Towards Distributed Battery Switch Based Electro-Mobility Using Publish/Subscribe System

Yue Cao, *Member, IEEE*, Omprakash Kaiwartya, *Member, IEEE*, Chong Han, Kezhi Wang, *Member, IEEE*, Houbing Song, *Senior Member, IEEE* and Nauman Aslam, *Member, IEEE*

***Abstract*—With the growing popularization of Electric Vehicle (EVs), Electro-mobility (in terms of where to charge EV) has become an increasingly important research problem in smart cities. One of the major concerns is the anxiety of EVs, as drivers may suffer from discomfort due to long charging time. In this article, we leverage the battery switch technology to provide an even faster charging than plug-in charging service, by cycling switchable (fully-recharged) batteries at Charging Stations (CSs). Upon that, a cost-efficient Publish/Subscribe (P/S) system is provisioned, to facilitate the design of distributed charging manner for privacy guarantee. The proposed communication framework utilizes Mobile Edge Computing (MEC)-functioned Road Side Units (RSUs) to bridge, process and aggregate the information flow between CSs and EVs. We further design an advanced reservation based charging system, in which the knowledge of EVs' reservations is utilized to predict how likely a CS will be congested. This benefits to a smart transportation planning on where to charge, in order to improve charging comfort. Results show the advantage of our enabling technology comparing to other benchmark solutions, in terms of minimized waiting time for the battery switch (as the benefit for EV drivers), and a higher number of batteries switched (as the benefit for CSs).**

***Index Terms*—Electric Vehicle, Battery Switch, E-Mobility, Delay Tolerant Networks.**

I. Introduction

THE popularity of Electric Vehicles (EVs) [1] has been playing an increasingly important role in Electro-Mobility (E-Mobility). Due to short anxiety of EVs, how to explore the E-mobility to improve drivers' comfort, is a vital research issue for the success and long-term viability of the EV industry. Majority of previous works investigate "charging scheduling" [2] (concerning when/whether to charge EVs), while EVs have already been parked at homes/Charging Stations (CSs). In contrary, we focus on "CS-selection" (concerning where/which CS to charge) [3] when EVs are on-the-move, that has recently attracted attention thanks to the popularity of EVs. In order to improve the charging experience of EV drivers, one solution is to optimally deploy CSs at the places where there is high high EVs concentration, such as shopping mall parking places. Another complementary solution is to optimally manage where to charge, when EVs are with low energy status and need to seek CSs for charging.

Literature works [4]–[6] have addressed charging recommendation to improve the charging Quality of Experience (QoE), e.g., to reduce the service waiting time for charging. Usually, the local condition of CSs (e.g., number of EVs being parked and their remaining charging time) [6] is considered to make charging recommendation decision. Inevitably, only using the CS's local condition for CS-selection would bring potential charging hotspot, this mainly happens if many EVs head to the same CS for charging. In this context, the EV reservation [1], [7]–[9] initiated from EV, has been considered as an additional signalling delivered to the selected CS. Here, at what time and which CS will be heavily congested can be predicted, to avoid selecting that CS as the best charging plan.

From transport and energy aspect, even if EV drivers can benefit from the smart CS-selection to potentially experience a shorter charging service waiting time, the widely applied plug-in charging technology still requires a relatively longer duration to complete battery charging (typically, half to several hours [10]). In contrary, as a promising alternative approach, the battery switch service, has the potential to replace a fully charged battery for an EV just within several minutes (running with a lower charging power for green battery cycling), thanks to involved elaborate industrial automation robots to execute fast battery switch. There have been a few works [11]–[15] on either the energy scheduling, or deployment at the battery switch based CS, whereas [16] firstly integrates ICT with the system focusing on transportation aspect.

From Information Communication Technology (ICT) aspect, the CS-selection decision is generally made by Global Controller (GC) in a centralized manner. Here, the GC monitors CSs' condition seamlessly through cellular communications[1]. In comparison, the distributed system alleviates privacy concern, as the CS-selection is made by EV individually (based on their accessed condition information from CSs). In most of previous works [6], [9], [18], the cellular infrastructures are typically applied in the centralized manner, for the benefit of real-time optimization thanks to the good network coverage. Alternatively, a cost efficient solution is by the deployment of fixed Road Side Units (RSUs) [19], supported by licence-free WiFi but with limited network coverage. This supports the distributed charging manner, where RSUs (with functioned

Y.Cao; K.Wang (corresponding author) and N.Aslam are with the Department of Computer and Information Sciences, Northumbria University, UK. email: yue.cao; kezhi.wang; nauman.aslam@northumbria.ac.uk

O.Kaiwartya is with the School of Science and Technology, Nottingham Trent University, UK. email:omprakash.kaiwartya@ntu.ac.uk

C. Han is currently with pureLiFi Limited, UK, email: l: chong.han@purelifi.com

H.Song is with the Department of Electrical, Computer, Software, and Systems Engineering, Embry-Riddle Aeronautical University, USA email: h.song@ieee.org

[1]Concerning privacy issue [17] of hiding sensitive information of EV, e.g., ID, State of Charge (SOC) or location, the attacker may manipulate such information and degrade driver's charging experience. Concerning reliability, the entire charging system may be affected by the failure at the GC side.

light-weight edge computing, and authorized network entities) bridge information from power grid to EVs. In [1], we have proposed a distributed plug-in charging based CS-selection scheme, via Publish/Subscribe (P/S) [20] system. Therein, EVs subscribe to the CSs' condition information from RSUs, through Vehicle-to-Infrastructure (V2I) communication [21], [22].

The rapid growth of mobile applications have placed severe demands on cloud infrastructure, which has led to moving computing and data services towards the edge of the cloud, resulting in a novel Mobile Edge Computing (MEC) [23] (also known as fog computing) architecture. MEC could reduce data transfer times, remove potential performance bottlenecks, and increase data security and enhance privacy while enabling advanced applications. In spite that the battery switch technology has been investigated in the "charging scheduling" [24] from energy scheduling aspect, efforts towards distributed "CS-selection" from transportation planning aspect (with advanced reservation service and provisioning of cost-efficient ICT framework) have not been addressed in literature. Motivated by above, our two contributions are as follows:

Provisioning of Basic P/S Mode With Enhanced CS-selection: Our preliminary work [16] has brought the P/S system with RSU for battery switch service, study shows the advantage of that over traditional plug-in charging system for CS-selection. Here, we extensively present the detail design and analysis of battery switch based P/S system, with a fundamental study on how to achieve the best driving comfort, e.g., the minimum Expected Waiting Time to Switch (EWTS), through an enhanced CS-selection scheme over that in [16]. The CS with the minimum EWTS is selected by the EV which needs battery switch service.

Study of Advanced P/S Mode Enabling Reservation: Upon above, we further study the benefit to bring reservation service for CS-selection. This concerns that congestion may occur at CS side, if many EVs travel towards the same CS for charging in a near future. Here, those EVs which are travelling towards their selected CSs for charging, additionally send their reservations[2]. Such knowledge will be utilized to estimate whether a CS will be congested in a near future, in order to make optimal CS-selection to experience the minimum waiting time for battery switch service.

The EV reservation is aggregated by MEC functioned RSUs, in order to reduce communication signalling cost in the system (due to implementing necessary data transmission over more expensive wireless links, e.g., cellular network communication), that is bounded by the delay constraint of actual CSs publication. The EV mobility prediction is also taken into account for smart reservation uploading, through the cellular network as the back-up solution if no RSU is accessible along the route an EV traverses.

[2]The reservation includes when an EV is expected to arrive and how long its battery needs to get fully charged, is harvested by CSs for processing and future publication.

II. Related Work

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 [16], 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. 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 but 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 than plug-in charger), certainly removes that burden from EV drivers to maintain batteries.

B. CS-selection

In recent few years, the "charging recommendation" problem has started to gain interest from industrial thanks to the popularity of EVs. The generic solutions [6], [18] make decision based on the queueing information at CSs, and the one with the minimum queueing time is recommended. This feature has been evaluated in [4] against with the charging recommendation just taking the closest distance to CS, the former is deemed as an effective guidance in urban city with limited charging infrastructures.

Beyond that, the integration of ICT and energy network is of importance for the sustainability of EV charging, where a set of works have addressed the constraint of energy network and study its impact. From ICT aspect, additional communication signalling is built to support the advanced charging recommendation, to bring anticipated EVs mobility information (charing reservations). The work in [7] concerns a highway scenario where the EV will pass through all CSs. Other works [1], [8], [9] focus on urban city scenario, where the EV travels towards a single CS (which is geographically distributed in city) for charging. Inherently, the expected waiting time for charging is associated to that CS, rather than a subsequent charging in highway case.

C. Our Motivation

Further to our previous works [1], [8], [9] based on the plug-in charging system, we herein bring the battery switch service upon which the reservation service is designed to improve driving comfort. The proposed smart CS-selection would of course benefit from the distributed charging manner for privacy guarantee. Also, a cost-efficient P/S system with delay-tolerant (bounded by the time slot of subsequent CS publication) and opportunistic (due to the encounter between EV and RSU, via wireless communication) reservation uploading is proposed for performance optimization.

TABLE I
TOPICS DEFINED IN BASIC P/S MODE

Topic	Dissemination Nature	Publisher(s)	Subscriber(s)	Payload
CS_Condition_Update	One-to-Many	CS	RSUs	<CS ID & CS's ATS, N_B, Publication Time Slot>
Cached_CSs'_Condition_Access	Many-to-Many	RSUs	EVs	<All Cached CS IDs & CSs' ATS, N_B, Publication Time Slot>

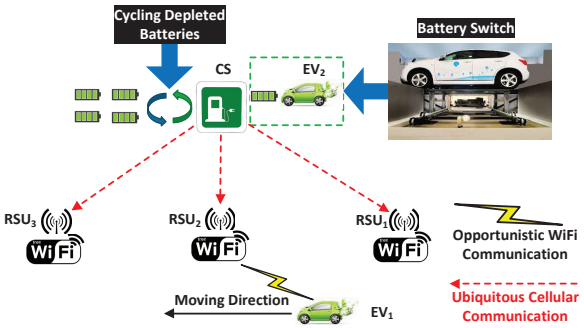


Fig. 1. Big Picture of Network Entities And Scenario

III. SYSTEM MODEL

A. Basic P/S Mode

In our proposed system, the locations of CSs are known by all EVs in advance, this is achievable through vehicle On-Board Unit (OBU) system. Each CS is connected to all RSUs using authorized cellular network communication (3G/LTE), publishes its Available Time for Switch[3] (ATS) and number of switchable batteries N_B (how many fully charged batteries are ready for switch) periodically. How frequent these are published, depends on a system-level control strategy. Here a tight interval implies the requirement for peak hour charging demand, and vice versa.

Concerning the practical infrastructure deployment strategy, there will not be an overlap between the radio coverage of adjacent RSUs. This inevitably results in an obsolete[4] information accessed by EVs, due to the missed encounter with RSUs.

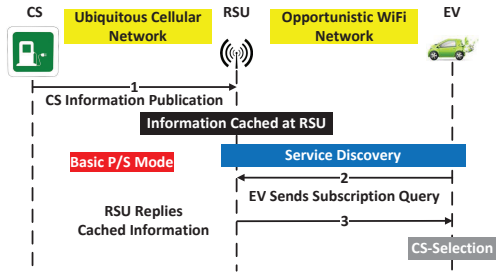


Fig. 2. Time Sequences of Basic P/S Mode

[3]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.

[4]This happens when RSU has cached the information published at 12:00 AM and accessed by EV, but later an EV has never traversed RSU before 12:30 AM. Therefore, that EV (to make CS-selection decision at 12:30) will use the knowledge it accessed at 12:00 AM.

The communication in Intelligent Transportation Systems (ITS) enables the information broadcasting to involved entities. Here, the basic application of "ETSI TS 101 556-1" [25] standard is to notify EV drivers about the CSs condition information, which is to be used for selecting a CS for battery switch. Further to [1] which focuses on the plug-in charging technology, we herein enhance this communication framework with additional effort to reduce communication cost and bring it to the battery switch service. The time sequences are illustrated in Fig. 2:

- **Step 1:** All CSs' condition publications are synchronized. Each CS periodically (with interval T) publishes its condition information (including ATS and N_B) to RSUs, using the topic "*CS_Condition_Update*" defined in TABLE I. This refers to a "One-to-Many" nature, as each CS's publication is cached at all RSUs. In the meanwhile, RSUs will merge information from multiple CSs and cache it. RSUs will also replace the obsolete one cached in the past, when they have received the publications from CSs released in a new interval.
- **Steps 2-3:** When encountering with RSU, the EV being aware of updated service from that RSU, will send a subscription query[5] using the topic "*Cached_CS_Condition_Access*". This is generally based on V2I communication initiated from the EV to RSU, via a short range WiFi technology. This refers to a "Many-to-Many" nature as EVs opportunistically access information from RSUs, and there is no need for EV to perform a periodical subscription particularly when there is no RSU in proximity.

Note that the communication between EVs and RSUs is event driven, that is triggered by EV's subscription. All related information will be included using a specific topic, unambiguous information, e.g., not used in EV battery switch application will not be accessed using topics defined in TABLE I.

Compared to [1] via single topic for accessing CSs' queueing time, two desiderated topics illustrated in TABLE I are used in Basic P/S Mode to enable computation at RSUs side. This is motivated by shifting the data services towards the network edges which are closer to EV drivers, known as MEC [23] which is deemed for increasing data security while reducing information access times. If using single topic for publication, there is no information merged at RSUs. In that case, an EV needs to use different subscription topic (associated to a CS) to access all CSs information from

[5]Upon receiving the subscription queries from EVs, RSUs only reply the aggregated CSs' ATS associated to the updated time slot. If both pairwise EV and RSU currently maintain the aggregated CSs' ATS associated to the same publication time slot, the RSU will deny the EV's subscription request. This network intelligence benefits to an efficient radio resource utilization and alleviates communication interference with multiple EVs.

RSU, particularly when CS is owned by different stakeholders. In comparison, in the MEC based system, all merged CSs information at RSUs can be subscribed by an EV using a unique topic. Each RSU can further verify the information of CSs and selected authorized one for caching, meanwhile check the time slot involved in the EV subscription.

1) Other Alternative Modes: We also present two alternative modes that can support information dissemination, namely, **Centralized Mode** and **Periodical Broadcasting (PB) Mode**.

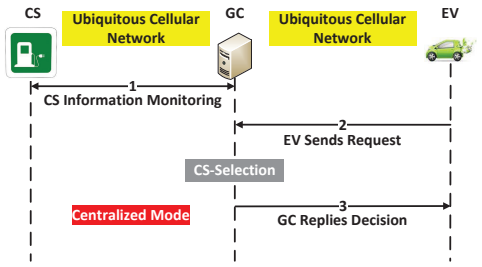


Fig. 3. Time Sequences of Centralized Mode

Centralized Mode is widely adopted by majority of previous works. As shown in Fig. 3, the GC monitors CSs' condition through cellular network, and processes charging requests from on-the-move EVs. The CS-selection decision is solely implemented by the GC in a centralized manner.

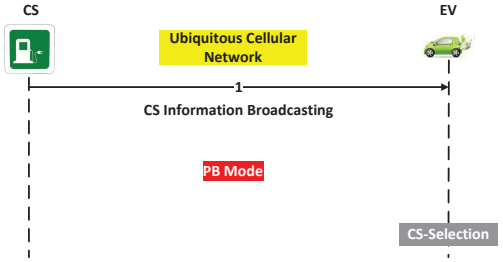


Fig. 4. Time Sequences of PB Mode

PB Mode is the case where each CS periodically (with interval T) broadcasts its condition information to all EVs. Particularly, this mode is also similar to a cloud system where CSs publish information to a cloud connecting all RSUs, from which users would access through cellular network link. As shown in Fig. 4, since there is no RSU involved, the communication between CSs and EVs is based on the cellular network communication. In this context, each EV can definitely access CSs' condition information within T, different from **Basic P/S Mode** affected by opportunistic encounters.

2) Possibility to Access Information in Basic P/S Mode: The P/S system has been proposed in [1] for the plug-in charging service (with CS queuing time published). The possibility that an EV can access CSs' condition information from RSUs depends on:

- If an encounter between EV and RSU happens.
- If the RSU (encountered by EV) has cached the information published from CSs.

The possibility $P_{p/s}$ for an EV to access information from at the least one (or more than one) of N_{rsu} RSUs along road, has been given by:

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

Here, V is the distance between adjacent RSUs along the road, T is the CS's publication interval, and R stands for a valid communication range between EV and RSU. Note that, R depends on the transmission power and other practical configurations at EV side, as it is the initiator to establish communication with RSU for information subscription. Besides, S is the EV moving speed (we assume as a constant speed, where the influence of dynamic traffic on moving speed will be of interest for further study), while $F \geq R$ is the distance from the starting point to the center of first RSU.

In spite that the above analysis is modeled on a straight road where an EV will pass through a number of deployed RSUs with equal distance, the features of the proposed ICT system are certainly also applicable under a complex/realistic city scenario. Under city scenario, the distance between any adjacent RSUs is not straight road based and not equal, while EV moving speed is not constant. Just take a simple example, even if there is the path with a number of RSUs deployed for EV to pass, the actual distance the EV from one RSU to another RSU, can be mapped from nonlinear path to a straight road. That is to say, the model represents a wide application.

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

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

3) Communication Cost: Concerning the scalability of communication system, we denote N_{ev} as number of EVs in the network, and discuss the communication costs of **Basic P/S Mode**, **Centralized Mode**, and **PB Mode** as follows:

- In **Basic P/S Mode**, the cost for N_{ev} EVs to access CS' condition is given by $O\left(\frac{P_{p/s} \times N_{ev}}{T}\right)$. This is because there are $\left(P_{p/s} \times N_{ev}\right)$ subscriptions sent from EVs within each T interval.
- In **Centralized Mode**, the cost at GC side for handling EVs' charging requests is $O(N_{ev})$, and is linearly increased by EVs density.
- In **PB Mode**, each CS broadcasts its condition information to all N_{ev} EVs, within in interval T. Therefore, the communication cost is bounded by $O\left(\frac{N_{ev}}{T}\right)$.

Due to decoupling between CSs (publishers) and EVs (subscribers), the end-to-end connections between CSs and EVs in the **Basic P/S Mode** and **PB Mode** are avoided. Different from the **Centralized Mode**, the system can benefit from scalability (i.e., the number of connections at CS side is not linked to the number of EVs, as referred to **Basic P/S Mode**).

4) Privacy and Security Concern: The distributed manner (**Basic P/S Mode** and **PB Mode**) does not need to release any information from EV side, due to the local computation on CS-selection. However, the **Centralized Mode** is privacy sensitive, where EV's ID, location will be required by the GC.

The solutions to achieve trusted message exchange for EV charging use case is to encrypt the sensitive information and hide the real identity. One development aspect of the encryption involves the light-weight and highly secured encryption algorithm, while another one is to design an efficient and scalable key management scheme. As for the privacy side, pseudonym is proposed to hide the identities. This including the pseudonym changing algorithms and pseudonym reuse schemes, both are required to be implemented in efficient and scalable manners.

B. Battery Switch Based Charging Management Cycle

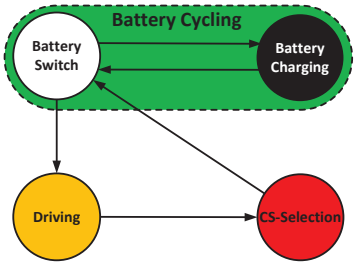


Fig. 5. System Cycle of EV Battery Switch

Fig. 5 presents four phases of the battery switch system:

- **Driving Phase:** The EV is moving on the road during driving phase.
- **CS-selection Phase:** The EV with its battery volume below the SOC threshold, starts to find a CS for the battery switch. Here, based on the CSs' condition information accessed through the P/S system, the EV implements CS-selection decision.
- **Battery Cycling Phase:**
  - **Battery Switch Phase:** When reaching the selected CS, the EV's own battery (electricity consumed) is depleted, while EV is switched with a battery (which has been fully charged) by CS. Initially, the CS would have sufficient (fully charged) batteries to switch for incoming EVs, whereas the service waiting time is only due to the actual battery switch time (several minutes). However, with the fully charged batteries been switched from CS and consumed batteries from EVs been depleted, if the number of fully charged batteries at CSs is less than the number of EVs currently been parked, the charging scheduling (concerning when/whether to charge those depleted batteries) is based on the First Come First Serve (FCFS) order. This regulates that the EV with an earlier arrival time will be scheduled with a higher charging priority.
  - **Battery Charging Phase:** Those batteries depleted from EVs will be charged by CSs in parallel (depending on the number of charging slots), and they become switchable once been fully recharged. Note that the transition between **Battery Switch Phase** and **Battery Charging Phase** is bidirectional.

TABLE II
LIST OF NOMENCLATURES

γ	System resolution
N_B	Number of switchable batteries at CS
N_D	Number of batteries depleted from incoming EVs
$T_{\mathcal{B}}^{sw}$	Time to switch a battery
N_C	Number of batteries being charged
N_W	Number of EVs waiting for battery switch
δ	Number of charging slots at CS
β	Charging power at CS
$E_{\mathcal{B}}^{max}$	Full volume of EV battery
$E_{\mathcal{B}}^{cur}$	Current volume of EV battery
ATSLIST	Output list about ATS
$T_{\mathcal{B}}^{fin}$	Charging finish time of EV battery
N_B^E	Expected number of switchable batteries at CS
T_{ev}^{arr}	EV's arrival time at CS
T_{ev}^{tra}	Time for EV to travel towards a CS
T_{cur}	Current time in network
N_R	Number of EVs made reservations

C. Battery Cycling

Algorithm 1 Battery Cycling at CS

1: **for** each EV parked at CS **do**
2: **if** $(N_B > 0)$ **then**
3: start to switch a battery for EV
4: **else**
5: wait until a battery becomes switchable
6: **end if**
7: **if** a fully recharged battery is switched, with duration $T_{\mathcal{B}}^{sw}$ **then**
8: $N_B = N_B - 1$
9: include depleted battery from EV into the queue of N_D
10: **end if**
11: **end for**
12: **for** each interval γ **do**
13: **while** $(N_C < \delta)$ **do**
14: sort the queue of N_W according to STCF
15: schedule a depleted battery from the queue of N_D
16: **end while**
17: **for** $(i = 1; i \leq N_C; i++)$ **do**
18: **while** $\left(E_{\mathcal{B}_{(i)}}^{cur} < E_{\mathcal{B}_{(i)}}^{max}\right)$ **do**
19: $E_{\mathcal{B}_{(i)}}^{cur} = E_{\mathcal{B}_{(i)}}^{cur} + \beta \times \gamma$
20: **end while**
21: remove this battery from the queue of N_D
22: $N_B = N_B + 1$
23: **end for**
24: **end for**

Throughout the battery switch system, we denote as N_D the number of batteries depleted from EVs, and as N_C the number of batteries being charged by the CS. Upon arrival at a CS, the incoming EVs that need battery switch services are managed as follows:

- If there are switchable batteries at the CS, given by the condition $(N_B > 0)$ at line 2 in Algorithm 1, the EV will be directly switched with a fully charged battery.
- Alternatively, presented between lines 4 and 5, the EV has to wait until the recharging of a battery is finished. This is because there has not been any switchable (fully charged) battery available at the CS.

We herein denote as $T_{\mathcal{B}}^{sw}$ the time to switch a battery (normally takes several minutes). Here, the number of switchable batteries N_B decreases by 1, after the period of $T_{\mathcal{B}}^{sw}$ for switch operation. Meanwhile, the depleted battery from EV

will be included into the queue of N_D (the queue of number of batteries waiting to be charged). This refers to the operations between lines 8 and 9.

Note that each CS is with δ charging slots, meaning that at most δ depleted batteries can be charged in parallel. Here, depleted batteries are sorted following the Shortest Charging Time First (SCTF) order, meaning the depleted battery with the earliest time to be fully charged, is with the highest priority for charging. Note that the way to cycle batteries has been studied in [16], therein the SCTF provides the best performance. A depleted battery will be scheduled from the queue of N_D into the queue of N_C, only if $(N_C < \delta)$ as presented at line 15. This happens when there is still at least one available charging slot could be utilized for battery charging.

From line 18, for each battery in the queue of N_C, it will be charged with $(\beta \times \gamma)$ electricity per time interval γ. If a battery is fully recharged given by the condition $\left(E^{cur}_{\mathcal{B}_{(i)}} = E^{max}_{\mathcal{B}_{(i)}}\right)$, N_B increases by 1 since a fully charged battery is switchable. Then, the information regarding this given battery is removed from the queue of N_D, at line 21.

IV. CS-Selection in Basic P/S Mode

Here, the CS-selection is based on local condition information of CSs (as published to RSUs and further accessed by opportunistically encountered EVs). Algorithm 2 details the logic to generate the ATS, upon which Algorithm 3 gives the CS-selection based on the EWTS.

A. Generation of Available Time for Switch

Algorithm 2 Generation of ATS

1: **for** $(i = 1; i \leq N_C; i++)$ **do**
2: add $\left(\frac{E^{max}_{\mathcal{B}_{(i)}} - E^{cur}_{\mathcal{B}_{(i)}}}{\beta} + T_{cur}\right)$ into ATSLIST
3: add $\left(\frac{E^{max}_{\mathcal{B}_{(i)}} - E^{cur}_{\mathcal{B}_{(i)}}}{\beta} + T_{cur}\right)$ into TLIST
4: **end for**
5: sort ATSLIST with ascending order
6: **if** no battery is waiting for charging **then**
7: **return** ATSLIST
8: **else**
9: sort the queue of N_W according to STCF
10: **for** $(j = 1; j \leq N_D; j++)$ **do**
11: sort TLIST with ascending order
12: $T^{fin}_{\mathcal{B}_{(j)}} = \left(\text{TLIST}_1 + \frac{E^{max}_{\mathcal{B}_{(j)}} - E^{cur}_{\mathcal{B}_{(j)}}}{\beta}\right)$
13: replace TLIST_1 with $T^{fin}_{\mathcal{B}_{(j)}}$
14: add $T^{fin}_{\mathcal{B}_{(j)}}$ into ATSLIST
15: **end for**
16: **return** ATSLIST
17: **end if**

Algorithm 2 starts from processing each battery (in the queue of N_C), where the time duration $\left(\frac{E^{max}_{\mathcal{B}_{(i)}} - E^{cur}_{\mathcal{B}_{(i)}}}{\beta}\right)$ to fully recharge a battery, will be summated with T_{cur}. This calculates the charging finish time of battery, and it is included into ATSLIST and TLIST (for temporary computation purpose).

By checking the status of above batteries being charging, Algorithm 2 will return the ATSLIST, if there is no additional batteries waiting to be charged (the condition at line 6), or upon checking those batteries to be scheduled for charging thorough a loop operation (between lines 10 and 16).

In the latter case, the loop operation firstly sorts the queue of N_D, following the SCTF charging scheduling order. Meanwhile, the TLIST containing elements about the charging finish time of those batteries (in the queue of N_C), is initialized with an ascending order. This means the earliest time to finish charging a battery is placed as the first element in TLIST, denoted by TLIST_1.

Within each loop, the time $T^{fin}_{\mathcal{B}_{(j)}}$ to finish charging of a battery (in the queue of N_D) will replace with TLIST_1. At line 12, $T^{fin}_{\mathcal{B}_{(j)}}$ is given by the summation of time to start charging (the TLIST_1), and battery charging time given by $\left(\frac{E^{max}_{\mathcal{B}_{(j)}} - E^{cur}_{\mathcal{B}_{(j)}}}{\beta}\right)$. Furthermore, $T^{fin}_{\mathcal{B}_{(j)}}$ will be included into ATSLIST. The loop operation will process all batteries (in the queue of N_D), then the ATSLIST is returned.

B. CS-Selection Based on EWTS

We introduce the following notations to facilitate problem formulation for fundamental CS-selection:

- $\gamma_{l_{cs}}$: Number of EVs currently being parked at a CS, with location l_{cs}.
- $\omega_{l_{cs}}$: Average time for each EV to wait for the battery switch (not included the time to switch battery $T^{sw}_{\mathcal{B}}$).
- $\mathcal{W}$: Total battery switch waiting time for all EVs in network.

Here, note that $\gamma_{l_{cs}}$ is a function of N_{cs}, as the number of CSs in network. This is because that a larger number of N_{cs} drives a small $\gamma_{l_{cs}}$ EVs distributed at each CS. Furthermore, $\omega_{l_{cs}}$ is related to $\gamma_{l_{cs}}, \delta$ and β. Given a number of switchable batteries N_B, we aim to minimize $\mathcal{W}$:

$$\mathcal{W} = \begin{cases} \sum_{l_{cs} \in N_{cs}} \left(\gamma_{l_{cs}} \times \left(\omega_{l_{cs}} + T^{sw}_{\mathcal{B}}\right)\right) & \text{if } (N_B < \gamma_{l_{cs}}) \\ \sum_{l_{cs} \in N_{cs}} \left(\gamma_{l_{cs}} \times \left(0 + T^{sw}_{\mathcal{B}}\right)\right) & \text{otherwise} \end{cases} \quad (2)$$

- The first sub-condition implies that a potential charging congestion would happen if larger number of $\gamma_{l_{cs}}$ EVs intend to charge at a CS, this inevitably increases their average battery switch waiting time at CS. Of course, applying fast charging power β and deploying more charging slots δ benefit to reduced waiting time.
- The second sub-condition implies that $\omega_{l_{cs}}$ tends to 0, when each CS maintains sufficient number of switchable batteries, given by $(N_B \geq \gamma_{l_{cs}})$.

In order to achieve the minimum EVs' battery switch waiting time among N_{cs} CSs, $(\gamma_{l_{cs}} \times (\omega_{l_{cs}} + T^{sw}_{\mathcal{B}}))$ should be equal among all CSs, as ideal situation given in [7], [9]. Since all CSs are assumed to share the same β and δ for simplicity[6], we obtain $\gamma_{l_{cs}} = \mathcal{F}(\frac{1}{N_{cs}})$, and $\omega_{l_{cs}} = \mathcal{F}(\frac{\gamma_{l_{cs}}}{\delta \times \beta})$ to achieve the minimum $\mathcal{W}$. Also, enabling a large N_B is an alternative to minimize $\mathcal{W}$.

[6]Practically thinking, there have been many EV manufacturers in market and each type of EV may not be compatible with batteries used by other types of EVs. This realistic concern requires further efforts on cycling batteries, such that different type of EVs can experience a fast battery switch without waiting for their compatible batteries. Meanwhile, the way to estimate the availability compatible batteries should also be taken into account.

In this context, the CS with the highest number of available batteries for switch, is selected with the highest priority, in order to hold the second sub-condition. In case that all CSs have run out of batteries for switch, the CS through which an EV experiences the minimum time to wait for the battery switch is selected.

Algorithm 3 Estimation of EWTS in Basic P/S Mode

1: **for** $(j = 1; j \leq |\text{ATSLIST}|; j++)$ **do**
2: **if** $\left(T^{fin}_{\mathcal{B}_{(j)}} < T^{arr}_{ev_{(r)}}\right)$ **then**
3: $N_B = N_B + 1$
4: **end if**
5: **end for**
6: **if** $(N_B > 0)$ **then**
7: **return** EWTS $= T^{sw}_{\mathcal{B}}/N_B$
8: **else**
9: **return** EWTS $= \text{ATSLIST}_1 - T^{arr}_{ev_{(r)}} + T^{sw}_{\mathcal{B}}$
10: **end if**

Our proposed CS-selection scheme is detailed as follows. In Algorithm 3, the arrival time of EV_r as $T^{arr}_{ev_{(r)}}$, will be compared with the charging finish time $T^{sw}_{\mathcal{B}_{(j)}}$ in ATSLIST. If $T^{fin}_{\mathcal{B}_{(j)}}$ is earlier than $T^{arr}_{ev_{(r)}}$ happens at line 2, one more battery will be switchable upon the arrival of EV_r, with N_B increases by 1.

- If $(N_B > 0)$ happens at line 6, $T^{sw}_{\mathcal{B}}/N_B$ is returned at line 7. This is because a battery will be available upon the arrival of EV_r.
- Otherwise, the EWTS is given by $\left(\text{ATSLIST}_1 - T^{arr}_{ev_{(r)}} + T^{sw}_{\mathcal{B}}\right)$ at line 9, where $\left(\text{ATSLIST}_1 - T^{arr}_{ev_{(r)}}\right)$ is the time to wait until a fully recharged battery is switchable. Note that ATSLIST_1 is the value with the earliest switchable time in the ATSLIST.

C. Performance Evaluation

1) Simulation Configurations: We have built up an EV charging system in Opportunistic Network Environment (ONE) [26]. In Fig. 8, the scenario with 4500×3400 m^2 area is shown as the down town area of Helsinki city in Finland.

There are 300 EVs with $[30 \sim 50]$ km/h variable moving speed placed in the simulation. The setting of EVs associates to the charging specification (Maximum Electricity Capacity, Max Travelling Distance: 16.4 kWh, 140 km) of Hyundai BlueOn EV[7]. We configure a distribution of State Of Charge (SOC), ranging from 15% to 45% for all EVs. The actual route of EV is formed based on the shortest path feature, considering a practical mobility pattern. Here, the shortest path towards a CS is formed considering the Helsinki road topology.

There are totally 5 CSs deployed with sufficient electric energy for battery charging, where the suggested battery switch time is given as 5 minutes. Each CS maintains $N_B = 30$ batteries (which are fully recharged) from beginning, and is able to charge $\delta = 30$ batteries (which are depleted from EVs) in parallel, based on $\beta = 10$ kW low charging power. Referring to [16], EVs would need to wait for additional time for battery switch, and thus the impact of $P_{p/s}$ can be examined. There are 7 RSUs and 300 EVs in network, based on 300m radio coverage for communication pattern. The default information dissemination interval (CSs publication frequency) of CS is $T = 120$s, and the simulation time is 43200s = 12 hours.

Fig. 8. Simulation Scenario of Helsinki City

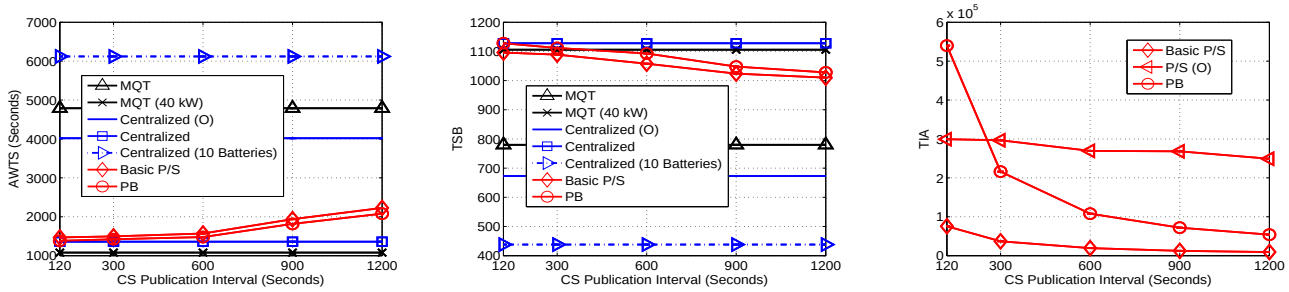
The following metrics are evaluated:

- **Average Waiting Time for Switch (AWTS)**: The average period between the time an EV arrives at the selected CS and the time it finishes battery switch. This is the charging performance metric at EV side.
- **Total Switched Batteries (TSB)**: The total number of EVs have been switched with batteries at CSs. This is the charging performance metric at CS side.
- **Total Information Accesses (TIA)**: The total number of accesses at EV side, in terms of communication cost.

It is worthy noting that key advantage of battery switch system over plug-in charging system has been presented in [16]. We herein focus on the advantage of the proposed CS-selection scheme, with those based on the centralized Minimum Queueing Time (MQT) under plug-in charging technology [6], and the centralized scheme based on battery switch [16] namely **Centralized (O)** which does not consider the switchable batteries. Upon that, the influence of **Basic P/S Mode**, **Centralized Mode** and **PB Mode** based on the proposed scheme in Section III are evaluated.

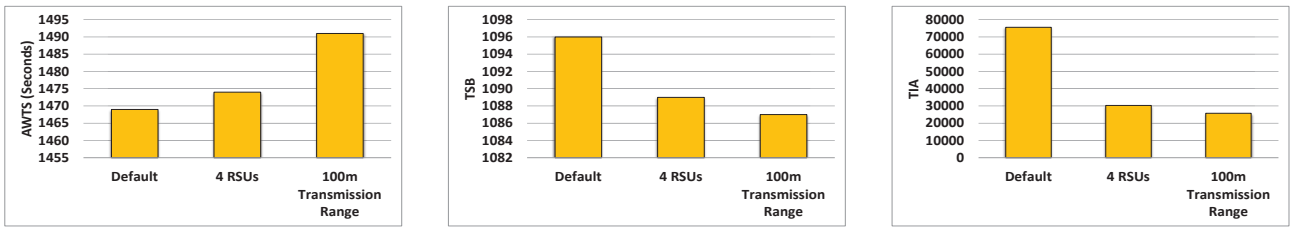
2) Influence of CS Publication Interval: Firstly, we compare the fundamental performance of all CS-selection schemes implemented in centralized manner. In Fig. 6(a), we observe the MQT (with 40 kW charging power in plug-in charging system) just achieves a close performance of that under the battery switch service (with 10 kW charging power). This implies the advantage of cycling switchable batteries for fast charging service, over that plug-in charging system. From realistic concern, the battery switch system can alleviate the peak load in power grid, by running a lower charging power. Of course, a decrease from 30 to 10 batteries initialized at each CS, inevitably degrades AWTS and TSB. This is because EVs will need to wait for much longer time to get batteries switched. By comparing with the Centralized (O) [16], the

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



(a) AWTS (b) TSB (c) TIA

Fig. 6. Influence of CS Publication Interval



(a) AWTS (b) TSB (c) TIA

Fig. 7. Influence of RSUs Deployment and Transmission Range

proposed CS-selection scheme (Centralized Mode) achieves noticeable improvement, by considering average service intensity.

Secondly, we observe the influence of CS publication interval T. Both Basic P/S Mode and PB Mode benefit from frequent CS publication interval (120s). This follows the discussion on access possibility, where a higher $P_{p/s}$ implies CSs' condition information can be accessed timely. As such, the minimized AWTS can be achieved by distributed manner (Basic P/S Mode and PB Mode), compared to the Centralized Mode. Due to the same reason, the TSB is increased in Fig. 6(b) because more EVs can experience fast battery switch services. In Fig. 6(c), we observe the PB Mode involves much communication costs (with frequent CS publication), which is inefficient compared to the Basic P/S Mode (concerning their close AWTS and TSB). Besides, the P/S system without MEC-functioned RSU is evaluated as P/S (O), which suffers from much higher communication cost. This is mainly due to the lack of mechanism to deny redundant subscription.

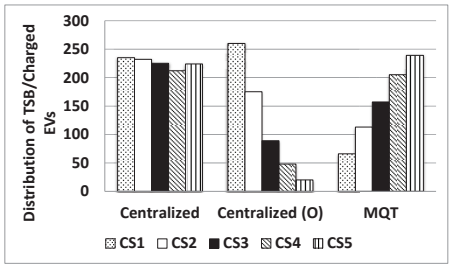


Fig. 9. Distribution of TSB at CSs

Fig. 9 further shows the distribution of TSB (charged EVs in case of MQT) among CSs, in case of centralized manner to examine the feature of compared CS-selection schemes. Noticeably, the proposed scheme achieves the best balance, by jointly considering the AWTS and TSB.

3) Influence of RSUs Deployment and Transmission Range: Results in Fig. 7(a), Fig. 7(b), Fig. 7(c) show that, either decreased RSUs density (by excluding RSU_1, RSU_2 and RSU_5) or shorter transmission range also degrades performance because of decreased $P_{p/s}$. This is mainly because that EVs will have less chance to communicate with encountered RSUs and thus fail to subscribe to the most latest CSs status information for making CS-selection.

V. Advanced P/S Mode Enabling Reservation

In previous section, we have proposed a distributed CS-selection under the **Basic P/S Mode**. Nevertheless, that decision making only considers the local condition of CSs (ATS and N_B), not with the capability to predict congestion level of CSs in a near future. Although sharing the general battery switch framework in Fig. 5, the **Advanced P/S Mode** integrates EVs' reservations (including at what time EV would reach its selected CS, and how long it will take to charge its depleted battery) into the CS-selection. Here, the reservation from EVs (those have selected where to charge), will be bridged by RSUs (with MEC functioned information aggregation and mining) to their selected CSs. As summarized in Algorithm 4, the EV needs battery switch service will keep track of those switchable batteries, those being charged locally at a CS (already considered in **Basic P/S Mode**), and other EVs with an earlier arrival time to reserve charging at this CS.

In summary, the MEC functions positioned at RSUs, mainly operate:

- Prevent redundant transmission from RSU to EV, at the stage when EV subscribes to information, covered in **Basic P/S Mode**.

TABLE III
TOPICS DEFINED FOR RESERVATION

Topic	Dissemination Nature	Publisher(s)	Subscriber(s)	Payload
EV_Reservation_Upload	One-to-Any (One)	EV which has selected CS	Any encountered RSU (selected CS)	<Reservation defined in TABLE V>
Aggregated_EVs'_Reservations_Upload	Many-to-One	RSUs	CS selected by common EVs	<Aggregated reservations defined in TABLE V>

- Analyse collected EVs' reservation, and identify only the valid information, covered in **Advanced P/S Mode**.
- Aggregate valid EVs' reservations and report to CS once (over the case the RSU relays per EV reservation to CS upon an encounter with an EV), covered in **Advanced P/S Mode**.

A. Signallings of Advanced P/S Mode

TABLE IV
FORMAT OF CS PUBLICATION IN ADVANCED P/S MODE

—CS ID—		
CS_1		
—Number of Switchable Batteries—		
$N_B = 7$		
—Available Time For Switch—		
ATS = [1000s, 1400s, 1900]		
—Anonymous EVs' Reservations—		
Entry	Arrival Time	Expected Charging Time of Depleted Battery
1	3500s	730s
2	4700s	700s

Regarding the practicality consideration, the "ETSI TS 101 556-1: Electric Vehicle Charging Spot Notification Specification" [25] and the "ETSI TS 101 556-3: Communications System for the Planning and Reservation of EV Energy Supply Using Wireless Networks" [27] can potentially support the reservation based battery switch service. In Fig. 10, signallings are listed:

- **Steps 1-3:** An EV accesses CSs' publications (given in TABLE IV) from encountered RSUs, following the same procedure in **Basic P/S Mode** (Section III-A). The EV selects where to charge if with low electricity status threshold than SOC threshold.
- **Steps 4:** Two options are designed for reservation uploading, through the "*EV_Reservation_Upload*" topic in TABLE III:
  - The direct cellular link will be established to EV's selected CS, if there will not be any (accessible) RSU along the trajectory towards that selected CS. This refers to a "One-to-One" nature, as the EV's reservation is solely uploaded to its selected CS.
  - Alternatively, the EV's reservation will be uploaded to an encountered RSU (with MEC intelligence detailed in Section V-E). This refers to a "One-to-Any" nature, as the uploading happens at any one of RSUs.
- **Step 5:** At the time slot approaching the next CSs' publication, RSUs report their aggregated EVs' reservations to associated CSs, through the "*Aggregated_EVs'_Reservations_Upload*" topic. This refers to a "Many-to-One" nature, as RSUs will simultaneously send aggregated EVs' reservation to their associated CS.

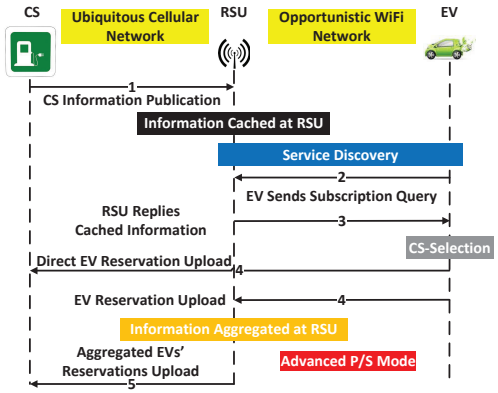


Fig. 10. Time Sequences for Advanced P/S Mode

B. Format of EV's Reservation

Once a CS-selection decision is made from on-the-move EV with pending battery switch request, the following information in TABLE V will be included as the EV's reservation:

TABLE V
FORMAT OF EV RESERVATION

EV ID	ID of Selected CS	Arrival Time	Expected Charging Time of Depleted Battery

Arrival Time: We denote T_{ev}^{arr} as the EV's arrival time at its selected CS:

$$T_{ev}^{arr} = T_{cur} + T_{ev}^{tra} \tag{3}$$

Here, T_{ev}^{tra} is as the travelling time to be taken from the current location of EV to the selected CS, and T_{cur} is as the current time in network. Note that, the actual travelling path is formed based on the shortest road path topology, with an assumption of constant moving speed.

Expected Charging Time: We denote as $T_{\mathcal{B}}^{cha}$ the expected charging time of EV's depleted battery, upon its arrival at selected CS:

$$T_{\mathcal{B}}^{cha} = \frac{E_{\mathcal{B}}^{max} - E_{\mathcal{B}}^{cur} + S_{ev} \times T_{ev}^{tra} \times \alpha}{\beta} \tag{4}$$

Here, $(S_{ev} \times T_{ev}^{tra} \times \alpha)$ is the energy consumed for the movement to reach the selected CS, based on a constant α specified as the energy consumption per meter. Therefore, $(E_{\mathcal{B}}^{max} - E_{\mathcal{B}}^{cur} + S_{ev} \times T_{ev}^{tra} \times \alpha)$ is the expected electricity of the battery (will be depleted from that EV upon arrival) to

be recharged by a CS, depending on the charging power β of that CS.

C. Privacy Concern

TABLE VI
STRUCTURE OF INFORMATION MAINTAINED AT RSU AND EV

Key	Value		
ID	ATS	N_B	EVs' Reservations
CS_3	[3060s, 3300s, 3520s]	20	[3500s, 730s], [4700s, 700s]

Upon the reservation uploading to CS (through opportunistic communication with RSU, or direct cellular network), the CS will process its captured reservations (formatted in TABLE V) within current publication interval T. Then the CS aggregates them with the local condition (ATS and N_B) for publication at the next T.

Both RSUs and EVs will maintain a "Map <Key, Value>" data structure following TABLE VI. The "Key" is the entry for each CS, while the "Value" is a tuple consisting of the CS local condition (ATS and N_B), and those EVs' reservations. Note that, the "Value" associated with previous CS publication time slot, will be replaced with that currently published.

As formatted in TABLE IV and TABLE VI, the defined information format well alleviates privacy concern. As such, EV_r will not obtain any knowledge about ID of those have reserved for battery switch, this is because only the arrival time and expected charging time of batteries (to be depleted from those EVs) are included. Besides, the locations of those EVs when made reservations are also hidden. This is because the calculation of an EV's arrival time is depending on its location and speed, whereas these two factors are not released.

D. Estimation of EWTS in Advanced P/S Mode

Algorithm 4 requires the knowledge of from Algorithm 2, as well as those EVs made reservations (detailed in TABLE V). Throughout Algorithm 4, the EWTS at a given CS can be estimated by EV_r locally. Here, T_k^{arr} and T_k^{cha} are denoted as the arrival time and expected charging time at the k^{th} entry.

Algorithm 4 initially sorts the queue of N_R following the FCFS order, as the charging scheduling priority been discussed in Section III-C. Here, EV_k stands for the k^{th} EV in the queue of N_R. Besides, the expected number of switchable batteries N_B^E, is initialized with the value of N_B at line 2. The arrival time T_k^{arr} of each EV_k (in the queue of N_R) made reservation at its selected CS, will be compared with $T_{ev_{(r)}}^{arr}$ (arrival time of EV_r). As highlighted at line 5, for each EV_k with its T_k^{arr} earlier than $T_{ev_{(r)}}^{arr}$, the former will involve the dynamic update of the ATSLIST from line 6.

Note that the ATSLIST has been initially sorted according to the ascending order (at line 1), such that the earliest available time for switch is at the head of ATSLIST. From line 6, $T_{ev_{(k)}}^{arr}$ is compared with the charging finish time of each battery (being charged or waiting to be charged, as included in ATSLIST) at this CS. If $T_{\mathcal{B}_{(j)}}^{fin}$ is earlier than $T_{ev_{(k)}}^{arr}$ happens at line 7, one more battery will be switchable upon the arrival of EV_k, with N_B^E increases by 1 at line 8.

Algorithm 4 Estimation of EWTS in Advanced P/S Mode

1: sort ATSLIST returned by Algorithm 2, with ascending order
2: define TEMLIST, $N_B^E = N_B$
3: sort the queue of N_R according to FCFS
4: **for** $(k = 1; k \leq N_R; k++)$ **do**
5: **if** $(T_k^{arr} < T_{ev_{(r)}}^{arr})$ **then**
6: **for** $(j = 1; j \leq |\text{ATSLIST}|; j++)$ **do**
7: **if** $(T_{\mathcal{B}_{(j)}}^{fin} < T_k^{arr})$ **then**
8: $N_B^E = N_B^E + 1$
9: delete $T_{\mathcal{B}_{(j)}}^{fin}$ from ATSLIST and TEMLIST
10: **end if**
11: **end for**
12: **if** $(|\text{ATSLIST}| \geq \delta)$ **then**
13: **if** $(|\text{TEMLIST}| = 0)$ **then**
14: include first δ elements $T_{\mathcal{B}_{(j)}}^{fin}$ into TEMLIST
15: **end if**
16: sort TEMLIST with ascending order
17: $T_{\mathcal{B}_{(k)}}^{fin} = \text{TEMLIST}_1 + (E_{\mathcal{B}_{(k)}}^{max} - E_{\mathcal{B}_{(k)}}^{cur})/\beta + T_{\mathcal{B}}^{sw}$
18: replace the TEMLIST_1 with $T_{\mathcal{B}_{(k)}}^{fin}$
19: **else**
20: $T_{\mathcal{B}_{(k)}}^{fin} = T_{ev_{(k)}}^{arr} + (E_{\mathcal{B}_{(k)}}^{max} - E_{\mathcal{B}_{(k)}}^{cur})/\beta + T_{\mathcal{B}}^{sw}$
21: include $T_{\mathcal{B}_{(k)}}^{fin}$ into TEMLIST
22: $N_B^E = N_B^E - 1$
23: **end if**
24: include $T_{\mathcal{B}_{(k)}}^{fin}$ into ATSLIST
25: **end if**
26: **end for**
27: **for** $(j = 1; j \leq |\text{ATSLIST}|; j++)$ **do**
28: **if** $(T_{\mathcal{B}_{(j)}}^{fin} < T_{ev_{(r)}}^{arr})$ **then**
29: $N_B^E = N_B^E + 1$
30: **end if**
31: **end for**
32: **if** $(N_B^E > 0)$ **then**
33: **return** $\text{EWTS} = T_{\mathcal{B}}^{sw}/N_B^E$
34: **else**
35: **return** $\text{EWTS} = \text{ATSLIST}_1 - T_{ev_{(r)}}^{arr} + T_{\mathcal{B}}^{sw}$
36: **end if**

As such, the given $T_{\mathcal{B}_{(j)}}^{fin}$ will be removed from ATSLIST (and also TEMLIST initialized from line 14), means the number of batteries being charged or to be charged decreases. This is because a fully charged battery will be switched to EV_k. Then:

- As given by the condition $(|\text{ATSLIST}| \geq \delta)$ at line 12, the number of batteries being charged or to be charged, is larger than δ as the total number of charging slots a CS is equipped. This reflects any incoming EV_k still needs to wait an additional time for a switchable battery. In this case, the charging finish time $T_{\mathcal{B}_{(k)}}^{fin}$ of the battery depleted from EV_k, is given at line 17:

$$T_{\mathcal{B}_{(k)}}^{fin} = \text{TEMLIST}_1 + (E_{\mathcal{B}_{(k)}}^{max} - E_{\mathcal{B}_{(k)}}^{cur})/\beta + T_{\mathcal{B}}^{sw} \quad (5)$$

where TEMLIST_1[8] is the time slot when a charging slot is available at the CS, $(E_{\mathcal{B}_{(k)}}^{max} - E_{\mathcal{B}_{(k)}}^{cur})/\beta$ is the time duration to fully recharge the battery depleted from EV_k, while $T_{\mathcal{B}}^{sw}$ is the time duration to deplete this battery from EV_k and switch with a fully recharged battery.

[8]As we also define TEMLIST at line 2, the first δ value in ATSLIST are included into TEMLIST. This certainly reflects the charging finish time of batteries being charged at CS. At line 18, replacing $T_{\mathcal{B}_{(k)}}^{fin}$ with TEMLIST_1 thus updates the charging finish time of batteries in TEMLIST, for the computation that EV_k involves in next loop.

- Otherwise, EV_k will be directly switched with a fully recharged battery (without waiting), then $T^{fin}_{\mathcal{B}_{(k)}}$ is given at line 20:

$$T^{fin}_{\mathcal{B}_{(k)}} = T^{arr}_{ev_{(k)}} + (E^{max}_{\mathcal{B}_{(k)}} - E^{cur}_{\mathcal{B}_{(k)}})/\beta + T^{sw}_{\mathcal{B}} \tag{6}$$

  Note that the time to start battery switch is as $T^{arr}_{ev_{(k)}}$ (arrival time of EV_k). At line 22, the number of switchable batteries decreases by 1, meaning EV_k will be replaced with a fully charged battery.

Furthermore, the charging finish time of each battery depleted from incoming EV_k, will be included into ATSLIST at line 24.

Above loop operation is repeated, until all EV_k (in the queue of N_R) have been processed. Then, $T^{arr}_{ev_{(r)}}$ is compared with the charging finish time $T^{fin}_{\mathcal{B}_{(j)}}$ included in ATSLIST. If there is any $T^{fin}_{\mathcal{B}_{(j)}}$ earlier than $T^{arr}_{ev_{(r)}}$ (the condition ($T^{fin}_{\mathcal{B}_{(j)}} < T^{arr}_{ev_{(r)}}$) at line 28), this means one more battery will be available for switch when EV_r arrives. As such, the expected number of switchable batteries N^E_B increases by 1. Finally:

- The EWTS is returned as $T^{sw}_{\mathcal{B}}/N^E_B$ at line 33, if there will be a switchable battery given by ($N^E_B > 0$).
- Alternatively, the EWTS is returned as $\left(\text{ATSLIST}_1 - T^{arr}_{ev_{(r)}} + T^{sw}_{\mathcal{B}}\right)$ at line 35. This implies that there will not be any battery available for switch, when EV_r arrives at its selected CS. In other words, EV_r will need to wait $\left(\text{ATSLIST}_1 - T^{arr}_{ev_{(r)}}\right)$, and experience $T^{sw}_{\mathcal{B}}$ for battery switch.

E. Reservation Uploading

The motivation for each RSU to aggregate EVs' reservations, is to reduce the communication cost (in terms of how many times the connections are established to CSs). In detail, as CSs publish their information at previous publication time stamp $\mathcal{P}$, it is compulsory that the aggregated EVs' reservations is required to be delivered at associated CSs, before given $(T + \mathcal{P})$. This means the information collection is to be operated within the interval T.

Therefore, the EV's reservation does not need to be sent instantaneously, as it is with a delay tolerance of $(T + \mathcal{P})$. By means of optimally deployed RSUs, all EVs' reservations can be ideally collected by RSUs in a V2I manner. However, it is by no means that all EV's reservations will be successfully delivered to their associated CSs. This is mainly due to the opportunistic encounters between EVs and RSUs. In the worst case, an EV's reservation must be delivered to its associated CS, before any RSU is encountered. This means the time to encounter the first RSU along the trajectory towards an EV's selected CS, is later than $(T + \mathcal{P})$.

In the light of this, the proposed reservation uploading considers the trajectory towards the EV's selected CS, and those locations of RSUs along that trajectory, specifically:

- **MEC-Functioned RSU Uploading:** If any RSU is accessible before $(T+\mathcal{P})$, the reservation uploading will be delayed until that encounter happens. The valid reservation refers to that of which the EV's arrival is reserved later than $(T + \mathcal{P})$. This is because an EV's reservation will be deleted by its selected CS, when it is parked therein. Then any arrival happens before the next CS's publication will be removed from RSUs, this potentially reduces the size of data to be uploaded to CSs. The EV's reservation gathered by MEC-functioned RSU will be aggregated with those select the common CS, and reported at $(T+\mathcal{P})$.
- **Direct Cellular Networking Uploading:** Alternatively, the cellular network is established, where the EV's reservation is directly uploaded to the selected CS.

F. Communication Efficiency

Firstly, if EVs' reservations are delivered to their selected CSs through the cellular network, ideally, there will not be any delivery delay because we assume it is with ubiquitous communication range. Here, the communication cost is scaled by $O(N_{ev})$, as the number of reservations made is directly related to that of EVs.

Secondly, we consider that EVs' reservations are delivered to their selected CSs through RSUs in proximity. Referring to Fig. 10, the delay only depends on the time for the EV to encounter an RSU, because the communication between RSUs and CSs can be considered as delay free (thanks to the cellular network communication). Therefore, the communication cost is scaled by $O(P_{p/s} \times N_{ev})$, recall that $P_{p/s}$ is the possibility that an EV to encounter at least one of N_{rsu} RSUs. This refers to the reservation uploading in an opportunistic manner, as implemented in [1].

Thirdly, we consider the case with aggregated EVs' reservations uploading to CSs, before $(T + \mathcal{P})$. Here, the communication cost is scaled by $O(\frac{N_{rsu}}{T})$, as the communication is established from N_{rsu} RSUs within interval T. In order not to miss-upload any EV's reservation, the cellular network is applied as the back-up solution[9].

Based on above, the communication cost is scaled between $O\left(\left(1 - P_{p/s}\right) \times N_{ev}\right)$ and $O\left(\frac{N_{rsu}}{T}\right)$. Note that $P_{p/s}$ also benefits from a larger N_{rsu} and shorter T, that is consistent to $O\left(\frac{N_{rsu}}{T}\right)$. As such, excluding the deployment of RSUs, in nature, a larger N_{ev} drives the sustainable communication efficiency for the long term EVs popularity.

G. Discussion

1) Integration of Renewable Energy: The mismatch between EVs and infrastructures would potentially hinder the deployment rate of EVs. With the ever increasing penetrations in EVs, the resultant charging energy imposed on the electricity network could lead to grid issues such as voltage limits violation, transformer overloading, and feeder overloading at various voltage levels. Coordination of the charging depleted batteries with renewable energy source provides a more straightforward approach to cope with the potential network issues as mentioned above. Future works would be on the integration of power network [28], to achieve an interdisciplinary work on ICT, route planning and energy integration.

[9]For example, any EV_r will not encounter any RSU along the trajectory towards its selected CS, with possibility $\left(1 - P_{(p/s)}\right) \times N_{ev}$.

2) Heterogeneity of Batteries: Of course, it is practical to consider the compatibility of heterogeneous batteries switched between different type 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. As such the estimation of batteries number and AWTS should differentiate each type of battery and its support EVs' reservations.

3) Combination of Battery Switch and Plug-in Charging: Concerning the service provisioning, those EVs (private drivers) which are not with emerging demand could experience plug-in charging service, whereas those (public taxis) are suggested to experience battery switch service due to demand of being actively hired. The deployment of these two types of stations requires analysis on EVs traffic history, and could share the same ICT framework that we propose in this article.

H. Performance Evaluation

The performance is also based on the configuration in Section IV-C. We further bring two previous works on reservation enabled CS-selection (under plug-in charging system) for comparison, namely **Reservation-1** [1] and **Reservation-2** [8] both are implemented in centralized manner. Besides, we consider the **Total Reservations Making (TRM)** as the additional communication cost brought in reservation service.

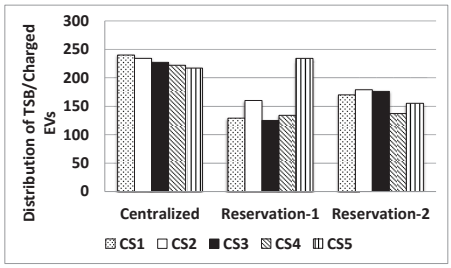


Fig. 12. Distribution of TSB at CSs

1) Influence of CS Publication Interval: In Fig. 11(a) and Fig. 11(b), we observe the Advanced P/S Mode outperforms Basic P/S Mode, in terms of reduced AWTS and increased TSB. This mainly thanks to bringing the knowledge of EVs' reservations, which helps to avoid planning charging at likely congested CSs. Thus EVs experience shorter time to wait for service and more batteries can be switched. For fundamental comparison, the centralized version of CS-selection in Section IV (namely Centralized herein) still outperforms Reservation-1 and Reservation-2, due to the advantage of battery switch system. By prolonging the CS publication interval from 120s to 1200s, the decentralized manners, e.g., Advanced P/S Mode, Basic P/S Mode, and Reservation-1 (P/S) (the disturbed manner of [1]) suffer from performance degradation. Such a nature can be referred to the observation in Section III, where the information (ATS, N_B and associated EVs' reservations of CSs) accessed by EVs is obsolete due to infrequent publication.

In Fig. 11(c), all centralized manners (Reservation-1, Reservation-2 and Centralized) experience higher communication cost for reservations making, as solely the cellular network is established. The decentralized manners are with lower cost, where Reservation-1 (P/S) only relies on opportunistic encounters between RSUs for reservation uploading. The Advanced P/S Mode runs the reservations aggregation at MEC-functioned RSUs (upon collected EVs' reservations), and alternatively utilizes the cellular network as back-up solution. As CSs publication interval increases, the TRM becomes decreased.

Fig. 12 further shows the distribution of TSB (charged EVs) among CSs, in case of centralized manner with reservation function enabled. Regardless of charging system (battery switch vs plug-in charging), our proposed scheme achieves the best balance.

2) Influence of EVs Density: In Fig. 13(a), Fig. 13(b) and Fig. 13(c), all schemes experience an increased AWTS and TSB, following the increased EVs' density. This is because of congestion happened at CSs, as such most likely EVs have to wait for longer time to get battery switched while the less batteries can be switched during simulation time. Here, Centralized also achieves the best performance, as an optimal case of Advanced P/S Mode. With strategically deployed RSUs applied in Section III, most of EVs' reservations can be captured and aggregated, thus alleviates the cost through cellular network in Fig. 13(c). The performance of other compared schemes also follows similar observation in case of varied CSs publication interval.

3) Influence of RSUs Deployment and Transmission Range: The decreased number of RSUs and reduced transmission range also degrade performance in Fig. 14(a), Fig. 14(b) and Fig. 14(c), similar to that discussed in Section IV-C. Particularly, we observe the reservations making through the cellular network dramatically increases due to missed opportunistic encounter, compared to that through the RSUs. This implies that the importance of infrastructures positioning and ICT configuration to maintain a good coverage of information dissemination.

VI. Conclusion

In this paper, we proposed a distributed charging system supported battery switch service, in line with the P/S communication framework (applying MEC-functioned RSUs for intermediate information handling). The communication efficiency of P/S system has been studied and compared with that using the cellular network communication and broadcasting. We further propose the Advanced P/S Mode which enables EVs to publish their reservations (intelligently uploaded through opportunistically encountered MEC-functioned RSUs, or cellular network) for communication efficiency. Results show the charging system benefits from this anticipated information to make CS-selection decisions, which further reduces the EVs' waiting time for battery switch and increased CSs' switched batteries. Further results also imply the strategies on position of RSUs and ICT configurations, to support low cost information exchange within E-Mobility system.

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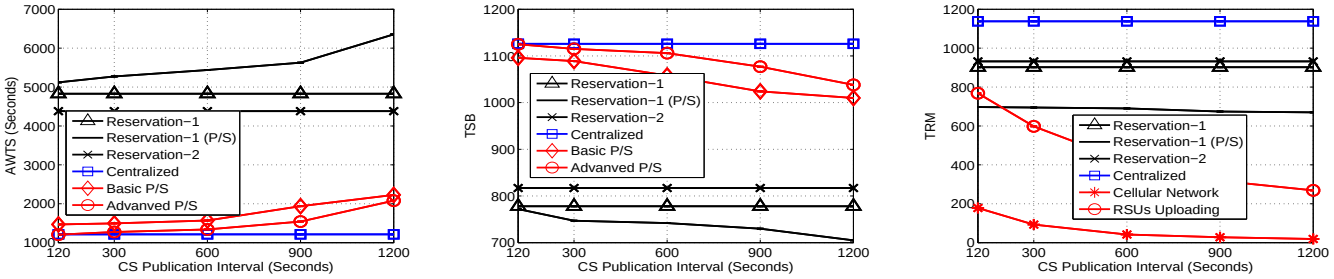
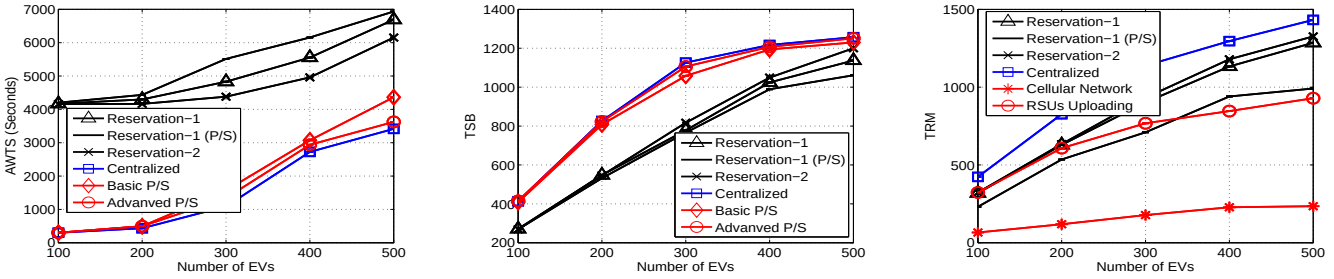


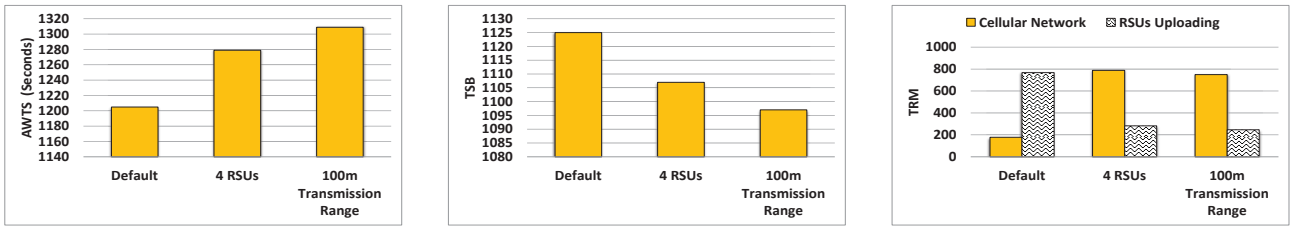
(a) AWTS (b) TSB (c) TRM

Fig. 11. Influence of CS Publication Interval



(a) AWTS (b) TSB (c) TRM

Fig. 13. Influence of EVs Density



(a) AWTS (b) TSB (c) TRM

Fig. 14. Influence of RSUs Deployment and Transmission Range

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Yue Cao received the PhD degree from the Institute for Communication Systems (ICS), 5G Innovation Centre (5GIC), at University of Surrey, Guildford, UK in 2013. He was a Research Fellow at the ICS until September 2016, and Lecturer in Department of Computer and Information Sciences, at Northumbria University, Newcastle upon Tyne, UK until July 2017, and currently the Senior Lecturer since August 2017. His research interests focus on Intelligent Mobility. He is the Associate Editor of IEEE Access and International Journal of Vehicular Telematics and Infotainment Systems.

Omprakash Kaiwartya is a Visiting Research Scholar at the Department of Computer and Information Sciences, Northumbria University, UK. He received his Ph.D. degree in Computer Science from Jawaharlal Nehru University, New Delhi, India in 2015, and worked as Postdoctoral Research Fellow at Faculty of Computing, Universiti Teknologi Malaysia (UTM), Johor Bahru, Malaysia. His research interests focus on Internet of Vehicles, EVs charging, and IoT.

Chong Han received her PhD degree from the ICS, at University of Surrey, UK, in 2012. She has been a Research Fellow at the ICS, home of 5G Innovation Centre (5GIC) for 5 years. Dr Han has participated many V2X research projects since 2009. Her research interests focus on Connected Autonomous Vehicles (CAVs), DSRC and long-range communication techniques such as LTE-A and 5G. Currently she is with pureLiFi working on standardisation for optical wireless communications.

Kezhi Wang received his B.E. and M.E. degrees in College of Automation from Chongqing University, China, in 2008 and 2011, respectively. He received his Ph.D. degree from the University of Warwick, U.K. In 2015. He was a senior research officer in University of Essex, U.K. Currently he is a lecturer in Department of Computer and Information Sciences, Northumbria University. His research interests include wireless communication, signal processing and mobile cloud computing

Houbing Song received the Ph.D. degree in electrical engineering from the University of Virginia, Charlottesville, VA, in August 2012, and the M.S. degree in civil engineering from the University of Texas, El Paso, TX, in December 2006. In August 2017, he joined the Department of Electrical, Computer, Software, and Systems Engineering, Embry-Riddle Aeronautical University, Daytona Beach, FL, where he is currently an Assistant Professor and the Director of the Security and Optimization for Networked Globe Laboratory (SONG Lab, www.SONGLab.us). He served on the faculty of West Virginia University from August 2012 to August 2017. In 2007 he was an Engineering Research Associate with the Texas A&M Transportation Institute. He serves as an Associate Technical Editor for IEEE Communications Magazine. His research interests include cyber-physical systems, cybersecurity and privacy, internet of things, edge computing, big data analytics, unmanned aircraft systems, connected vehicle, smart and connected health, and wireless communications and networking.

Nauman Aslam is a Reader in Department of Computer and Information Sciences, at Northumbria University, Newcastle upon Tyne, UK. He received PhD in Engineering Mathematics from Dalhousie University, Halifax, Nova Scotia, Canada in 2008. He worked as an Assistant Professor at Dalhousie University, Canada until 2011. His research interests include wireless ad hoc and sensor networks, fault tolerant and reliable communication, remote health monitoring application.