electricity flow from EVs to the main grid is not easily allowed due to unverified reliability and security issues. Here, the V2G application necessarily works in a microgrid level. This scenario allows us to achieve not only temporal but also spatial load shift between different microgrids for electricity consumption.

In this regard, this paper designs a tour scheduler capable of achieving desired goals for EVs visiting multiple destinations. The scheduling goal will be maximizing the reward obtained by selling surplus electricity to a V2G grid while maintaining the waiting time and the tour length within the tolerable bound. Specifically, when the SoC (State of Charge) is close to full, it is not necessary to visit places having chargers. On the contrary, some subsequence may make the EV be charged to get energy enough to reach the next destination, even if the drivers complete their activities in the spot. The respective features for each destination, such as inter-destination distance, charging facility availability, and most importantly V2G demand, the amount of surplus electricity and thus the sales amount will be different for each visiting sequence. Our scheduler finds a schedule maximizing this sales amount.

2. Related Work

To begin with, the bidirectional chargers open a way for EVs to play a role of large battery device in the grid. Most EVs are parked and connected to the grid for a large amount of time during a day, as their driving time is not so long. The most promising application with the connected vehicle is frequency regulation, which minimizes the system-wide frequency fluctuation stemmed from temporal supply-demand imbalance. [4] designs a distributed V2G control scheme to reduce the peak load by shifting EV charging or even makes EVs inject power back to the grid, detecting a system-level frequency drop. Both are called *Battery SoC Holder* and *Charging with Frequency Regulation*, respectively. Here, for scheduled charging, the compromise with user-requirements on the completion time must be incorporated. V2G also makes it possible for connected EVs to provide potential storage for the intermittent renewable energies [5].

[6] addresses that a real-time management infrastructure must be required to cope with dynamic load change and reactive power injections for the integration of V2G in the power system. The uncontrolled V2G operation increases the possibility of system disturbances. Here, the mismatch between power generation and load leads to power imbalance and voltage fluctuations. In their real-time management system design, the RDAP (Radical Distribution Analysis Package) traces the impact of V2G power injection on the electric grid. The authors identify monitoring parameters such as power loss, energy loss, voltage stability, step voltage regulator operations, and economic analysis. The monitoring-based analysis finds out that optimal location selection for the real-time power injection can achieve up to 95 % power/energy loss reduction.

As for scheduling for EV tours, [7] has developed a waiting time estimation model based on the observation that charging can be done while the tourists are taking their tours provided that chargers are available. The SoC change is traced along a visiting sequence, and waiting time is added when battery remaining is not enough to reach the next spot. In this case, the EV is required to stay at the current spot until sufficient electricity is charged in its battery. Then, it is possible to find a route having the smallest or sufficiently small waiting time via exhaustive or genetic algorithm-based searches [8]. Moreover, insertion of additional places, essentially having chargers, can further reduce the waiting time. Tourists prefer to visit another spot rather than to waste their time, even if the total tour length may increase [9]. As such, many types of tour schedule variants can be developed for the specific tour goals.

3. Tour Scheduler Design

3.1. System Model

Figure 1 depicts our system model in which an EV wants to visit multiple destinations. A driver selects the destinations via the map interface. Then, the tour scheduler finds the optimal sequence and path over the road network. This service can be implemented on the vehicle telematics server or in-vehicle computer devices [10]. Here, how to decide the visiting sequence belongs to the TSP (Traveling Salesman Problem) category and its execution time is $O(n!)$, where n is the number of destinations. Hence, it is reasonable that the complex computation can be conducted in the high-performance server, while the in-vehicle device provides user interfaces. The modern communication technology allows them to efficiently exchange messages and interact with each other even within fast moving vehicles.

Destinations can be restaurants, shopping malls, tour places, and the like. Drivers park their EVs and do their work. For each place, the expected stay time can be specified by the driver or obtained by statistical observation. During the stay, each EV can be charged if it can be connected to the grid. Moreover, in some places like shopping malls which consume a lot of energy during the specific time interval, bidirectional chargers can be available to support V2G applications and allow EVs to sell surplus electricity [11]. The purchase price will be higher than the cheap overnight rate by which the EV was charged. The shopping mall can avoid the consumption of expensive peak-hour electricity. Such a trade can be profitable for both parties. Moreover, shopping malls have many ways to give rewards to the seller including credit money, discount coupons, and the like.

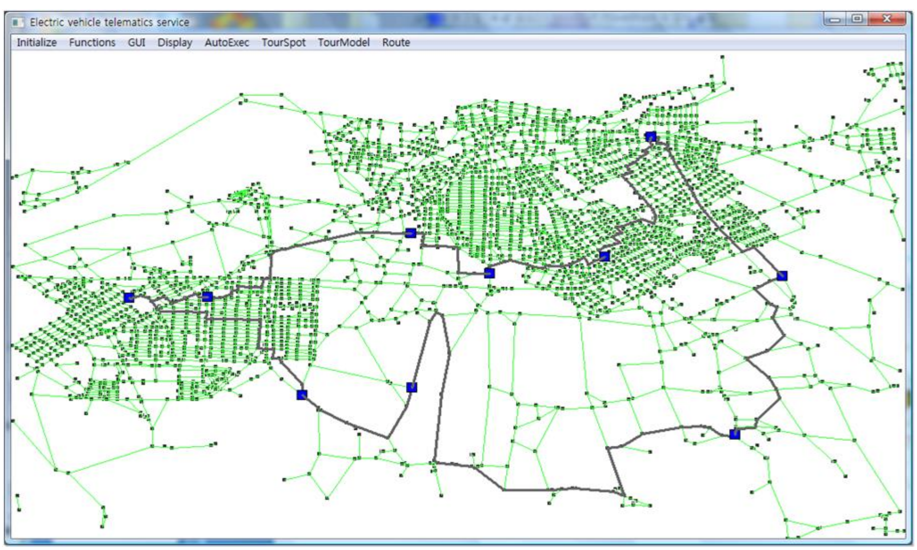


Figure 1. V2G-combined Tour Schedule

3.2. V2G-combined Schedule

The number of feasible sequences for n destinations, say, V_0, V_1, ..., V_{n-1}, is $n!$. For a daily tour, it is possible to traverse the whole search space for the given criteria to find the best one.

Hence, we will measure the effect of the sales amount to the waiting time and the tour length. To begin with, how to estimate the waiting time is previously addressed in [7], but this paper also includes a brief explanation for self-containment. For waiting time formulation at a tour spot, V_i, let B^i_{in} denote the distance credit, when the EV arrives at V_i. B^i_{av} denotes currently available battery. W_i is the waiting time at V_i, and B^i_{out} is battery remaining on its departure. Then,

$$\begin{aligned} B^i_{av} &= min(B_{max}, B^i_{in} + T(V_i)) \\ W_i &= -min(0, B^i_{av} - D(V_i, V_{i+1}))/C_r \\ B^i_{out} &= max(0, B^i_{av} - D(V_i, V_{i+1})) \end{aligned} \quad (1)$$

, where B_{max} is the maximum battery capacity, $T(V_i)$ is the stay time at V_i, and $D(V_i, V_{i+1})$ denotes the road network distance between V_i and V_{i+1}.

Here, B^i_{in}, B^i_{out}, B^i_{av}, and B_{max} are converted to distance reachable with respective SoC values. W_i will be either 0 or $B^i_{av} - D(V_i, V_{i+1}))/C_r$, where C_r is the charging ratio, that is, the time amount needed for an EV to get power to drive the unit distance, for example, 1 *km*. W_i is positive only when $B^i_{av} - D(V_i, V_{i+1})$ is larger than B^i_{av}. For more details, refer to [7]. After all, the total waiting time or the final cost, W, is the sum of all W_i's as shown in Eq. (2).

$$W = \Sigma W_i \quad (2)$$

Next, the tour length of a schedule, L, is straightforwardly calculated as shown in Eq. (3)

$$L = \Sigma^{n-2} D(V_i, V_{i+1}) + D(V_{n-1}, V_0) + \Sigma^{n-1} T(V_i) \quad (3)$$

Now, each EV can calculate the amount to sell according to the current SoC and the remaining tour schedule, specifically, the driving distance and availability of chargers. We assume that there are just a single V2G spot in the set of destinations, as it is possible to force an EV to sell electricity just at one place. This assumption makes the problem much simpler when calculating the amount to sell, as we don't have to consider further selling.

The scheduler checks if the battery can be fully charged somewhere on the remaining route and also if additional waiting time arises. In the first case, as the battery cannot be charged beyond its capacity. But, the missed amount can be sold in the V2G spot and filled later, enabling the EV to sell more to the grid. On the contrary, if the EV must wait on the remaining route, no electricity can be sold to the grid. Excluding the two cases, the sales amount will be the difference between the remaining SoC after the completion of a trip and the current SoC. If the V2G spot is the *c*-th in the sequence, the amount to sell, SG can be calculated as in Eq. (4)

$$S_G = \begin{cases} B^{Final} - B^c + \Delta & B^i_{out} = B_{max} \text{ for } \exists i \ i \geq c, \\ 0 & W_i = 0 \text{ for } \exists i \ i \geq c, \\ B^{Final} - B^c & Otherwise \end{cases} \quad (4)$$

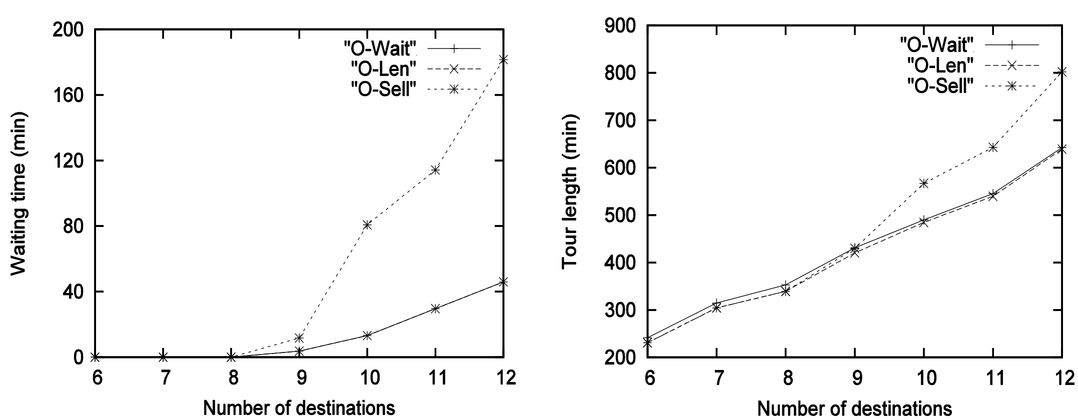
, where Δ is the amount of chargeable electricity beyond the battery capacity while B^{Final} is the SoC when the EV completes the tour and returns to V_0.

4. Experiment Result

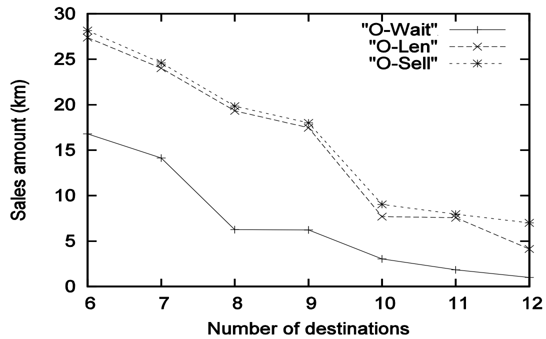
This section implements the prototype version of the proposed scheme to measure its performance. The inter-destination distance distributes exponentially with the average of 10 *km*. The maximum battery capacity is set to 90 *km*, taking into account the safety margin. In the experiment, SoC is converted to the distance reachable with the amount. In addition, we consider slow chargers and it takes 6 hours to fully charge an EV battery [12]. The performance metrics will be waiting time, tour length, and sales amount. Our scheduler traverses the whole search space and picks the sequence which maximizes one of the three criteria. In addition, the tour begins with the EV battery fully charged, assuming overnight charging. For each parameter selection, 20 sets are generated and their results are averaged.

Main performance parameters are the number of destinations, the availability of chargers, and the average stay time. A tour begins and ends at the same spot. However, this restriction can be removed. The availability of chargers is the possibility that a destination has chargers. If there are multiple EVs which want to be charged at the same spot, the queuing delay must be considered. However, the charging load is not severe yet and the external chargers allow EVs to be plugged in the regular outlet. Hence, this experiment assumes that EVs can be charged as long as the visiting spot is equipped with chargers. Finally, the stay time at a spot can be obtained from statistical observation. For example, the general stay time at a tour spot is usually estimated in tour information database. Our experiment makes the stay time distribute exponentially with the given average. At a spot having long stay time, EVs can be charged more. Each graph has 3 curves for schedules minimizing waiting time (O-Wait), minimizing tour length (O-Len), and maximizing sales amount (O-Sell).

The first experiment measures the effect of the number of destinations, ranging from 6 to 12, and the results are plotted in Figure 2. According to Figure 2(a), up to 8 destinations, no waiting time arises, as the total driving distance is covered by battery capacity. O-Wait and O-Len show the same waiting time for the whole experiment range. However, O-Sell lengthens the waiting time when there are 12 destinations. It tries to put the V2G spot as close to the last as and get as much electricity as possible from the precedent spots. The effect to the tour length shown in Figure 2(b) is similar to Figure 2(a). From the case of 10 destinations, the difference to O-Sell is found, reaching 135 *min* for 12 destinations. In Figure 3(c), the amount of sold electricity decreases for all 3 cases according to the increase in the number of destinations, as the battery consumption for driving EVs increases. O-Sell outperforms the others, but the gap is not so significant compared with O-Len until 11 destinations. For the case of 12 destinations, O-Sell outperforms by 85.6 % and 45.0 %, respectively.



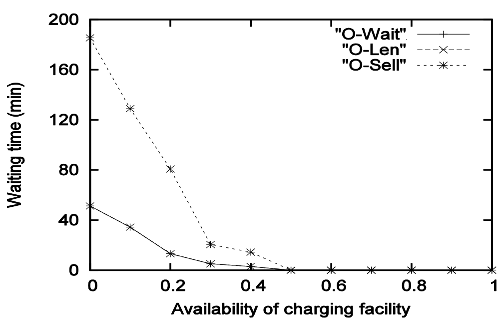
(a) Waiting Time (b) Tour Length



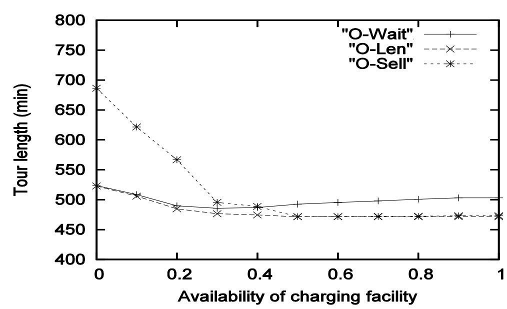
(c) Sales Amount

Figure 2. Effect of the Number of Destinations

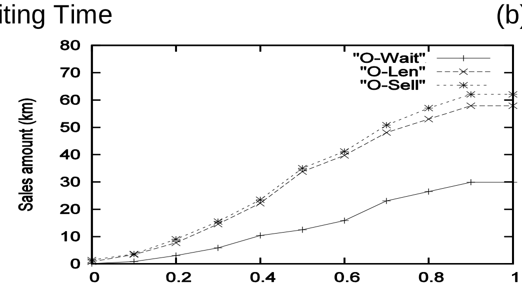
Next experiment measures the effect of the availability of charging facilities in each spot, its results being plotted in Figure 3. A spot has a charger randomly with the given probability. With higher availability, EVs can obtain more electricity. If there is no charging facility on the route, the EV visits a charging station and wait without doing anything. As for other parameters, the number of destinations is set to 10 and the average stay time is to 30 *min*. According to Figure 3 (a) and Figure 3(b), the waiting and the tour length show the similar pattern, that is, beyond the facility availability of 0.3, they hardly change, as the waiting time reaches 0. The tour length just includes the pure driving and stay time. Essentially, the sales amount increases when there are more charging facilities. As explained previously, the scheduler places the V2G spot to the latter part of a schedule, achieving 51.7 % improvement compared with O-Wait. However, O-Len also shows a reasonable performance, the gap to O-Sell being just 6.6 %.



(a) Waiting Time



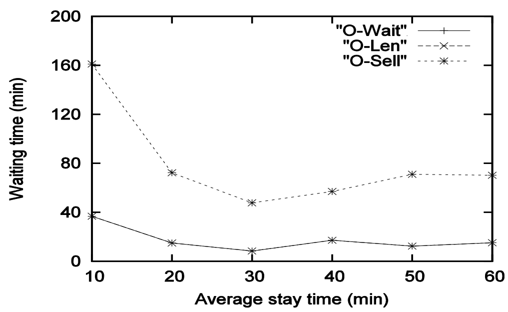
(b) Tour Length



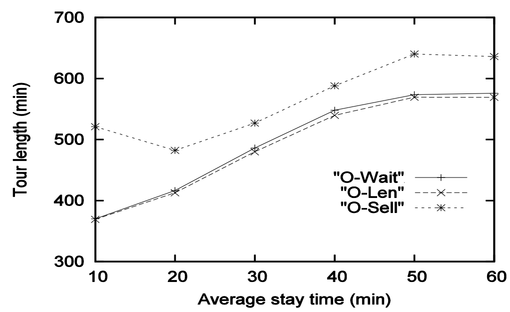
(c) Sales Amount

Figure 3. Effect of the Availability of Chargers

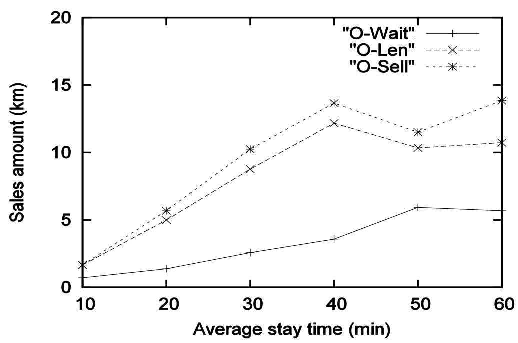
Finally, Figure 4 shows the effect of the average stay time. Here, the number of destinations is set to 10 and the availability of chargers is to 0.2. According to the increase in the stay time, the waiting time decreases as shown in Figure 4(a). If the stay time is longer than 30 *min*, all 3 curves show just a little change. The greedy nature of O-Sell worsens the waiting time by about 40 *min*, except the case when the stay time is 10 *min*. In addition, the tour length of O-Sell differs from the other two, by up to 13.6 %, indicating that the tour length is less affected by V2G applications. Figure 4(c), as in the case of Figure 3(c), O-Sell maximizes the sales amount. The gaps from O-Sell to O-Len and O-Wait are measure to be 22.5 % and 58.9 % at maximum, respectively. O-Len is efficient for all criteria, as it reduces the driving distance, saving the electricity consumption.



(a) Waiting Time



(b) Tour Length



(c) Sales Amount

Figure 4. Effect of the Average Stay Time

5. Conclusions

Modern grid systems are pursuing energy efficiency even in the transportation, not restricted to the classic power generation-consumption chain. Particularly, EVs are the key element of the smart transportation, as they can participate in frequency regulation and other energy-related applications in addition to their basic role, namely, driving. They can achieve temporal and spatial load shift by charging batteries at a spot and selling surplus electricity to other spots, especially when they visit multiple destinations. In this paper, we have designed a tour scheduler for V2G-combined route selection capable of maximizing sales amount while keeping the waiting time and the tour length below the tolerable range. To estimate the sales amount at a spot, it is necessary to check if a full or empty battery state arises on the remaining route. With this investigation, we can find the optimal schedule by traversing the whole search space.

The performance is measured via a prototype implementation. O-Sell improves the amount of sold electricity by up to 85.6 % and 45.0 %, compared with O-Wait and O-Len, respectively. It can be also recognized that tour length reduction basically cuts down the battery consumption, generally showing reasonable waiting time and sales amount.

As future work, we are planning to design a power trading service which dynamically connects buyers and sellers of the surplus energy. It will be necessary to clearly specify the requirement from both parties and schedule the connection time to the grid for each EV.

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