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Electric Vehicles Network with Nomadic Portable Charging Stations

Zheng Li†, Zafer Sahinoglu‡, Zhifeng Tao‡ and Koon Hoo Teo‡
†Electrical and Computer Engineering, University of Delaware, Newark, DE 19716
‡Mitsubishi Electric Research Laboratories, Cambridge, MA 02139
†zhli@ee.udel.edu, ‡{zafer, tao, teo}@merl.com

***Abstract*—A novel concept of portable charging station networks to serve Electric Vehicles is described. An optimum charging station deployment method is explained, and its performance has been simulated for single highway, two intersecting highways, and Manhattan-like grid traffic models. Outage probability and service waiting delay performances are evaluated. Impact of the number PCSs and the ratio of EVs to PCSs in the service area on outage probability and waiting delay are studied. The gained insights will be used in extending this pioneer step to a stochastic framework with more realistic traffic models.**

I. Introduction

Faced with the long-term rising energy cost and increasing concern of the environmental impact, the use of Electric Vehicles (EVs) is fast becoming recognized as an economically viable alternative to traditional internal combustion engine based transportation in many developed and developing countries. EVs will begin its rollout in large volume in 2010.

The Government of United States has proposed the goal of placing one million EVs on the road around 2015 [1]. The widespread use of EVs will need to be supported by government policy and regulations and the appropriate infrastructure such as battery charging station at home, at work and in and around the city. In North America, EVs will likely be mainly charged at home. However, for many big cities where majority of the households do not have their own garages, charging may then take place outdoor. Infrastructure and the appropriate methodology for charging EVs are vital to the success and long-term viability of the electric vehicle industry.

EVs provide plenty of opportunities for utility companies to more efficiently manage their generating capacity by exploiting under-utilized energy capacity during the off-peak time (e.g., nights) when many of the power generators have to continue to run and renewable energy source such as wind power is usually at its peak. By allowing EVs and other forms of energy storage stations to charge up during the nights, it would help to ”soak up” the energy which would otherwise be wasted. These charged vehicles and energy storage stations could then deliver the energy back to other users, including those vehicles which have no means to charge during the nights.

In this paper, we propose a kind of energy storage stations which is called nomadic Portable Charging Stations (PCSs) concept which can provide energy to EVs that need to charge on the road when they are traveling. This novel concept of dispatchable network of PCSs brings about the following advantages.

- EVs will be isolated from the power grid infrastructure with the presence of PCS networks. Thus, during peak hours, load demand from the grid due to charging EVs will be reduced by directing a large number of EVs towards PCSs.
- Portability of PCSs will help the energy service provider optimize placement of PCSs. By this way, cost of energy for the EVs would be reduced. PCSs can be replaced when they are out of energy and also can be moved to some ”hot spot” area whenever needed.

In this paper, we will first present the proposed architecture of EV networks with PCSs in Section II. The optimal placement principle of the PCSs will then be elaborated in Section III. We will also discuss the optional communications protocols in Section IV. We have evaluated the performance through simulations based on some simple but useful traffic models. The simulation results will be discussed and insights will be shared in Section V. Section VI concludes the paper with possible extensions for future work.

II. Proposed Electric Vehicle Network Architecture

The proposed portable EV charging station network consists of EVs, portable charging stations (PCSs), PCS transportation vehicles, and an operation center with a PCS repository as illustrated in Fig. 1.

Each PCS is assigned a unique identification number, and equipped with sensors to measure their remaining energy level, internal and external temperatures. Even though the operation center (OC) can determine and record the global location coordinates of PCSs, each PCS has also an on-board GPS receiver used primarily to detect any unauthorized movement. Communication between OC and PCSs is essential. Therefore, PCSs are deployed with bidirectional communication modules.

Each EV is assumed to monitor battery temperature, remaining energy level, current energy demand and energy consumption rate. These values are reported to the OC either periodically or when polled by the OC. EVs can directly transmit their data to the OC. Alternatively, PCSs can relay EV data.

PCS transportation vehicles (TV) are responsible for dropping PCSs in specified locations, picking up PCSs that need to

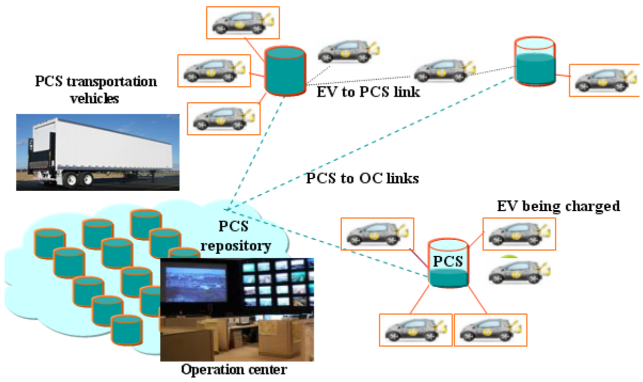

Fig. 1. Illustration of the portable EV charging station network concept. The thick dashed lines indicate communication links between the PCSs and the operation center. The thin dashed lines indicate communication links between PCSs and EVs.

be recharged and relocating PCSs that are active in the service area to increase revenue. TVs can get their commands from the OC directly, and also can exchange information with PCSs within their proximity.

Depending on the energy demand distribution in a given service area within a certain time period, the PCSs need to be relocated. The OC is responsible for determining the optimum relocation coordinates of the PCSs and then informing the TVs of these new coordinates with corresponding PCS identifications.

III. Optimal Charging Station Placement Principle

Consider N EVs in a one-dimensional movement platform with $[0, \mathrm{D}_{\max}]$ as the beginning and end points of the platform. Let $\mathbf{\Omega}_\mathrm{i}$ denote a set of points *x* on the platform that EV *i* traverses without draining and recharging its battery. A reward function $\Delta(x^{(i)})$ for point *x* regarding EV *i* is defined as follows:

$$\Delta(x^{(i)}) = \begin{cases} 1 & \text{if } x \in \mathbf{\Omega}_\mathrm{i} \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

Then, the total reward of point *x* is given by

$$\Delta(x) = \sum_{i=1}^{N} \Delta(x^{(i)}), \ \forall x \in [0, \mathrm{D}_{\max}] \tag{2}$$

The optimum point x_{opt} for deploying a single PCS would be the point that has the maximum total reward.

$$x_{opt} = \arg\max_{x} \Delta(x) \tag{3}$$

It is possible that multiple points can have the same total reward. In this case, the PCS can be located at any of those points. In the case of multiple local maximums, PCSs are deployed starting from the highest local maximum as shown in Fig. 2.

Using the insight for the 1D case, the analysis can be extended to two dimensional service area cases for which the new reward function is given by

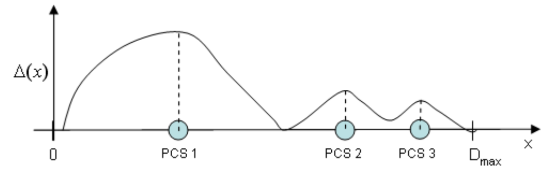

Fig. 2. Illustration of optimum PCS deployment in one-dimensional movement platform with one global maximum and two local minimums.

$$\Delta(x^{(i)}, y^{(i)}) = \begin{cases} 1 & \text{if } (x,y) \in \mathbf{\Omega}_\mathrm{i} \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

where $\mathbf{\Omega}_\mathrm{i}$ now denotes the set of coordinates (along the route of EV *i*) that EV *i* would pass by without a need to recharge its battery. Then, the total reward of coordinates *(x,y)*, $\forall x \in [0, \mathrm{D}_{\mathrm{x}_{\max}}]$, $\forall y \in [0, \mathrm{D}_{\mathrm{y}_{\max}}]$ is given by

$$\Delta(x, y) = \sum_{i=1}^{N} \Delta(x^{(i)}, y^{(i)}), \tag{5}$$

where $[0, \mathrm{D}_{\mathrm{x}_{\max}}]$ and $[0, \mathrm{D}_{\mathrm{y}_{\max}}]$ denote the service boundaries in x and y dimensions, respectively.

The optimum coordinates (x_{opt}, y_{opt}) for deploying a single PCS would be the coordinates with the maximum total reward.

$$(x_{opt}, y_{opt}) = \arg\max_{(x,y)} \Delta(x, y) \tag{6}$$

IV. Associated Communications Protocol

Once power charging stations are deployed, communications would play a central role in enabling EVs to utilize these PCSs most efficiently. Given the nascent nature of EV network communications, however, only a few prior work exist. Moreover, most of the prior work focus on communication functions in the physical chargers. For example, [2] has described how power grid and EVs should communicate via charger such that EVs can become both distributed energy consumers and distributed energy suppliers/storage. Meanwhile, Society of Automotive Engineers (SAE) International has produced a set of standards (e.g., J1772, J2293, etc. [3], [4], [5]) to specify the communications component in physical chargers.

Since none of the above methods can address our specific need, we will outline two possible solutions for communications below.

A. Peer-to-Peer Approach

No telecommunication operator is involved in peer-to-peer approach. PCSs periodically broadcast a wireless ”hello” message, announcing their availability and location. Each EV on the road continuously monitors the channel to receive such ”hello” messages, and decides whether or not to charge at a particular PCS based on the distance between the EV and PCS, the remaining energy level at the EV, and unit energy buy price etc.

B. Centralized Approach

Centralized approach relies on a wireless infrastructure (e.g., GSM, CDMA, WiMAX and LTE, etc.) to facilitate PCS selection. More specifically, each EV on the road shall use wireless infrastructure to inform an operation center (OC) of the service provider of its current location, target destination, its current energy level, and its energy demand. The OC then notifies the EV of the location of available PCSs on the planned route. Such information will then be used by the EV to select a PCS for energy charging.

V. Performance Evaluation

In this section, we will evaluate the performance of an EV network that uses PCSs according to the placement principle described in Section III. Since around 90% of the vehicles in U.S. are ”light duty cars” that will drive at most 100 km daily [6], in our simulations we set the maximum travel distance of EVs to 100 km. Given this travel distance and the capacity of today's state-of-art battery, it is practical to further assume that one full charge will enable an EV to drive 100 km [7]. We also assume that each EV starts its trip with an arbitrary initial energy level, which is uniformly distributed to correspond to sustainable distances between 10km to 100km. Thus, some of the EVs can drive to their destinations without a need to recharge, and others have to recharge their batteries to reach their intended destinations. We assume a PCS will fully charge an EV so that the EV will have sufficient energy to complete its remaining trip after at most one charging. All the simulation results presented here are averaged over 1000 runs.

The simulations will be based on following three simple yet realistic traffic models.

A. Single Highway

In this case, EVs will travel on a 100 km highway in the same direction. We assume there are totally 100 EVs, each of which starts at an arbitrary location on the highway chosen according to a uniform distribution. In the following, we will show the outage performance when using different number of PCSs. Here the outage performance is measured by the ratio of the number of EVs who can drive to the destinations successfully (including the EVs who can drive to the destinations directly without charge and the EVs who can drive through a PCS to charge) and the total number of EVs in the traffic.

TABLE I
Outage Performance vs. Num of PCSs

Num of PCSs	1	2	3	4	5
Successful Prob.	86.1%	94.3%	98.3%	99.6%	99.9%

Table I shows the outage performance versus the number of PCSs on the highway according to the proposed placement principle. We can see that 5 PCSs are enough to guarantee that 99.9% of the EVs driving on the highway to arrive at the destinations successfully.

B. Two Intersecting Highways

In this case, there are two intersecting straight highways $X = C_1$ and $Y = C_2$ with the equal length of 100 km in a 100×100 km^2 square area. The intersection of the two highways has the coordinate $Z = (C_1, C_2)$. All the EVs on X travel towards the top end of the highway, while all the EVs on Y will travel towards the right end of the highway. We assume the total number of EVs on each highway is 100, and each EV will choose its initial position according to a uniform distribution on the road.

TABLE II
Outage Performance vs. Location of the PCS
$X = 50, Y = 50, Z = (50, 50)$

Location	*On* X	*On* Y	*At* Z
Successful Prob.	70.7%	70.7%	82.2%

TABLE III
Outage Performance vs. Location of the PCS
$X = 10, Y = 10, Z = (10, 10)$

Location	*On* X	*On* Y	*At* Z
Successful Prob.	70.7%	70.7%	66.1%

Table II and Table III show the outage performance versus the location where we deploy the first PCS. It is evident that the placement of the first PCS depends on the position of the intersection. In Table II, the intersection Z is in the middle of each straight highway. Thus, it is better to put the first PCS at the intersection so that the PCS can serve EVs from both highways. However, when the intersection Z is close to the end of each line, it can be confirmed by data in Table III that the better choice is to put the first PCS on one of the highway. This is because the number of EVs that will drive through the intersection is fewer in this case.

C. Manhattan Type Grid Traffic

In this case, we consider a $50km \times 50km$ square service area with 102 routes and 2601 intersections. We assume the total number of EVs in the square is 100 and each EV will choose its initial position and destination according to a uniform distribution from the 2601 intersections. Each EV will only choose the shortest route toward its destination.

TABLE IV
Outage Performance vs. Num of PCSs

Num of PCSs	1	5	9	13
Successful Prob.	80.1%	91.2%	96.5%	99.3%

Data in Table IV suggests that we need more PCSs in the grid traffic scenario in order to minimize the outage probability as compared to the previous two traffic models. For instance, we need 13 PCSs for the grid model to achieve a successful probability of 99.3%. The reason is that the grid traffic spans a two-dimensional area in which the EVs are moving randomly in two possible directions.

TABLE V
OUTAGE PERFORMANCE VS. NUM OF PCSS WITH SERVICE RADIUS

Num of PCSs	1	3	5	7
Successful Prob.	84.5%	94.4%	98.6%	99.9%

Since the grid traffic covers a two-dimensional area, we can introduce the concept of service radius for PCSs. Specifically, each PCS will have a service radius which means any EV who is within the service radius can drive to the PCS to get charged if needed. Table V shows the successful probability versus the number of PCSs when we allow the PCSs to have a service radius of 5 km which means that any EV whose distance to the PCS is within 5 km can drive to that PCS to get charged if needed. We can see that the number of PCSs is reduced by introducing the service radius for the PCSs. For example, 7 PCSs can achieve a successful probability of 99.9%.

D. The Waiting Delay of Using PCSs

From the above simulation results, we can see that using a limited number of PCSs can serve most of the EVs in the traffic. However, although most of the EVs can find a PCS to get charged along their route, they may have to wait for service at the PCSs due to queuing. The waiting delay, which is also known as queueing delay, will significantly degrade PCSs' user experience especially when the number of EVs in the traffic is increasing.

Fig. 3 shows the average waiting delay when using only one PCS in the single highway scenario when there are different number of EVs in the traffic. Here the average delay is defined as the ratio of total waiting delay in minutes and the number of EVs who need charge. We assume that the 10-minute fast full charging technology is available and all the EVs are moving with the same velocity of 60 km/hour. We can see that the average waiting delay increases significantly when the number of EVs increases. Also, when the number of EVs is increased 5 times from 20 to 100, the average waiting delay increases by 11 times from 8 minutes to 89 minutes. For other traffic models, the waiting delay also increases when the number of EVs in the traffic increases. Thus, using PCSs has the advantage of achieving high successful probability. In other words, in PCS networks, most of the EVs in the traffic can be served, however, we need to optimize the number of PCSs and their locations to reduce the service delay experienced by EVs.

One method to reduce the waiting delay is to equip each PCS with the capability of serving multiple EVs simultaneously,i.e., each PCS has more than one outlet. Fig. 4 shows that by deploying multiple outlets per PCS, we can substantially reduce the waiting delay. In Fig. 4, we simulate the average waiting delay in the single highway scenario with 100 EVs and only one PCS. We can see that using 4 outlets on one PCS can lower the average waiting delay to be only 5 minutes, which is a significant improvement compared with the 89 minutes by using single outlet PCS.

Another method to reduce the waiting delay is to let PCSs serve the same number of EVs on average, i.e., each PCS will serve the same amount of EVs who need to charge, in this case, the average waiting delay for all the PCSs is the smallest. From Table I, we can see that the first PCS serves the most EVs who need to charge, the following PCSs serve less and less EVs. However, some EVs may drive through multiple PCSs, it means those EVs can choose the PCS to get charged, but they don't necessarily get charged at the first PCS they meet.

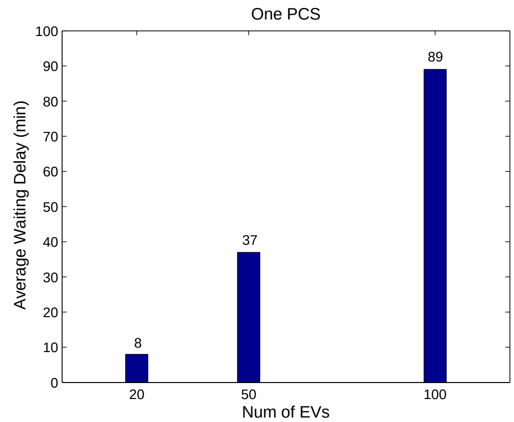

Fig. 3. Average Waiting Delay vs. Num of EVs

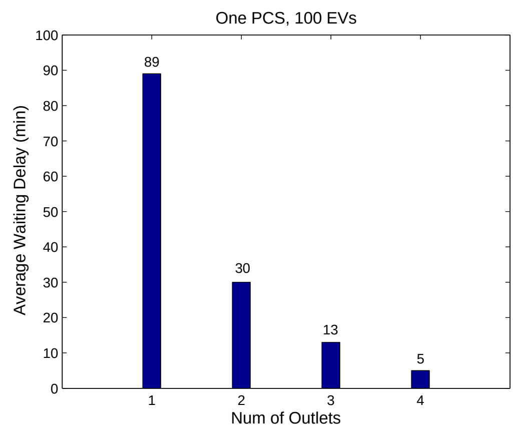

Fig. 4. Average Waiting Delay vs. Num of Outlets

In Fig. 5, we show the average waiting delay when all the PCSs can serve the same number of EVs who need to charge. We again use the single highway scenario with 100 EVs. We can see that when we use more PCSs, the waiting delay decreases if each PCS serves the same number of EVs. Note that this is the best performance we can achieve in theory. In practice, it is less likely to let all PCSs serve exactly the same number of EVs.

In order to guarantee the successful probability and reduce the average waiting delay, we can combine the above two methods, and use enough number of PCSs to guarantee the successful probability first. Then we let each PCS to have multiple outlets to serve approximately the same number of EVs that need to charge. By doing so, we can expect that

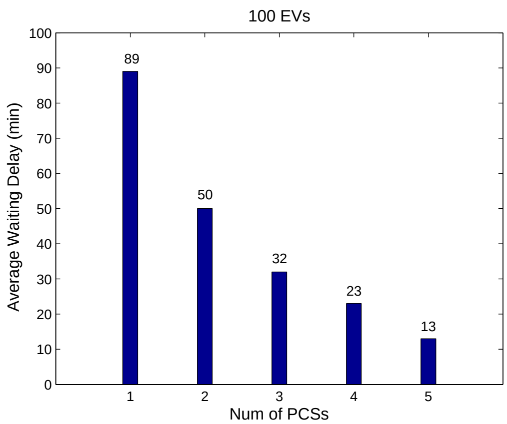

Fig. 5. Average Waiting Delay (Best Performance) vs. Num of PCSs

using PCSs can serve most of the EVs within an acceptable waiting delay bound. Although the simulations are only based on the single highway scenario for simplicity, the proposed two methods are also valid for other traffic models.

VI. Conclusion

In this paper, we propose the nomadic Portable Charging Stations as a kind of energy storage. We present the Electric Vehicles' network architecture and the optimal placement principle. The communications protocols are also discussed. We also evaluate the performance of using the Portable Charging Stations through simulations to justify the insights we have gained.

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