A Cost-Efficient Communication Framework For Battery Switch Based Electric Vehicle Charging

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***Abstract*—Charging management for Electric Vehicles (EVs) on-the-move has become an increasingly important research problem in smart cities. Major technical challenges include the selection of Charging Stations (CSs) to guide charging plans, and the design of cost-efficient communication infrastructure between the power grid and EVs. In this article, we first present a brief review on state-of-the-art EV charging management schemes. Next, by incorporating battery switch technology to enable fast charging service, a Publish/Subscribe (P/S) communication framework is provisioned to support the EV charging service. Upon that, we develop a fully distributed charging management scheme with the consideration of urban travel uncertainties, e.g., traffic congestions and drivers' preferences. This would benefit from low privacy sensitivity, as EVs' status information will not be released through management. Results demonstrate a guidance for the provisioning of P/S communication framework to improve EV drivers' experience, e.g., charging waiting time and total trip duration. Also, the benefit of P/S communication framework is reflected in terms of the communication efficiency. Open research issues of this emerging area are also presented.**

I. Introduction

As the emerging key urban infrastructures, the Smart Grid and Intelligent Transportation Systems (ITS) have been playing increasingly important roles in modern cities. This enables Electric Vehicles (EVs) that are expected to be widely adopted as individual, commercial, and public vehicle fleets.

However, compared with traditional gasoline-powered vehicles, on-the-move EVs are more likely to run out of energy and need to be charged during their journeys. As a result, how to manage the charging processes of EVs to improve their drivers' comfort, is a vital research issue to the success and long-term viability of EV industries.

Existing charging techniques still require a relatively long duration to complete battery charging (typically, half to several hours [1]), leading to frequently overloaded Charging Stations (CSs) caused by their typically limited forecourt areas [2]. The time and efforts spent for seeking available CSs over the city, and waiting in the service queue would bring uncomfortable and anxious driving experience for EV drivers. A promising alternative approach to the traditional charging service, the battery switch service [3], can replace a fully charged battery for an EV within several minutes, by using industrial automation robots.

As EVs become more prevalent, their charging demands will significantly rise for CSs throughout the smart cities. Therefore, there is a necessity to design the communication infrastructure with efficiency and sustainability in mind. We aim to answer the following four questions in this article:

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1) How to provision an ITS enabled communication framework for EV charging management, via techniques include the Road Side Unit (RSU), Global Position Systems (GPS), standardization of Vehicles to Infrastructures (V2I) communications (e.g., 802.11p [4])?
2) How does the provisioning of communication framework affect the actual driving experience, and how cost-efficient it is?
3) Which CS is ranked as the best plan for an EV on-the-move needs the battery switch service, to perceive the comfortable driving experience (e.g., minimized charging waiting time and trip duration)?
4) What are the influence of urban driving uncertainties (e.g., traffic conditions and drivers' trip preferences) and battery switch system on the driving experience?

By facilitating the battery switch service, we provision an ITS-enabled Publish/Subscribe (P/S) [5] communication framework, where necessary information (availability to provide the battery switch service) is shared among different EVs and other ITS entities such as RSUs. We further propose a CS-selection scheme driven by the drivers' trip preferences. Throughout case study under the Helsinki city scenario, the influence of communication provisioning and urban driving uncertainties on driving experience are studied.

II. Review on EV Charging Management

A. Parking Mode

Majority of previous works have addressed this use case (concerning when/whether to charge EVs), where EVs have already been parking at homes/CSs. Details could be referred to [6], herein we briefly summarize these works as:

- Schedule and control the charging/discharging of EVs [7] (depending on different charging technologies, such as normal and fast charging), with different durations such that power grid constraints are maintained. This benefits power grid such that peaks and possible overloads of the electricity network may be avoided.
- Address pricing issue [8] in order to encourage EVs not to charge during periods of high demand. This is mainly related to the economy issue, as the charging price is normally higher in peak hours, than that in off-peak hours.
- Integrate renewable energy, mainly solar and wind into grid as complimentary solution, from which sustainable energy could be provided to support massive demands.

B. On-the-move Mode

A few works have been studied to manage the EV drivers' charging plans, when they are on-the-move:

- Route EVs (with charging event [9]) to minimize energy loss and maximize energy harvested during a trip, such that the time spent to fully recharge EVs is minimized. This would consider EV speed, as part of the efficiency of EVs results from their ability to recover some energy during deceleration.
- Where to deploy CSs (providing either plug-in charging or battery switch service [3]) such that EVs can access CSs within their driving ranges. Besides, the capabilities of CSs to handle peak demands are taken into account, due to different number of EV arrivals at different times.
- Select the appropriate CS as charging plan (or refer to where to charge). For example, to select the CS which is not highly congested [10], so as to experience a minimized charging waiting time.

III. Provisioning of P/S Communication Framework For Battery Switch Service

In this article, we focus on the latter user case (i.e., *On-the-move Mode*), and aim to determine where (which CS) to charge at real time. Since previous works have not brought the benefit of battery switch technology for enabling fast EV charging in *On-the-move Mode*, we lead an interdisciplinary contribution, by bridging that advanced charging technology and provisioning of cost-efficient communication to drive information exchange within EV charging system.

A. Battery Switch Service

To promote the popularization of EVs, it is necessary to build the infrastructure for charging batteries. Traditional plug-in recharging is accomplished by plugging EVs into charging slots (set by CSs placed at different city locations). In contrast, at the CS providing the battery switch service [3], the automated switch platform switches the depleted battery from an EV, with a fully charged battery it maintains. The depleted battery is placed and recharged so that it can be used by other EV drivers. This means that each CS is able to maintain a certain number of batteries for switch.

The battery switch service could be described as a mixture of a drive-through car wash, which normally switches an EV's battery in several minutes, while without requiring the driver to get out of the EV. Note that, as the cost to the battery's lifespan may be taken into account, the fast charging still takes a toll that should be avoided when possible. The nature that depleted batteries are charged by CSs (normally via a lower power), certainly removes that burden from EV drivers to maintain batteries.

B. Centralized vs Distributed Charging Management

In general, the on-the-move EV charging management can be executed in both centralized and distributed manners. With the centralized manner, the charging management is executed by a Global Controller (GC) or other third party who is interested in charging management. However, this arises much privacy concern, because the EV status information (e.g., location, trip destination and ID) needs to be reported to the GC. The distributed manner benefits from a low privacy sensitivity, where the charging management is executed by EV individually (using accessed condition information from CSs). Thus the accuracy of information plays an important role in the charging management. This is because that the CS-selection decisions made by EVs would be suboptimal, due to imperfect information acquired.

C. The Publish/Subscribe Communication Paradigm

The Publish/Subscribe (P/S) [5] paradigm, is a suitable communication paradigm for building applications in Vehicular Ad hoc NETworks (VANETs) with a highly dynamic and flexible nature, e.g., Delay Tolerant Networking (DTN) [11]. The following three network entities are involved:

- **Road Side Unit (RSU):** It is strategically deployed at a certain location, and behaves as broker to bridge the information flow from CSs to EVs. Each RSU is able to aggregate all CSs condition information and caches it in local storage.
- **Electric Vehicle (EV):** Each EV is with a Status Of Charge (SOC). The EV as subscriber, actively sends query to subscribe to the information relayed by RSUs. If the ratio between its current energy and maximum energy is below the value of SOC, EV starts to select a CS for the battery switch, based on its gathered information.
- **Charging Station (CS):** CSs need to be distributed in a different way, usually in special parking spots or near shopping malls. Each CS maintains a number of fully charged batteries to provide the battery switch service. As EVs arrive, the number of maintained (fully charged) batteries will decrease because of switch. These depleted batteries from EVs may have some residual electricity but have not been fully charged yet. Since each CS needs to charge depleted batteries, its maintained number of fully charged batteries will increase. It periodically publishes its condition information to legitimate RSUs.

In Fig. 1, each CS as publisher, publishes its condition information (i.e., availability of batteries for switch), to EVs as subscribers of this information. Along with this, strategically deployed RSUs can support information dissemination, through the V2I communication. The provisioning of P/S communication framework well fits the distributed charging management, where EVs could access CSs condition information from opportunistically encountered RSUs (within the RSUs cloud to share all CSs condition information), and make their individual charging managements when needed.

D. The Design of P/S Communication Framework For Battery Switch Service

All CSs are geographically deployed and their locations are pre-known by all EVs. Each CS is connected to all RSUs using reliable channel such as authorized cellular network

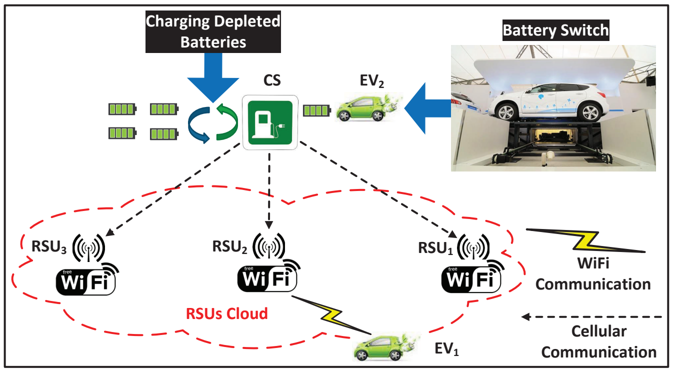

Fig. 1. Big picture where EVs access periodically published CSs information from RSUs, and further utilize collected information for CS-selections.

communication, and periodically publishes its condition information, e.g., the Available Time for Switch[1] (ATS). Given strategically deploying RSUs, there will not be an overlap between the radio coverage of adjacent RSUs. Such opportunistic communication between RSUs and EVs, inevitably results in an obsolete information accessed by EVs. The information exchange between CSs and EVs through RSUs is based on the P/S communication framework.

The communication in ITS enables the information broadcasting to involved entities. In the case of EV charging application, the "ETSI TS 101 556-1" [12] standard is brought. Its basic application is to notify EV drivers about the CSs condition information, such that they are able to select a CS for battery switch. Further to [10] enabling the plug-in charging technology, we enhance its communication framework with additional effort to enable the battery switch, with time sequences illustrated in Fig. 2:

- **Step 1:** All CSs information publications are synchronized. Each CS periodically publishes its ATS to RSUs, using the topic "ATS_Update" defined in TABLE I. Strategically deployed RSUs could aggregate information from multiple CSs and cache it. Note that once new condition information has been received from CSs, RSUs will replace the obsolete one cached in the past.
- **Steps 2-3:** Given an encounter opportunity with RSU, the EV being aware of updated service from that RSU, will send a subscription query[2] using the topic "Aggregated_ATS_Access". This normally requires a communication established from the EV to RSU, via a WiFi technology enabling V2I communication.

Compared to [10] via single topic for accessing CSs' queuing time, we bring two desiderated topics illustrated in TABLE I and enable computation at RSUs side. Here, the basic idea is by placing light-weight cloud-like facilities (e.g., RSUs) at the proximity of mobile users (e.g., EVs moving on the road), for authentication and reducing redundant information subscription. This is motivated by the recent trend of data services towards the edge of the cloud, resulting in novel architectures called "Fog computing" [13].

[1]This information reflects the status of those batteries being charged. For example, given that a CS initially maintains 10 batteries, as time passes the status that 7 batteries are switchable while 3 batteries are being charged, is published regarding the charging finish time (availabilities) of these 3 batteries being charged.

[2]It is worthy noting the subscription query received from EVs will be processed by RSUs, which only reply the aggregated CSs' ATS associated to the updated time slot. Such a way facilitates an efficient radio resource utilization and alleviated interference to EVs.

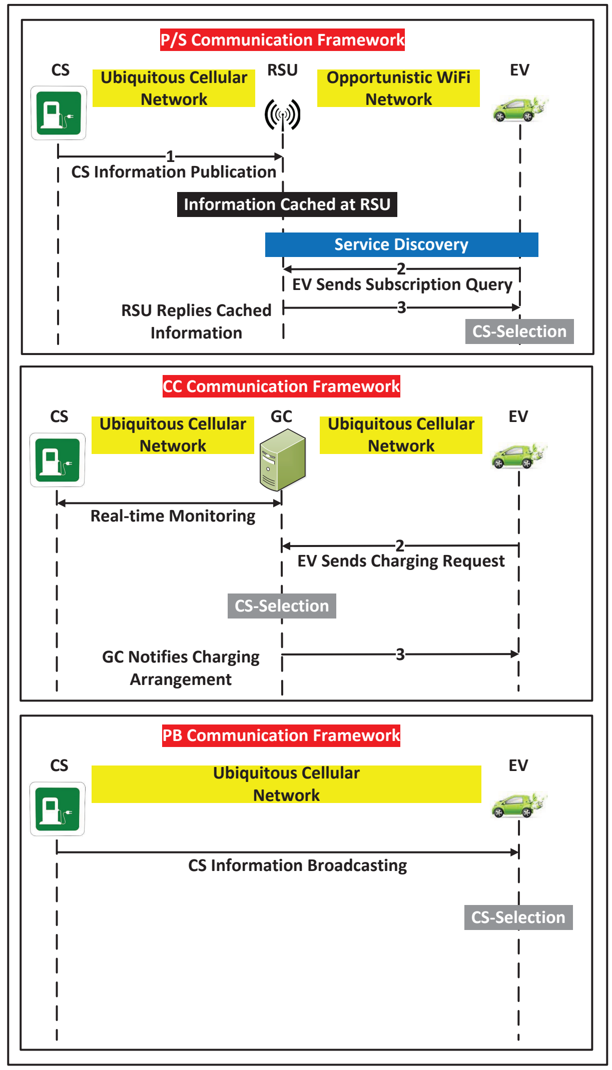

Fig. 2. Time sequences of P/S, CC and PB communication frameworks

E. Other Alternative Options

In Fig. 2, we also present other two alternative options that can support information dissemination in the system:

1) Centralized Case (CC): It has been widely adopted by majority of previous works. Throughout the cellular network communication, the GC globally monitors real-time CSs' ATS, and processes charging requests from on-the-move EVs.

2) Periodical Broadcasting (PB): This is a simple case where each CS periodically (with interval T) broadcasts its ATS to all EVs, also equivalent to the case where drivers use mobile phones to collect broadcasted CSs' ATS. The broadcasting is through the cellular network communication, and there is no RSU involved. Each EV can definitely access CSs' ATS within interval T, different from P/S affected by opportunistic encounters.

TABLE I
TOPICS DEFINED IN P/S SYSTEM

Topic	Dissemination Nature	Publisher(s)	Subscriber(s)	Payload
ATS_Update	One-to-Many	CS	RSUs	<CS ID & CS's ATS, Publication Time Slot>
Aggregated_ATS_Access	Many-to-Many	RSUs	EVs	<Aggregated CS IDs & CSs' ATS, Publication Time Slot>

F. Discussion on Communication Cost

1) Possibility to Access Information in P/S: In [10], the P/S communication enabling the plug-in charging service (with CS queuing time published) has been discussed. The fact that information is accessible depends on:

- Whether there is an encounter between the EV and RSU.
- Whether an RSU (encountered by EV) has cached the information published from CSs.

The analysis is based on straight road model, where an EV (with constant/average moving speed) will pass through a number of N_{rsu} RSUs. The possibility $P_{p/s}$ for an EV to access information from at the least one of N_{rsu} RSUs, is given by:

$$P_{p/s} \leq 1 - \prod_{i=1}^{N_{rsu}} \left\{ 1 - \left[\frac{(i-1)S + F + R}{V \cdot T} \right] \right\} \tag{1}$$

Where N_{rsu} is the number of RSUs on the road, S is the distance between adjacent RSUs, and T is the publication interval (how often the information is published) of CS. Besides, V is the EV moving speed, while F is the distance from the starting point to the center of the first RSU.

In order to increase $P_{p/s}$, we obtain:

- To increase radio coverage R.
- To increase the number of RSUs N_{rsu}.
- To reduce CS publication interval T (To increase CS publication frequency).

2) Communication Cost: Further to above, we herein denote N_{ev} as number of EVs in the network. Then the communication costs of P/S, CC, and PB are given:

- In P/S, the cost for information access is given by $O\left(\frac{P_{p/s} \times N_{rsu}}{T}\right)$, since there are only $\left(P_{p/s} \times N_{rsu}\right)$ subscribers within each T interval.
- In CC, the cost at GC side for handling EVs' charging requests is $O(N_{ev})$.
- In PB, each CS experiences a communication cost of $O\left(\frac{N_{ev}}{T}\right)$, for broadcasting its ATS to all EVs.

Different from the CC communication framework, we can obtain scalability (i.e., the number of connections at CS sides does not depend on the number of EVs, as referred to PB), as the benefits of P/S based communication against point-to-point communication.

IV. ON-THE-MOVE EV CHARGING MANAGEMENT VIA P/S COMMUNICATION FRAMEWORK

A. Urban Driving Uncertainties

1) Mobility Uncertainty: It refers to the situation that there are several traffic jams happen in a city. An EV within a certain range of traffic jam has to slow down its speed, and it will accelerate its speed once leaving from the range of that traffic jam. In particular, an EV may temporarily stop for a while, if it is close to the traffic central. In such case, an EV only resumes its movement once the closest traffic jam disappears. Due to the mobility uncertainty, the variation of EV moving speed will inevitably affect the arrival time at the CS, and the electricity consumption for travelling towards that CS. Further to this, the mobility uncertainty also affects the travelling time taken from a CS to EV's trip destination.

2) Trip Preference Uncertainty: It refers to the situation that, the EV drivers' intention on where to travel is uncertain. Here, EV drivers may have their daily routes or Point Of Interests (POIs) to visit, e.g., shopping malls or public parks for leisure. The trip preference uncertainty affects the CS-selection, where a suboptimal charging during journey may degrade drivers' comfort.

B. System Cycle of On-the-move EV Charging Management

Fig. 3 describes the system cycle of charging management:

- **Driving Phase:** The EV is travelling towards its trip destination. This phase is affected by both the mobility uncertainty and trip preference uncertainty.
- **Charging Planning Phase:** The EV reaching a threshold on its residual battery volume applies a policy to find a CS for the battery switch. Based on the locally recorded CSs condition information, the EV runs a CS-selection logic.
- **Battery Switch Phase:** Upon arrival at the selected CS with parking place navigated [14], the EV's battery (electricity consumed) is switched with the one (fully charged) maintained at that CS. This happens if the selected CS already maintains a number of fully charged batteries for switch. Particularly, if the number of fully charged batteries at CSs is less than the number of EVs already parking herein, the EV charging scheduling (concerning when to charge) is based on the First Come First Serve (FCFS) order. This means that the EV with an earlier arrival time will be scheduled with a higher charging priority.
- **Battery Charging Phase:** A number of batteries depleted from EVs will be charged by CSs in parallel. They will be switchable once being fully recharged. Note that the transition between **Battery Switch Phase** and **Battery Charging Phase** is bidirectional.

C. CS-Selection Logic

Note that, the EV might have received aggregated CSs condition information for several times, before it reaches the threshold for requesting the battery switch. The CS-selection logic is to find the CS through which the EV will experience the shortest trip duration, including:

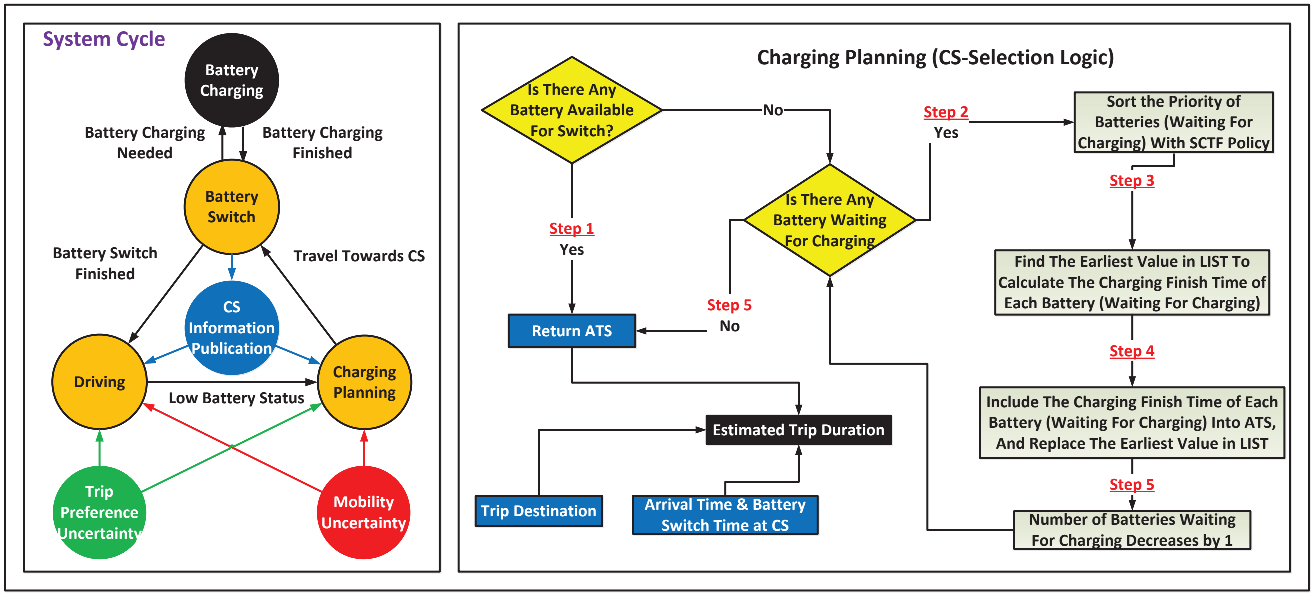

Fig. 3. System cycle of on-the-move EV charging management via battery switch

- Time to travel towards the selected CS.
- Time to travel from the selected CS to EV's trip destination.
- Time to spend staying at the selected CS.

The first two metrics can be computed directly, we introduce following steps to estimate the third metric:

- **Step 1:** Run at the CS side, it firstly checks the maintained number of fully charged batteries. If with an availability for switch, the ATS is returned without containing those batteries status. This means that the CS is currently able to provide the battery switch service.
- **Step 2:** Run at the CS side, alternatively, if it is currently without switchable batteries, it then checks the number of batteries waiting for charging. Here, those batteries waiting for charging are sorted following the Shortest Time Charge First (STCF) policy. This implies that the depleted battery with much remaining volume is charged with a higher priority.
- **Step 3:** Run at the CS side, only concerning those batteries already being charged, their charging finish time is included in a temporary list, namely LIST for computation purpose. Then the earliest time of LIST could be obtained, while all information in LIST is copied into ATS.
- **Step 4:** Run at the CS side, the output of LIST from Step 3 plus the charging time of each battery (waiting for charging) is calculated as the charging finish time of that battery, which is further included in ATS. Such value is also replaced with the earliest value in LIST.
- **Step 5:** Steps 2-4 are repeated, until the number of rest batteries (waiting for charging) reaches 0. Then an updated ATS is returned.

Note that if the EV arrival time is later than any value in ATS, this means it would not experience any delay for battery switch upon arrival at CS. Otherwise, the waiting time for battery switch is given by "The Earliest Value in ATS - Arrival Time".

V. Case Study

We have built up an entire system for EV charging in Opportunistic Network Environment [15]. In Fig. 4, the default scenario with 4500×3400 m^2 area is shown as the down town area of Helsinki city in Finland. 200 EVs with $[30 \sim 50]$ km/h variable moving speed are initialized in the network. The configuration of EVs follows the charging specification (maximum electricity capacity, max travelling distance: 16.4 kWh, 140 km) of Hyundai BlueOn EV[3], and we set SOC ranging from 15% to 45% for all EVs.

Each CS maintains 30 fully recharged batteries at the beginning of simulation, and can charge 20 depleted batteries from EVs in parallel, using 10 kW power. The battery switch time is fixed as 5 minutes. There are totally 5 CSs provided with sufficient electric energy for battery charging. Besides, 300m radio coverage is applied for 7 RSUs and 200 EVs. The default update interval (publication frequency) of CS is 120s, and the simulation time is 43200s = 12 hours.

The charging management scheme proposed in Section IV is evaluated under the P/S, CC and PB communication frameworks discussed in Section III. We are mainly interested in: **Average Charging Waiting Time** - The average period between the time an EV arrives at the selected CS and the time it finishes battery switch; **Average Trip Duration** - The average time that an EV experiences for its trip, through the battery switch service at an intermediate CS; **Number of Accesses** - Number of times that EVs access from CSs (through cellular network or RSUs).

[3]en.wikipedia.org/wiki/Hyundai BlueOn.

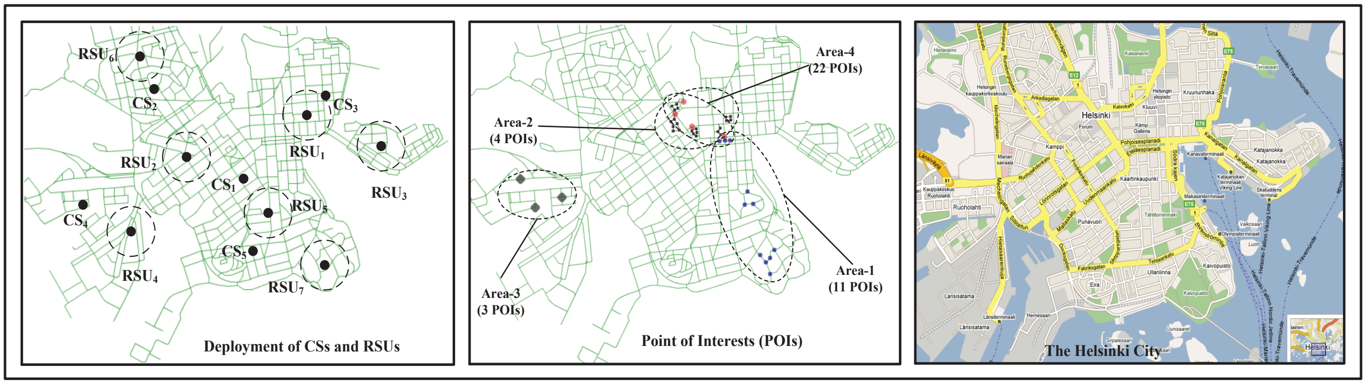

Fig. 4. Simulation scenario of Helsinki city (5 CSs, 7 RSUs, 200 EVs)

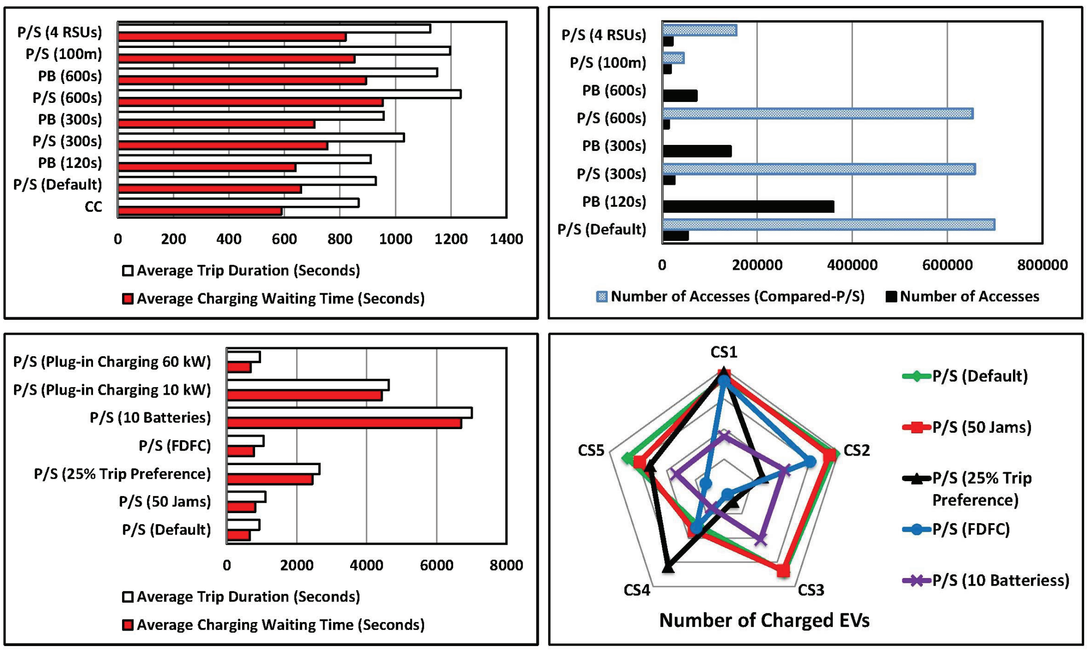

Fig. 5. Evaluation results of case study

A. *Influence of Communication Framework Provisioning*

Observation from Fig. 5 follows the analysis in Equation (1), where an infrequent CS publication (300s, 600s) degrades the charging performance. This is because the accuracy of ATS collected from CSs differs too much from the value when it is published, leading to suboptimal CS-selection. Besides, setting a smaller communication range (100m) and less number of RSUs (by removing RSU_1, RSU_2 and RSU_5) also degrade performance. This is because that EVs (far away from RSUs with certain distance) can not establish connections with RSUs, from which the ATS of CSs is less likely accessed.

Here, as decision making and information monitoring are simultaneous in CC, it is with the best charging performance, however with the concern on high privacy sensitivity. Besides, PB always outperforms P/S, however with an expense of higher number of accesses. By comparing the proposed P/S with [10], we observe a substantial improvement regarding number of accesses, thanks to the introduction of two dedicated topics involved in service discovery with RSUs.

B. *Influence of Urban Driving Uncertainties*

Envisioning for the mobility uncertainty, 50 randomly generated traffic jams happen for every 300s, while its range is 300m. Therefore, each EV will adjust its moving speed, if the distance between its location and a traffic jam is smaller than 300m. All traffic jams will last for 100s since generation. Obviously, with increased number of traffic jams in the city, the charging performance is inevitably degraded. This is due to that the uncertain arrival (due to speed reduction/stop) at CSs affects the accuracy of CS-selection.

Envisioning for the trip preference uncertainty, we assign four types of POIs, of which the distribution influences intention of EVs' trip destinations. By setting potential trip preference, the intention-driven CS-selection results in charging hotspots at those CSs around POIs (e.g., CS_1, CS_4, CS_5). Due to an increased number of EVs intend to switch batteries at these CSs, the average charging waiting time and trip duration are increased while the distribution of charged EVs among CSs changes. We observe that the mobility uncertainty does not remarkably result in charging hotspots, in sharp contrast to that under the trip preference uncertainty.

C. Influence of Charging System

Given the reduction of fully recharged batteries maintained at CSs, EVs have to wait for a longer time to get batteries switched and their total trip duration is increased. Besides, the performance becomes worse, if charging depleted batteries using the First Deplete First Charge (FDFC) rather than STCF policy. This implies the importance of providing a fast availability of switchable batteries.

Finally, the advantage of battery switch over plug-in charging technology is observed given 10 kW charging power. The former with 60 kW charging power can eventually achieve a close performance of the latter. This reflects a realistic concern, from which the battery switch system can alleviate the peak load in power grid, by running a lower charging power.

VI. Open Research Issues

A. Heterogeneity of EVs

There have been many EV manufacturers, and each type of EV may only be compatible with one or a few types of batteries. Assuming each CS maintains different types of batteries, it then publishes the integrated information about distinguished ATS (in relation to a certain type of battery). Besides, the underlying battery scheduling policy should adjust the availability of each type of battery, depending on demands from heterogeneous EVs..

B. Vehicle-to-Grid (V2G) Operation

The CSs providing battery switch services can operate either as an energy source when their maintained batteries are fully charged, or as an electrical load when the depleted batteries need to be charged. The residual electricity of depleted batteries from EVs could be sold back to grid. Instead, enabling the battery switch service in V2G operation, benefits both drivers and grid, because of short EVs' idle time at CS as well as flexibility of controlling those depleted batteries.

C. Business Model

Apart from strategically deploying CSs and V2G operation, the number of batteries to maintain at each CS should be decided, prior to knowing the future demand for batteries switch. Following our results, more batteries should be maintained at CSs which are in proximity to potential drivers' POIs. A dynamic pricing strategy to minimize congestion and maximize profit (by adjusting the switch price) is suggested.

D. Security

Malicious business may bombard an individual EV with unsolicited product or service, e.g., attracting drivers using manipulated CSs condition information. As such, security is required to maintain confidentiality, integrity and availability of information exchange between CSs and EVs. The credibility of CSs' ATS is required for the hazard-free decision of EVs. Thus, all messages must be digitally signed by CSs and later can be verified by EVs before making their CS-selection decisions.

VII. Conclusion

The effort towards green communication and charging system for EVs on-the-move has become important. Here, a cost efficient P/S communication framework enabling the battery switch service is provisioned to manage on-the-move EV charging, aiming to accelerate the charging process than traditional plug-in charging technology. Results of city-scale simulations demonstrate that a number of factors have the impact on the driving experience, through the battery switch services. Open research issues have also been discussed.

Acknowledgment

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BIOGRAPHIES

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