Study on Energy Efficient Path Planning for Airborne-based Dynamic Wireless Charging of Electric Vehicles

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드론 기반 전기차 동적 무선 충전을 위한 에너지 효율적인 경로 설정에 관한 연구

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Abstract

Roadway-based wireless charging (RWC) transfers energy through radio signals. Recent advances in RWC technology have made airborne energy delivery to electric vehicles (EVs) a reality. The use of an airborne-based energy charger (AEC) allows vehicles to replenish supply during trips without the need to stop. However, efficient AEC scheduling will be necessary in order to better serve EVs and optimize the AEC operation. In this paper, we model such an optimization as a variant of the Hamiltonian path formation problem which is an NP-hard problem and propose a heuristic for scheduling the charging service based on prioritizing the EV requests and forming the path based on an earliest deadline first strategy.
Keywords - Route Selection, Energy Efficient, Airborne Energy Charger, Electric Vehicle, Dynamic Wireless Charging.

I. Introduction

To support wide adaptation of battery-operated electric vehicles (EVs), the way such a transportation system is coupled with the electricity system has been evolved to avoid sole reliance on wired charging stations. Therefore, wireless electric vehicle charging systems have attracted attention, where charging pads are to be installed on roadways to charge EVs that pass over them [1-4]. The feasibility of such dynamic wireless charging (DWC) of EVs has been demonstrated while driving at speeds up to 100km/h [3]. However, such an approach requires major infrastructure investment and restricts the travel routes of EV. The high cost and path constraints diminish the practicality of such an approach. Recently airborne-based energy chargers (AEC) like drones have been introduced to enable energy replenishment of battery-operated industrial Internet of things [4]. AEC is also being viewed as a viable wireless EV charger by providing energy delivery service to driving EVs on the road as well as parked EVs [5-7].

With increasing preference for AECs, the usage of AECs should be optimized in order to minimize the wasted energy in flight and consequently boost the number of charged EVs. This paper tackles the problem of *minimizing AEC's path for charging EVs during their driving at different speeds while maximizing the number of charged EVs which is modeled as a variant of finding a Hamiltonian path which is to minimize a length of the path where AEC departs one of ground charging stations (GCSs), charges as many EVs on the run as possible and returns to one of GCSs*. Such a problem is known to be NP-hard; hence a heuristic is proposed considering charging urgency. The heuristic applies an earliest deadline first (EDF) discipline to reduce the number of EVs that unintentionally stop due to depleted batteries, where a charging AEC path is formed based on the urgency of EV needs.

II. Charging Service Architecture

As seen in Figure 1, the charging service architecture based on which the proposed algorithms work comprises three components linked with each other, which are a central server on the Internet, AECs in preparation for charging service at GCS and driving EVs on the road. The server performs three main tasks: (1) handling the registration of EVs, (2) grouping the charging requests in a particular area to assign a list of requesting EVs to the AEC responsible for the area, and (3) managing EVs' billing. A charging service is initiated when an EV, e_i sends a charging request message to the server which includes the identifier, location and requested battery amount of the requester, e_i. An AEC computes the expected rendezvous locations for each EV in the list of requesters received from a server and notifies EVs. The communication among the server, AEC, and EVs takes place using various types of network links like long-range Wi-Fi or a cellular network like 4G-LTE or 5G.

III. Earliest Deadline First (EDF)

An AEC strives to charge requester EVs so that they do not need to reroute to reach a ground charging station; thus, the charging urgency of an EV e_i denoted as $Urg(e_i)$ is considered as a top priority during charging scheduling. $Urg(e_i)$ is measured as a ratio of distance from e_i's current location to the closest GCS, G_r along its pre-planned route, $Rte(e_i, t)$ to the maximum distance to reach using residual battery, $\frac{Dist(Loc(e_i),\ Loc(G_r))}{ResidDist(e_i)}$, where $G_r = \min_{\forall G_j \in S_{GCS} \cap S'_{GCS}} Dist(Loc(e_i), Loc(G_j))$,

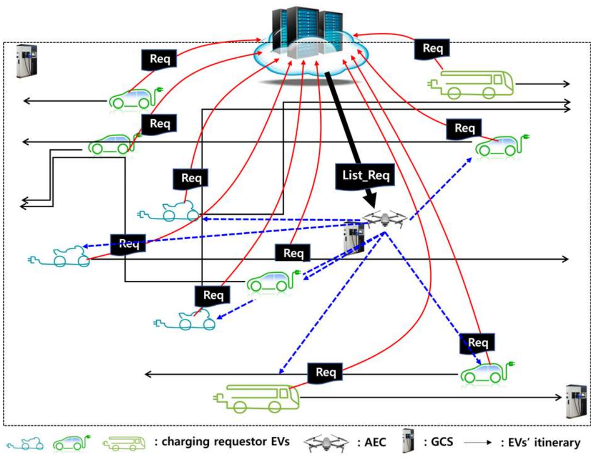

Figure 1. AEC-based dynamic EV charging architecture, where a set of charging requests of EVs is collected to a server on the Internet which communicates with the EVs during its service over 5G or long-range Wi-Fi.

S'_{GCS} is a set of GCS $\in S_{GCS}$ along with $Rte(e_i, t)$. Upon the selection of the next EV, U checks its battery level, $SoC(U)$. If $SoC(U) < RqB2D(e_i)$, then U reports its termination to the server prior to returning to the closest GCS (in line 7-12 of Algorithm I).

After that the rendezvous point on the driving road map of e_i, at which the selected e_i starts to be charged by U is computed based on the location where e_i will meet U in consideration of a real-time driving speed of e_i and U's flying speed, a charging range of U, as seen in $FindRdvLoc()$ of Algorithm I. Then the computed $RdvLoc(e_i)$ in line 15 is sent to e_i before U moves to e_i and U adjusts its altitude of a flight when arriving at $RdvLoc(e_i)$ to start charging e_i. The flight time of U during charging reflects the minimum distance to follow $Rte(e_i, t)$ in real-time as seen in line 17 that includes $Charge()$. By the time the charge is over, U computes the next urgent requester EV and updates a total flight distance, $Path_{Len}$. After charging all EVs in $List\_Req$, U returns to the closest GCS from the location where U serves the last EV (line 22 of Algorithm I).

TABLE 1. NOTATIONS AND DEFINITIONS

Symbol	Description
U	AEC
S_{GCS}	A set of GCSs in a serving area
G_i	GCS, $i = 1, \ldots, N_{GCS}$, $N_{GCS} = \lvert S_{GCS} \rvert$
N_{ChgReq}	Total number of charging requesters
e_i	i^{th} EV, $i = 1..N_{ChgReq}$
$S_{unchrgEV}$	A set of uncharged EVs
$SoC(X)$	State of Charge of X
$Loc(X)$	Current location of $X = U$ or e_i; updated when called
$RqB2D(e_i)$	Requested battery amount of EV driving from $Loc(e_i)$ to $Dst(e_i)$ on a map $Map(e_i)$ at a speed $Spd(e_i)$ (kW), where $Dst(e_i)$ is a destination of e_i.
$ChgTime(e_i)$	$\frac{RqB2D(e_i)}{ChgRt(e_i)}$; time to charge $RqB2D(e_i)$
$Dist(A, B)$	Euclidean distance between A and B
$DistM(M, A, B)$	Distance between A and B on the map M
$ResidDist(e_i)$	Distance for which e_i can drive using $Resid(e_i)$
$Spd(X)$	Real-time driving speed of X
$Map(e_i)$	Driving road map of e_i
$RdvLoc(e_i)$	Location where U can charge e_i
$Rte(e_i, t)$	Real-time (shortest or fastest) route of e_i at a time t on $Map(e_i)$ from $Loc(e_i)$ to $Dst(e_i)$
$Path(U)$	List in an increasing order of rendezvous time, $RdvLoc(U, e_i)$
$Path_{Len}(U)$	Total flying distance of AEC to $Path(U)$
$ChgRng(U)$	Charging range of U
$Urg(e_i)$	Charging urgency of e_i; a ratio of $Dist(Loc(e_i), \text{closest } G_i)$ to $ResidDist(e_i)$; The higher, the more urgent

Algorithm I. Pseudo code of EDF

EDF($List\_Req$) { // Charging urgency based scheduling

1. $S_{unchrgEV} \leftarrow List\_Req$; $Path_{Len} \leftarrow 0$; $N_{ChgReq} \leftarrow 0$;
2. **while** ($S_{unchrgEV} \neq \emptyset$) {
3. U obtains the updated locations of $\forall e_i \in S_{unchrgEV}$ via message exchange
4. $S'_{GCS} \leftarrow$ a set of GCSs $\in S_{GCS}$ which are on $Rte(e_i, t)$;
5. $G_r \leftarrow \min_{\forall G_j \in S_{GCS} \cap S'_{GCS}} Dist(Loc(e_i), Loc(G_j))$; // closest GCS
6. $e_x \leftarrow \min_{\forall e_i \in S_{unchrgEV}} \left(\frac{Dist(Loc(e_i),\ Loc(G_r))}{ResidDist(e_i)}\right)$; // most urgent EV
7. **if** $SoC(U) < RqB2D(e_x)$ **then** // U itself needs charge
8. The server dispatches another U to serve remaining e_i's;
9. $G_r \leftarrow \min_{\forall G_j \in S_{GCS}} Dist(Loc(U), Loc(G_j))$;
10. U terminates its operation and flies to G_r for full charge;
11. **endif**
12. $t \leftarrow t_{current}$;

    // Find rendezvous points where e_x and U meets
13. $RdvLoc(e_x) \leftarrow FindRdvLoc(e_x, Loc(e_x), Loc(U), t)$;
14. $Path_{Len}$ += $Dist2(Loc(U), RdvLoc)$;
15. U sends $RdvLoc(e_x)$ to e_x and flies to $RdvLoc(e_x)$;
16. **if** U reaches e_x in $ChgRng(U)$ **then** {
17. $Path_{Len}$ += $Charge(e_x, RdvLoc(e_x))$; N_{ChgRe} ++;
18. } **endif**
19. $S_{unchrgEV}$ −= $\{e_x\}$;
20. } **do**
21. Update $Loc(U)$;
22. $G_r \leftarrow \min_{\forall G_j \in S_{GCS}} Dist(Loc(U), Loc(G_j))$; U returns to G_r;
23. $Path_{Len}$ += $Dist(Loc(U), Loc(G_r))$;
24. return $Path_{Len}$ and N_{ChgReq};

// Compute the expected location where e meets U on $Map(e)$

FindRdvLoc(e, L_e, L_U, t)

1. Compute a coordinator $X = (x,\ y)$ on $Rte(e, t)$ satisfying that $\frac{Dist(e, X)}{Spd(e)} = \frac{Dist(U,\ X - ChgRng(U))}{Spd(U)}$;
2. return X;

Charge(e, $RdvLoc$)

1. U starts to charge e and follows $Rte(e, t)$;
2. $eLoc \leftarrow FindLoc(Map(e), Loc(e), ChgTime(e), Spd(e))$;
3. return $DistM(Map(e), RdvLoc, eLoc)$;

IV. CONCLUSION

In this paper we have presented the charging algorithm for battery-operated electric vehicles (EVs) based on dynamic wireless charging technology. We have formulated the dynamic wireless EV charging problem as a variant of the Hamiltonian path problem and proposed a heuristic with the objectives of increment on the number of served EVs and reduction of the number of EVs that unintentionally stop due to depleted batteries in consideration of battery urgency of EVs driving on the roads.

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REFERENCE

[1] Dimitriadou, Konstantina, et al. "Current Trends in Electric Vehicle Charging Infrastructure; Opportunities and Challenges in Wireless Charging Integration," *Energies*, Vol. 16, Issue 4, 2023.

[2] Wang, Yun, Yu Zhou, and Xuedong Yan. "Reliable dynamic wireless charging infrastructure deployment problem for public transport services," *European Journal of Operational Research*, Vol. 313, pp. 747-766, 2024.

[3] From wireless to dynamic electric vehicle charging: The evolution of Qualcomm Halo, "https://www.qualcomm.com/news/onq/2017/05/18/wireless-dynamic-ev-charging-evolution-qualcomm-halo," Oct. 2021.

[4] Guangjie Han, et al. "Dynamic Collaborative Charging Algorithm for Mobile and Static Nodes in Industrial Internet of Things." IEEE Internet of Things Journal, Early Access Article, 21 May 2021.

[5] Amazon's new patent: Drones that recharge your EV while you're driving "https://www.prescouter.com/2018/04/amazon-patent-drones-recharge-ev/," October 2021.

[6] Patents Assigned to NEXTEV USA, Inc., "https://patents.justia.com/assignee/nextev-usa-inc," October 2021.

[7] Nguyen, Dinh Hoa. "Dynamic Optical Wireless Power Transfer for Electric Vehicles." *IEEE Access* Ver. 11, pp.2787-2795, 2023.