# Toward Anycasting-Driven Reservation System for Electric Vehicle Battery Switch Service

Yue Cao, *Member, IEEE*, Tong Wang, Xing Zhang, *Member, IEEE*, Omprakash Kaiwartya, *Member, IEEE*, Mahmoud Hashem Eiza, *Member, IEEE*, and Ghanim Putrus

***Abstract*—Electro-mobility has become an increasingly important research problem in urban cities. Due to the limited electricity of battery, electric vehicle (EV) drivers may experience discomfort for long charging waiting time. Different from plug-in charging technology, we investigate the battery switch technology to improve EV drivers' comfort (e.g., reduce the service waiting time from tens of minutes to a few minutes), by benefiting from switchable (fully recharged) batteries cycled at charging stations (CSs). Since demand hotspot may still happen at CSs (e.g., running out of switchable batteries), incoming EVs may need to wait for additional time to get their battery switched, and thus, the EV drivers' comfort is degraded. First, we propose a centralized reservation-enabling service, considering EVs' reservations (including arrival time, expected charging time of their batteries to be depleted) to optimally coordinate their battery switch plans. Second, a decentralized system is further proposed, by facilitating the vehicle-to-vehicle anycasting to deliver EV's reservations. This helps to address some of the privacy issues that can be materialized in a centralized system and reduce communication cost (e.g., through cellular network for reservation making). Results under the Helsinki city scenario show a tradeoff between comparable performance (e.g., service waiting time, number of switched batteries) and cellular network cost for EVs' reservations delivery.**

***Index Terms*—Anyacsting, battery switch (BS), electric vehicle, Internet of Vehicles (IoV), transportation planning.**

## I. Introduction

ELECTRIC vehicles (EVs) [1] are expected to be widely adopted as individual, commercial, and public vehicle fleets. However, compared with traditional gasoline-powered vehicles, EVs are more likely to run out of energy, thus should be charged during their journeys. This is mainly due to the limited EV battery capacity and long trips in big cities (e.g., the current battery design only supports EV running with in the urban area). As a result, how to manage the charging processes of EVs to improve their 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" [1] (considering when/whether to charge) where EVs have already been parked at homes/charging stations (CSs). In contrast, we address "CS-selection" (considering where to charge), which has not been adequately investigated. In general, public CSs are typically deployed at places where there is high EVs concentration, e.g., shopping malls and parking places. Due to the relatively long time to charge an EV battery, optimally managing where to charge has become a critical issue in recent years due to the popularization of EVs.

The majority of previous works on CS-selection [2] are generally based on the centralized system. Here, by monitoring CSs' condition, the global aggregator (GA) as centralized controller implements the CS-selection decision whenever it receives a charging request from an EV on-the-move that needs charging. Several CS-selection schemes [3]–[9] have attempted to minimize the EVs' charging waiting time. Basically, the CS with the highest availability (e.g., minimum queuing time (MQT) [5]) will be selected as the best choice. Inevitably, a potential charging hotspot may happen, if many EVs travel toward the same CS for charging. If further bringing anticipated EVs' reservations[1] [10]–[13] (including when the EV will arrive at selected CS for charging, and how long its charging time will be upon the arrival), the congestion at CS could be alleviated. This is to identify which CS will be overloaded and at what time, so as to avoid selecting that CS as the charging plan.

Nevertheless, the plug-in charging technology still requires a relatively longer duration [14] to complete battery charging; thus, CSs will be overloaded. 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. In contrast to the plug-in charging technology, as a promising alternative approach, the battery switch (BS) service [15]–[17] has the potential to replace a fully charged battery for parked EV, just within several minutes. This envisions for an elaborate industrial automation robots to execute fast BS.

Even though the centralized system has been proven quite successful in economically scaling and providing optimal allocation, it has its own drawbacks. For instance, the failure of GA

[1]Note that the reservation of an EV observed by the GA will be taken into account for arranging the charging plans for other EVs that need the BS services in future. The EV's reservation only associates with those CSs with which it has charging intention. If the EV has not been with charging intention, both expected charging time and arrival time cannot be resolved; thus, no charging reservation will be generated. Note that the reservation is sent from an EV, only if it has accepted the CS-selection decision from the GA.

Manuscript received September 2, 2017; revised January 3, 2018; accepted March 4, 2018. This work was supported in part by the National Natural Science Foundation under Grant 61102105 and Grant 51779050, in part by the Harbin Science Fund for Young Reserve Talents (2017RAQXJ036), and in part by the EU - Interreg North Sea Region SEEV4-City projects (J-No.:38-2-23-15).
*(Corresponding author: Tong Wang.)*

Y. Cao, O. Kaiwartya, and G. Putrus are with the Department of Computer and Information Sciences, Northumbria University, Newcastle upon Tyne NE2 1XE, U.K.

T. Wang is with the College of Information and Communication Engineering, Harbin Engineering University, Harbin 150001, China (e-mail: wangtong@hrbeu.edu.cn).

X. Zhang is with the School of Information and Communication Engineering, Beijing University of Posts and Telecommunications, Beijing 100876, China.

M. H. Eiza is with the School of Physical Sciences and Computing, University of Central Lancashire, Preston PR1 2HE, U.K.
Digital Object Identifier 10.1109/JSYST.2018.2815156

leads to the service dropout for all EVs' drivers. The complexity and computation load of this centralized optimization solution increases exponentially with the number of EVs. Here, EVs' reservations are generally reported through the conventional ICT technologies, e.g., 4G cellular network. It is costly and sometimes over congested, causing the degradation of communications quality. In this context, a decentralized system is motivated.

Internet of Vehicles (IoV) [18] is one of the revolutions mobilized by Internet of things (IoT), where the concept of connected vehicle is highly appreciated. The wireless connectivity among EVs creates huge possibilities for sophisticated infotainment systems, application processors, heads-up displays, graphics accelerators, and vehicle-to-vehicle (V2V) [19] communications.

In the literature, in spite of that the BS technology has been investigated for "charging scheduling" [16], that effort toward "CS-selection".[2] Our contributions are as follows.

1) *Enabling reservation for BS service (centralized system):* In order to minimize the waiting time for BS as well as balance the demand load among CSs, we jointly consider the BS/charging procedure locally operated at CSs as already taken by [17], and reservations delivered from EVs investigated in this paper. Such anticipated information together with the local status of CSs are recorded by the GA, to estimate the future status of CSs [e.g., the expected number of switchable batteries and expected waiting time for switch (EWTS)]. The target is to select a CS, which will not be highly congested, so as to improve driver's comfort.
2) *Study of V2V-driven reservation delivery (decentralized system):* By transferring from above-mentioned reservation-enabling technology into a decentralized system, we propose a sustainable EV-assisted reservation delivery system to offload the reservations delivery, from the cellular network to IoV (formed by EVs). CSs are set up as mobile edge computing (MEC) [20] servers with information mining, aggregation and sharing of EVs' reservations with each other. Such a feature is deemed as a scalable solution to the long-term introduction of EVs, in terms of communication cost and system scalability.

## II. Related Work

### A. BS 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 the EV into charging slot set at CSs (placed at different city locations). In contrast, at the CSs providing the BS service [15], the automated platform switches the depleted batteries from EVs, with a fully-charged battery maintained by CSs. The depleted batteries are placed and recharged so that they can be used by other EV drivers. This means that each CS is able to maintain a certain number of batteries for switching. In particular, the BS service could be described as a mixture of a drive-through car wash, which normally switches an EV's battery in several minutes, without requiring the driver to get out of EV.

[2]Our preliminary work [17] has proposed the first work enabling a BS for ICT, this study shows that the advantage of that over a traditional plug-in charging system for CS-selection [17]. Further to the above-mentioned motivation for the provisioning of the BS through a decentralized way, there has not been previous work that brings the benefit of the IoV with anycasting nature for EVs' reservations delivery.

### B. Electro-Mobility for Where to Charge

In recent few years, the "CS-selection" problem has started to gain interest in industrial communities, thanks to the popularity of EVs. The works in [5], [7], and [9] estimate the queuing time at CSs, such that the one with the minimum queueing time is ranked as the best charging option. The work in [3] compares the schemes to select a CS based on either the closest distance or minimum waiting time, where results show that the latter performs better given high EVs density under the city scenario. In [4], the CS with higher capability to accept charging requests from on-the-move EVs will propose this service with a higher frequency, while EVs sense this service with a decreasing function of their current battery levels. The CS-selection scheme in [6] adopts a pricing strategy to minimize congestion and maximize profit, by adapting the price depending on the number of EVs been parked. Game theory strategy [8] is also applicable by balancing the charging plans among EV drivers.

Further to the above-mentioned works, which consider the local status of CSs, reservation-enabled CS-selection schemes bring anticipated EVs mobility information (reservations) deemed as an additional signaling, in order to estimate whether a CS will be overloaded in a near future. Qin and Zhang [12] considered a highway scenario where the EV will pass through all CSs. The expected charging waiting time is calculated for the EV passing through the entire highway, by jointly considering the charging waiting time at a CS where the EV needs charging for the first time and the time spent at subsequent CSs, before exiting the highway. Other works under the plug-in charging service [10], [11], [13] focus on city scenario, where the EV just heads to a single geographically distributed CS for charging. Here, the expected waiting time for charging is associated with that certain CS.

### C. Vehicle Delay/Disruption Tolerant Network (VDTN) Anycasting

The VDTNs extend vehicular ad hoc networks (VANETs) to tolerate communication disruptions in highly mobile situation. In VDTNs, vehicles store and carry network data, while waiting for opportunities to forward it to the destinations. Majority of VDTN routing schemes focus on unicasting (each message is associated with only one destination) and multicasting (the delivery is required by all destination members within a group). Apart from this, anycasting [21] is a service that allows a node to send a message to at least one, and preferably only one of the members in a group. The idea behind anycasting is that a client wants to send messages to any one of the several possible servers offering a particular service (but does not care any specific one). Note that in unicasting, each piece of data is with a single destination, where there is no such limitation in anycasting. Anycasting can be used to implement resource discovery mechanisms, which are powerful building blocks for many distributed systems, including file sharing, etc.

### D. Our Contribution

Beyond the literature summarized in Table I, we investigate the BS technology in this paper. This would lead to substantially different design and computation involved for charging management, e.g., how to manage charging and cycling of batteries maintained at the CS side. Based on the BS system,

TABLE I
SUMMARY OF LITERATURE

| | | |
|---|---|---|
| —Charging Scheduling— | | |
| [1], [16] | | |
| —CS-selection— | | |
| | Plug-in charging | BS |
| Reservation not-enabled | [2]–[7], [9] | [8], [17] |
| Reservation enabled | [10]–[13] | Our proposed solution |
| Anycasting-based IoV | N/A | Our proposed solution |

we further study the reservation-based CS-selection policy to guide BS plans.

Indeed, using a centralized system keeps the edge devices (EV side) simple and favors more sophisticated centralized optimizations from the GA side based on the aggregated global information. In contrast to the centralized system, a much scalable and decentralized system is preferred in a green city scenario, with alleviated privacy concern and less communication cost. In this context, all signaling handled by the GA will be decoupled between CSs and EVs, through periodical broadcasting and anycasting-driven reservation delivery.

## III. Reservation-Enabled BS Service (Centralized System)

### A. Network Entities

*EV:* Each EV is with a state-of-charge (SOC) threshold. If the ratio between its current energy and maximum energy is below the SOC threshold, the EV starts to negotiate with the GA to find an appropriate CS for BS. EV also reports its reservation to the GA, including "at what time it will arrive at the decided CS" and "how long the expected charging time will be for its depleted battery."

*CS:* It maintains a number of fully charged batteries for switching. Upon the arrival of EVs, the number of maintained (fully charged) batteries will decrease because of the 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 number of maintained batteries will increase. The condition information (number of batteries being switchable and being charged) of each CS is monitored by the GA.

*GA*: It is a centralized entity and requires CSs' condition information and EVs' charging reservations for decision making.

### B. Assumption

We consider a city scenario where CSs are geographically deployed in a city. EVs are equipped with wireless communication devices such as 3G/long-term evolution, which allows them to communicate with the GA for requesting/replying BS services. Each CS initially maintains a certain number of fully-charged batteries and has multiple charging slots, such that a number of depleted batteries from EVs can be charged in parallel.

In the case of a low-electricity stage, an on-the-move EV equipped with GPS navigation would head toward a selected CS (decided by the GA) for the BS service. The underlying EV BS policy (charging scheduling considering when/whether to switch a battery to a parked EV) at the CS side is based on the first-come first-serve (FCFS) order. This means that the parked EV with an earlier arrival time will be scheduled with a higher switch priority. If a CS is fully occupied (i.e., it runs out of fully recharged battery for switch), parked EVs need to wait until batteries are switchable. We assume that all EVs are with a unique type of battery in this paper, and further complexity considering heterogenous batteries is discussed in Section III-C.

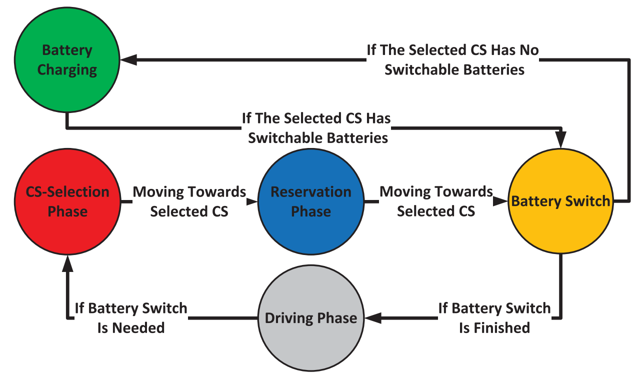



Fig. 1. System cycle of the proposed EV charging management.

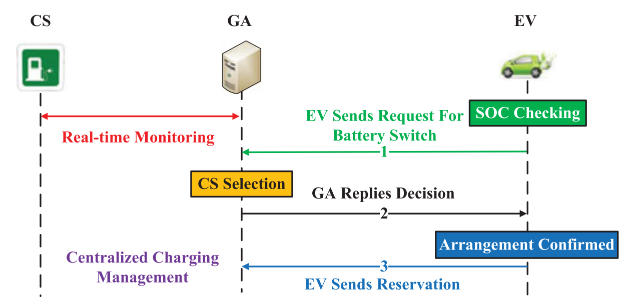



Fig. 2. Example of centralized EV charging management.

### C. System Cycle

Fig. 1 describes the cycle of EV charging management.

1) *Driving phase:* The EV is moving during its routine.
2) *CS-selection phase:* The EV reaching a threshold on its residual battery volume sends its request to the GA, shown in Fig. 2. The GA performs centralized CS-selection and replies the decision back to the EV.
3) *Reservation phase:* Upon accepting the allocation, the EV further makes its reservation (including its arrival time and expected charging time for its battery) associated with the selected CS, back to the GA.
4) *BS phase:* Upon arrival at the selected CS, the EV's battery is switched with the fully recharged battery maintained at that CS. This happens if the selected CS already maintains a number of fully charged batteries.
5) *Battery charging phase:* The batteries depleted from EVs will be charged by the CS in parallel (depending on charging slots), and they will be switchable upon being fully recharged. The transition between the *BS phase* and the *battery charging phase* is bidirectional.

Among them, both the *CS-selection phase* and *reservation phase* are implemented in a centralized manner, because interactions will be handled by the GA.

TABLE II
NOMENCLATURE

| $\gamma$ | Time interval of system resolution |
|---|---|
| $N_B$ | Number of switchable batteries at CS |
| $N_D$ | Number of batteries depleted from incoming EVs |
| $T_{\mathcal{B}}^{\text{sw}}$ | Time to switch a battery |
| $N_C$ | Number of batteries being charged |
| $\delta$ | Number of charging slots at CS |
| $\beta$ | Charging power at CS |
| $E_{\mathcal{B}}^{\text{max}}$ | Full volume of EV battery |
| $E_{\mathcal{B}}^{\text{cur}}$ | Current volume of EV battery |
| ATSLIST | Output list about time available for BS |
| $T_{\mathcal{B}}^{\text{fin}}$ | Charging finish time of EV battery |
| $\overline{N_B}$ | Expected number of switchable batteries at CS |
| $\alpha$ | Energy consumption per meter |
| $S_{\text{ev}}$ | EV speed |
| $T_{\text{ev}}^{\text{arr}}$ | EV's arrival time at CS |
| $T_{\text{ev}}^{\text{tra}}$ | Time for EV to travel toward a CS |
| $T_{\text{cur}}$ | Current time in network |
| $N_R$ | Number of EVs made reservations |
| EWTS | Expected waiting time for switch |

Fig. 2 shows a typical procedure.

1) The on-the-move EV that needs the BS service, namely EV$_r$, informs the GA about its request.
2) The GA compiles a list of CSs and ranks the most appropriate one (in terms of the balanced charging load among CSs and minimized EV driver's waiting time for the BS), and replies the CS-decision to EV$_r$.
3) Upon accepting the arrangement, EV$_r$ reports its reservation in relation to the selected CS, including its arrival time and the expected charging time of its battery upon that arrival.

**Algorithm 1:** Battery Switch at CS.

1: **for** each EV being 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 is available through battery charging procedure
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**

**Algorithm 2:** Battery Charging at CS.

1: **for** each interval $\gamma$ **do**
2:   **while** $(N_C < \delta)$ **do**
3:     sort the queue of $N_D$ according to STCF
4:     schedule a depleted battery from the queue of $N_D$
5:   **end while**
6:   **for** $(i = 1; i \leq N_C; i++)$ **do**
7:     **while** $\left(E_{\mathcal{B}_{(i)}}^{cur} < E_{\mathcal{B}_{(i)}}^{max}\right)$ **do**
8:       $E_{\mathcal{B}_{(i)}}^{cur} = E_{\mathcal{B}_{(i)}}^{cur} + \beta \times \gamma$
9:     **end while**
10:     remove this battery from the queue of $N_D$, $N_C$
11:     $N_B = N_B + 1$
12:   **end for**
13: **end for**

### *D. Battery Management at CS*

All notations are listed in TABLE II.

*1) BS Procedure:* Throughout the BS system, we denote as $N_D$[3] 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 BS services are managed as follows.

1) 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.
2) Alternatively, presented between lines 4 and 5, the EV has to wait (at the CS) 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 $T_{\mathcal{B}}^{\text{sw}}$ the time to switch a battery (normally takes several minutes depending on certain automation technology). Here, the number of switchable batteries $N_B$ decreases by 1, after the period of $T_{\mathcal{B}}^{\text{sw}}$ for switch operation. Meanwhile, the depleted battery from the 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.

*2) Battery Charging Procedure:* Note that the CS is with $\delta$ charging slots, which means that at most $\delta$ depleted batteries can be charged in parallel. As the number of charging slots is normally smaller than the number of depleted batteries, depleted batteries are sorted following the shortest time charge first (STCF) order, which means that the depleted battery with the earliest time to be fully charged has the highest priority for charging. 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 in line 2 in Algorithm 2. This is due to the availability of charging slots for battery charging.

From line 6, for each battery in the queue of $N_C$, it will be charged with $(\beta \times \gamma)$ electricity per time interval $\gamma$. If a battery is fully recharged given by the condition $(E_{\mathcal{B}_{(i)}}^{\text{cur}} = E_{\mathcal{B}_{(i)}}^{\text{max}})$, $N_B$ increases by 1 as a fully charged battery is switchable. Then, the information regarding this recently fully charged battery is removed from the queue of $N_D$, at line 10.

### *E. Objectives*

We introduce the following notations to facilitate problem formulation of waiting time to perceive the BS.

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

Here, note that $\gamma_{l_{\text{cs}}}$ is a function of $N_{\text{cs}}$, which is the number of CSs in network. This is because that a larger number of $N_{\text{cs}}$ drives a small $\gamma_{l_{\text{cs}}}$ EVs distributed at each CS. Furthermore, $\omega_{l_{\text{cs}}}$ is related to $\gamma_{l_{\text{cs}}}$, $\delta$, and $\beta$. Given a number of switchable

[3]In other words, $N_D$ can be considered as a temporary buffer for depleted batteries from EVs, while the CS just processes their charging, with maximum $\delta$ tasks running in parallel, where $(N_C \leq \delta)$.

batteries $N_B$, we aim at minimizing $\mathcal{W}$

$$\mathcal{W} = \begin{cases} \sum_{l_{\text{cs}} \in N_{\text{cs}}} (\gamma_{l_{\text{cs}}} \times (\omega_{l_{\text{cs}}} + T_{\mathcal{B}}^{\text{sw}})) & \text{if } (N_B < \gamma_{l_{\text{cs}}}) \\ \sum_{l_{\text{cs}} \in N_{\text{cs}}} (\gamma_{l_{\text{cs}}} \times (0 + T_{\mathcal{B}}^{\text{sw}})) & \text{otherwise.} \end{cases} \quad (1)$$

1) The first subcondition reflects that a larger number of $\gamma_{l_{\text{cs}}}$ EVs intended to charge at a CS inevitably increases their average BS waiting time at this CS. Of course, both a fast charging power $\beta$ and more charging slots $\delta$ will reduce such waiting time.
2) The second subcondition implies that $\omega_{l_{\text{cs}}}$ tends to 0, when each CS maintains a sufficient number of switchable batteries, given by $(N_B \geq \gamma_{l_{\text{cs}}})$.

As derived in [12], achieving the minimum waiting time under the plug-in charging system has been given, similarly in order to achieve the minimum waiting time for EVs allocated at $N_{\text{cs}}$ CSs under the BS system, thereby $(\gamma_{l_{\text{cs}}} \times (\omega_{l_{\text{cs}}} + T_{\mathcal{B}}^{\text{sw}}))$ should be equal among all CSs as an ideal situation. Note that under the complex city scenario, it is infeasible to achieve the optimal and equal distribution of EVs at all CSs, while our focus is to study the advantage of the BS system over plug-in charging, upon which we develop a scale and practical reservation solution and evaluate the impact of ICT. Since all CSs share the same $\beta$ and $\delta$, we obtain $\gamma_{l_{\text{cs}}} = \mathcal{F}(\frac{1}{N_{\text{cs}}})$ and $\omega_{l_{\text{cs}}} = \mathcal{F}(\frac{\gamma_{l_{\text{cs}}}}{\delta \times \beta})$ to achieve the minimum $\mathcal{W}$. Also, enabling a large $N_B$ is an alternative to minimize $\mathcal{W}$.

In this context, the CS with the highest number of available batteries for the switch is selected with the highest priority, in order to hold the second subcondition. In case all CSs have run out of batteries for the switch, the CS through which an EV experiences the minimum time to wait for the BS service is selected. Our proposed CS-selection indeed follows the above-mentioned discussion, and the following evaluation results will address all factors involved herein.

### *F. Reservation Enabled CS-Selection*

At the GA side, the decision making on where to switch battery considers those anticipated EVs' reservation information as well as the availability of CS to provide the BS service. With the knowledge about the EV's reservations as well as local status of CS, both the expected number of batteries available for switch (as denoted by $\overline{N_B}$) and EWTS at a CS can be estimated.

The CS-selection aims at reducing the average EV driver's perceived waiting time at CS, meanwhile balancing the load among CSs. In the special case, an EV driver may need to wait for additional time, in the case of the unavailability of batteries at a CS. Following Section III-E, we have the following.

1) First, to select the CS with the maximum value of $\overline{N_B}$ from all CSs.
2) Second, if all CSs are not eligible to provide the BS services (means none of them has a switchable battery), the one with the minimum EWTS is selected.

The entire logic is illustrated in Fig. 3. The available time for BS at a CS is estimated based on its local condition, as detailed in Algorithm 3. Upon this, those incoming EVs' reservations are jointly considered to estimate the future status of CS. Here, we refer to the future status as the expected number of batteries available for switch (as detailed in Algorithm 4), and EWTS (as detailed in Algorithm 5).

*1) Estimate Available Time for Switch:* For estimating the available time for a fully charged battery at a CS, we consider

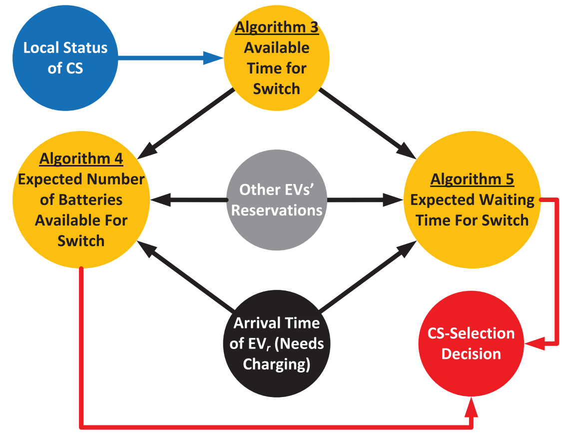



Fig. 3. Flowchart of computation logic.

**Algorithm 3:** Estimate Available Time for Switch.

1: **for** $(i = 1; i \leq N_C; i++)$ **do**
2: ATSLIST.ADD $\left(\left(E_{\mathcal{B}_{(i)}}^{max} - E_{\mathcal{B}_{(i)}}^{cur}\right)/\beta + T_{cur}\right)$
3: TLIST.ADD $\left(\left(E_{\mathcal{B}_{(i)}}^{max} - E_{\mathcal{B}_{(i)}}^{cur}\right)/\beta + T_{cur}\right)$
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 $N_D$ according to STCF
10: **for** $(j = 1; j \leq N_D; j++)$ **do**
11: sort TLIST with ascending order
12: $T_{\mathcal{B}_{(j)}}^{fin} = \left(\text{TLIST.GET(0)} + \left(E_{\mathcal{B}_{(j)}}^{max} - E_{\mathcal{B}_{(j)}}^{cur}\right)/\beta\right)$
13: replace TLIST.GET(0) with $T_{\mathcal{B}_{(j)}}^{fin}$
14: ATSLIST.ADD$\left(T_{\mathcal{B}_{(j)}}^{fin}\right)$
15: **end for**
16: **return** ATSLIST
17: **end if**

two types of queues. Those batteries that are under charging are characterized in the queue of $N_C$, while those still waiting for charging are characterized in the queue of $N_D$.

Algorithm 3 starts with processing each charging battery (in the queue of $N_C$), where its time duration $(E_{\mathcal{B}_{(i)}}^{\max} - E_{\mathcal{B}_{(i)}}^{\text{cur}})$ $/\beta$ to be fully recharged will be summated with $T_{\text{cur}}$. This summated value is considered as the charging finish time of the battery, and then, it is included into ATSLIST (as monitored by the GA) and TLIST (for computation purpose), presented at lines 2 and 3.

Upon processing those batteries under charging, Algorithm 3 will return the ATSLIST, if the number of batteries waiting for charging is 0 as the condition stated at line 6, or a loop operation for each battery waiting for charging has been processed (as stated between lines 10 and 16).

In the latter case, the loop operation starts by sorting the queue of $N_D$ based on the SCTF charging scheduling order. Meanwhile, the TLIST containing when the charging of those batteries (in the queue of $N_C$) will be finished, is initialized in

TABLE III
EV RESERVATION INFORMATION

| EV ID | Selected CS ID | Arrival time | Expected charging time |
|---|---|---|---|

the ascending order. Therefore, the earliest available time is at the head of TLIST, denoted by TLIST.GET(0).

Within each loop, the charging finish time $T^{\text{fin}}_{\mathcal{B}_{(j)}}$ of each battery (in the queue of $N_D$) will replace with TLIST.GET(0). At line 12, $T^{\text{fin}}_{\mathcal{B}_{(j)}}$ is calculated as the summation of time to start charging as denoted by TLIST.GET(0), and battery charging time given by $(E^{\max}_{\mathcal{B}_{(j)}} - E^{\text{cur}}_{\mathcal{B}_{(j)}})/\beta$. Furthermore, $T^{\text{fin}}_{\mathcal{B}_{(j)}}$ will be included into ATSLIST.

The above loop operation ends when all batteries (in the queue of $N_D$) have been processed, and then the ATSLIST is returned. By recursing Algorithm 3 for each CS, their available time for switch can be estimated by the GA.

*2) Reporting Reservation Information:* Whenever a CS-selection decision is made and returned to the EV$_r$ (the EV needs the BS service), which sends the request to the GA, the following information together with the IDs of EVs and the selected CS will be reported to the GA, as the EV's reservation information, given by an example in Table III.

*Arrival time:* We denote as $T^{\text{arr}}_{\text{ev}}$ the time slot during which an EV will arrive at the selected CS, where

$$T^{\text{arr}}_{\text{ev}} = T_{\text{cur}} + T^{\text{tra}}_{\text{ev}}. \tag{2}$$

Here, $T^{\text{tra}}_{\text{ev}}$ is the travelling time measured from the current location of EV to the selected CS, via the shortest road path. Note that $T_{\text{cur}}$ is the current time in the network.

*Expected Charging Time:* We denote $T^{\text{cha}}_{\mathcal{B}}$ as the expected charging time of the EV's depleted battery upon that arrival, where

$$T^{\text{cha}}_{\mathcal{B}} = \frac{E^{\max}_{\mathcal{B}} - E^{\text{cur}}_{\mathcal{B}} + S_{\text{ev}} \times T^{\text{tra}}_{\text{ev}} \times \alpha}{\beta}. \tag{3}$$

Here, $(S_{\text{ev}} \times T^{\text{tra}}_{\text{ev}} \times \alpha)$ is the energy consumed for the movement traveling to the selected CS, based on a constant $\alpha$ (depending on a certain type of EV) measuring the energy consumption per meter. Therefore, $(E^{\max}_{\mathcal{B}} - E^{\text{cur}}_{\mathcal{B}} + S_{\text{ev}} \times T^{\text{tra}}_{\text{ev}} \times \alpha)$ is the expected electricity of the battery (will be depleted from that EV upon arrival) needs to be recharged, depending on the charging power $\beta$ of the CS.

The assumption of a trustworthy reservation is vulnerable without ensuring the integrity of messages from EVs to the GA on end-to-end aspects, e.g., the forged or wrong reservation information are continuously delivered by the GA to compute quite imprecise estimation for charging waiting time. The general secured vehicular communication framework in [22] can be applied to enable secured delivery of EVs' reservation. Besides, in the case of uncertain EV arrival [13] due to traffic jam, it will also be of importance to periodically update EV's reservation to the GA, such that a revised decision could be recommended to an EV. In such a case, an EV may change the plan to switch the battery at the original CS and head to the CS, subject to the revised decision.

*3) Estimate Expected Number of Batteries Available for Switch:* Algorithm 4 presents the details to estimate the expected number of batteries available for switch, as denoted by

**Algorithm 4:** Estimation of Expected Number of Batteries Available for Switch.

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

$\overline{N_B}$. As indicated in Fig. 3, it also requires the knowledge of the available time for the BS from Algorithm 3, as presented at line 1. Here, we denote as $N_R$ the number of EVs that have already made reservations for the BS at the CS, and initialize $\overline{N_B}$ with the value of $N_B$.

In a special case that the CS is not reserved by any EV, as given by the condition $(N_R = 0)$ at line 4, the arrival time of EV$_r$ $T^{\text{arr}}_{\text{ev}_{(r)}}$ is compared with the charging finish time of each battery (being charged or waiting to be charged) at this CS. If any $T^{\text{fin}}_{\mathcal{B}_{(j)}}$ is earlier than $T^{\text{arr}}_{\text{ev}_{(r)}}$, this means that one more battery will be available for switch upon the arrival of $\text{EV}_r$, with $\overline{N_B}$ being increased by 1, as presented at line 7. Also, the given $T^{\text{fin}}_{\mathcal{B}_{(j)}}$ will be removed from ATSLIST, meaning the number of batteries (being charged or waiting to be charged) decreases.

Then, Algorithm 4 sorts the queue of $N_R$ following FCFS order, which is same as the charging scheduling priority upon EVs arrival. In this case, $\text{EV}_k$ stands for the $k$th EV in the queue of $N_R$. Normally, the arrival time $T^{\text{arr}}_{\text{ev}_{(k)}}$ of each $\text{EV}_k$ (in the queue of $N_R$), making reservation at the CS, will be compared with $T^{\text{arr}}_{\text{ev}_{(r)}}$ (the arrival time of $\text{EV}_r$). As highlighted at line 13, for each $T^{\text{arr}}_{\text{ev}_{(k)}}$, which is earlier than $T^{\text{arr}}_{\text{ev}_{(r)}}$, the former will involve the dynamic update of ATSLIST. This reflects only those EVs (in the queue of $N_R$) with an earlier arrival time than that of $\text{EV}_r$ and are considered for calculating $\overline{N_B}$.

Note that the ATSLIST has been initially sorted according to the ascending order, such that the earliest available time for switch is at the head of ATSLIST. From line 15, $T^{\text{arr}}_{\text{ev}_{(k)}}$ is compared with the charging finish time of each battery (being charged or waiting to be charged) at this CS. If $T^{\text{fin}}_{\mathcal{B}_{(j)}}$ is earlier than $T^{\text{arr}}_{\text{ev}_{(k)}}$, one more battery will be switchable upon the arrival of $\text{EV}_k$, with $\overline{N_B}$ being increased by 1, as presented at line 16. As such, the given $T^{\text{fin}}_{\mathcal{B}_{(j)}}$ will be removed from ATSLIST (and also TEMLIST initialized from line 24), meaning the number of batteries being charged or to be charged decreases.

At line 21, the number of switchable batteries decreases by 1, as $\text{EV}_k$ will be replaced with a fully charged battery. Then, either of the following two statements is true.

1) As given by the condition (ATSLIST.SIZE $\geq \delta$) at line 23, if the number of batteries being charged or to be charged, is larger than the total number of charging slots a CS is equipped with, this reflects that any incoming $\text{EV}_k$ still needs to wait for additional time until a fully recharged battery is available for switch. In this case, the charging finish time $T^{\text{fin}}_{\mathcal{B}_{(k)}}$ of the battery depleted from $\text{EV}_k$ is given at line 28

$$T^{\text{fin}}_{\mathcal{B}_{(k)}} = \left(\text{TEMLIST.GET(0)} + \left(E^{\max}_{\mathcal{B}_{(k)}} - E^{\text{cur}}_{\mathcal{B}_{(k)}}\right)/\beta + T^{\text{sw}}_{\mathcal{B}}\right) \tag{4}$$

where TEMLIST.GET(0)[4] is the time when a charging slot is available at the CS, $(E^{\max}_{\mathcal{B}_{(k)}} - E^{\text{cur}}_{\mathcal{B}_{(k)}})/\beta$ is the time to fully recharge the battery depleted from $\text{EV}_k$, while $T^{\text{sw}}_{\mathcal{B}}$ is the time duration to deplete this battery from $\text{EV}_k$ and switch it with a fully recharged battery.

2) Otherwise, $\text{EV}_k$ can be directly switched with a fully recharged battery without waiting, with $T^{\text{fin}}_{\mathcal{B}_{(k)}}$ given at line 31

$$T^{\text{fin}}_{\mathcal{B}_{(k)}} = \left(T^{\text{arr}}_{\text{ev}_{(k)}} + \left(E^{\max}_{\mathcal{B}_{(k)}} - E^{\text{cur}}_{\mathcal{B}_{(k)}}\right)/\beta + T^{\text{sw}}_{\mathcal{B}}\right). \tag{5}$$

Note that the time to start BS is $T^{\text{arr}}_{\text{ev}_{(k)}}$ which is the same as the arrival time of EV.

Furthermore, the charging finish time of each battery depleted from incoming $\text{EV}_k$ will be included into ATSLIST at line 34. This procedure is repeated until all $\text{EV}_k$ (in the queue of $N_R$) have been processed. Finally, the expected number of batteries available for switch $\overline{N_B}$ is given at line 38.

[4]As we also define TEMLIST at line 2, the first $\delta$ value in ATSLIST are included into TEMLIST. This certainly reflects the charging finish time of batteries being charged at CS. At line 29, replacing $T^{\text{fin}}_{\mathcal{B}_{(k)}}$ with TEMLIST.GET(0), thus, updates the charging finish time of batteries in TEMLIST, for the computation that $\text{EV}_k$ involves in next loop.

**Algorithm 5:** Estimation of Expected Waiting Time for Switch.

1: sort ATSLIST returned by Algorithm 3, with ascending order
2: define TEMLIST
3: set $\overline{N_B} = N_B$
4: **if** $(N_R = 0)$ **then**
5: **if** (ATSLIST.SIZE $< \delta$) **then**
6: **return** EWTS $= 0$
7: **else**
8: **for** ($j = 1; j \leq$ ATSLIST.SIZE; $j++$) **do**
9: **if** $\left(T^{fin}_{\mathcal{B}_{(j)}} < T^{arr}_{ev_{(r)}}\right)$ **then**
10: **return** EWTS $= 0$
11: **end if**
12: **end for**
13: **return** EWTS $= \left(\text{ATSLIST.GET(0)} - T^{arr}_{ev_{(r)}}\right)$
14: **end if**
15: **else**
16: Implement the operations between lines 11 and 36 in Algorithm 4
17: **end if**
18: **if** $\left(\overline{N_B} > 0\right)$ **then**
19: **return** EWTS $= 0$
20: **else**
21: Implement the operations between lines 8 and 13 in Algorithm 5
22: **end if**

*4) Estimate EWTS:* Similar to Algorithm 4, Algorithm 5, which presents the details to estimate the EWTS, also requires the knowledge from Algorithm 3 as well as those EVs making reservations. This provides a way to estimate $\omega_{l_{\text{cs}}}$, as discussed in Section III-E.

In another special case that there has not been any EV made reservation at the CS, the EWTS is only related to the local status of the CS. Here, $T^{\text{arr}}_{\text{ev}_{(r)}}$ is compared with the charging finish time $T^{\text{fin}}_{\mathcal{B}_{(j)}}$ of each battery (being charged or waiting to be charged) at this CS, specifically, if either of the following two statements is true.

1) If there is any $T^{\text{fin}}_{\mathcal{B}_{(j)}}$ earlier than $T^{\text{arr}}_{\text{ev}_{(r)}}$, this means one more battery will be available for switch upon the arrival of $\text{EV}_r$. As such, the EWTS is returned as 0 at line 10, since incoming EV will not experience any delay to wait for a switchable battery. Additionally, if the size of ATSLIST is smaller than the value of the charging slots, as given by (ATSLIST.SIZE $< \delta$), the EWTS is returned as 0 at line 6, as charging slots are not fully occupied (the CS can fully charge $\delta$ batteries).

2) Otherwise, the EWTS is returned as (ATSLIST.GET(0) $-$ $T^{\text{arr}}_{\text{ev}_{(r)}}$) at line 13 if there has not been any battery available for switch upon the arrival of $\text{EV}_r$. Here, ATSLIST.GET(0) is the earliest time to get a switchable battery.

From line 16, each EV (in the queue of $N_R$) made reservation will be processed, by following the same operations between lines 11 and 36 in Algorithm 4. This mainly involves the updation of ATSLIST and $\overline{N_B}$, depending on participated EVs reservations information. The above-mentioned procedure is repeated until all $\mathrm{EV}_k$ (in the queue of $N_R$) have been finally processed.

1) Presented between lines 18 and 19, the EWTS is returned as 0 if $\overline{N_B}$ is still larger than 0, since there is no waiting time to experience the BS service. This is also the same as the case if the arrival time of $\mathrm{EV}_r$ $T^{\mathrm{arr}}_{\mathrm{ev}_{(r)}}$ is later than the earliest time a battery is switchable, presented between lines 9 and 10.
2) Alternatively, EWST is given by the rule at line 21, following the same operation between lines 8 and 13 in Algorithm 5. This determines whether there is a switchable battery upon the arrival of $\mathrm{EV}_r$, by comparing each $T^{\mathrm{fin}}_{B_{(j)}}$ in ATSLIST with $T^{\mathrm{arr}}_{\mathrm{ev}_{(r)}}$.

## IV. Reservation Enabled BS Service (Decentralized System)

### A. Privacy Concern in Centralized System

In general, the BS service can be executed in both centralized and distributed manners. In the centralized manner, the CS selection is executed by the GA, as presented in Section III-F. However, this raises much privacy concern, because the EV status information (e.g., location, ID) needs to be released. In contrast, the decentralized manner benefits from a low privacy sensitivity, where the CS-selection decision is executed by an EV individually (using the information broadcasted from CSs). Importantly, the accuracy of information (ATSLIST calculated in Algorithm 3, $N_B$, and associated EVs' reservations formatted in Table III) plays an important role in CS-selection, particularly in a decentralized manner. This is because the CS-selection decision would be suboptimal, due to obsolete information involved for CS-selection.

### B. Communication Signalings

Motivated by the concern on privacy, we propose a decentralized system (without GA involved for handling optimization), where nonrealtime information is exchanged between CSs and EVs. Major differences from Section III-F are on the CS-selection phase and the reservation phase. In the decentralized system, each CS broadcasts its information, formatted in Table IV, to EVs through the cellular network and acquires its associated EV's reservations (primarily through IoV anycasting and, additionally, a cellular network as the back-up). Fig. 4 illustrates a typical procedure.

1) Each CS periodically (with interval $\Delta$) broadcasts its information throughout the cellular network. Thus, each EV in the network can always access broadcasted information from CSs, within interval $\Delta$.
2) The EV that has planned on where to charge, namely $\mathrm{EV}_r$, reports its reservation to its selected CS. The reservation could be relayed by any encountered EV, namely $\mathrm{EV}_x$ to a CS. Here, $\mathrm{EV}_x$ is qualified by whether it can help with delivery before the time slot $(\Delta + L)$ (as the time slot of the next CSs broadcasting),[5] where $L$ is the previous broadcasting time slot.

[5]We consider all CSs' broadcasting is synchronized, such a system is also applicable to the case where CSs are with different broadcasting intervals.

TABLE IV
Format of CS Broadcasting

| | | |
|---|---|---|
| —CS ID— | | |
| $\mathrm{CS}_1$ | | |
| —Number of switchable batteries— | | |
| $N_B = 3$ | | |
| —Available time for switch— | | |
| ATSLIST = [2000 s, 3400 s, 3900 s] | | |
| —Anonymous EVs' reservations— | | |
| Entry | Arrival Time | Expected charging time of depleted battery |
| 1 | 3300 s | 300 s |
| ..... | ..... | ..... |
| 6 | 4700 s | 700 s |

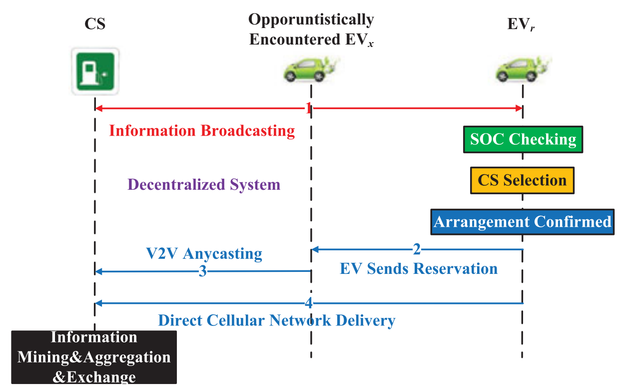



Fig. 4. Communication signalings.

3) The V2V anycasting will be repeated, until the reservation of $\mathrm{EV}_r$ is finally delivered to a CS. This refers to a "one-to-any" paradigm, as the delivery ends up at any one of CSs (does not need to be the CS selected by $\mathrm{EV}_r$). Here, an acknowledgement of successful reservation making will be replied to $\mathrm{EV}_r$ (omitted in signaling procedure).
4) Each CS analyzes and mines valid information from delivered EVs' reservations. The valid information refers to those reservations of which the EV's arrival is supposed to be later than $(\Delta + L)$. Such mined reservations will be aggregated and further exchanged among CSs through the Internet, depending on the ID of the CS (selected by the EVs with common charging intentions). As an example in Fig. 5, aggregated EVs' reservations associated with $\mathrm{CS}_3$ (delivered by $\mathrm{CS}_1$ through the V2V anycasting) will be sent to $\mathrm{CS}_3$ through the Internet. Then, at the time slot approaching $(\Delta + L)$.
   a) Each CS merges its associated EV's reservations with its local condition (ATSLIST and $N_B$) for broadcasting, following the format of Table IV.
   b) If the reservation of $\mathrm{EV}_r$ has not been delivered through the V2V anycasting (e.g., $\mathrm{EV}_r$ has not received acknowledgement from its planned CS), then $\mathrm{EV}_r$ directly reports its reservation to the selected CS through the cellular network.

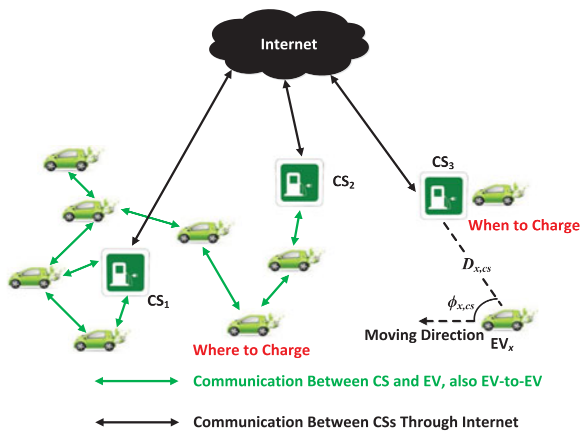



Fig. 5. Big picture of decentralized system.

### C. Analysis on Communication Cost

*1) Decentralized System:* Each CS experiences a communication cost of $O\left(\frac{N_{\text{ev}}}{\Delta}\right)$, for broadcasting its information (ATSLIST calculated in Algorithm 3, $N_B$ and associated EVs' reservations formatted in Table III) to all EVs. Here, $N_{\text{ev}}$ is the number of EVs. The situation for reservation making depends on following options.

1) If with the V2V anycasting for reservations delivery to any CS, such a way experiences a cost of $O(N_{\text{ev}})$, depending on EVs density. Of course, to appropriately select a small number of EVs as relays would further reduce the cost, as widely studied in DTN routing [21].
2) Note that, the cellular network is adopted as the backup solution by EV$_r$, only if its reservation has not been delivered at the time slot approaching $(\Delta + L)$. Here, EV$_r$ will wait for a certain time than use the cellular network, if it does not receive a confirmation. As such, the system experiences a cost of $O(\mathcal{R})$, where $\mathcal{R}$ is directly related to the number of BS requests.

*2) Centralized System:* The cost at the GA side for handling EVs' charging requests and reservations are both $O(\mathcal{R})$.

*3) Decentralized Versus Centralized System:* In reality, it is reasonable to meet $(\mathcal{R} \geq N_{\text{ev}})$, which means that each EV needs to charge more than once in the long term. Thus, we claim that the communication efficiency of the decentralized system, for sustainable delivery of reservations. This is achieved by transferring the communication cost from density of service requests $\mathcal{R}$, to the density of EVs $N_{\text{ev}}$.

### D. Reservation Delivery Intelligence

We assume EVs adopt pseudonyms scheme so that their real IDs would not be revealed or known to other vehicles. This is important to make sure the CS can also verify the received requests as legitimate. Otherwise, attackers could overload the CS with fake requests causing denial of service attack. As illustrated in Fig. 6, EVs' reservations are delivered through the following three options in the decentralized system.

*1) Vehicle-Assisted Direct Delivery:* If the encountered EV (namely EV$_x$) is also traveling toward its selected CS (with its arrival time $T^{\text{arr}}_{\text{ev}_{(x)}}$, which does not need to be the same CS selected by EV$_r$), we have

$$(T^{\text{arr}}_{\text{ev}_{(r)}} \geq (\Delta + L)) \text{ and } (T^{\text{arr}}_{\text{ev}_{(x)}} < (\Delta + L)) \tag{6}$$

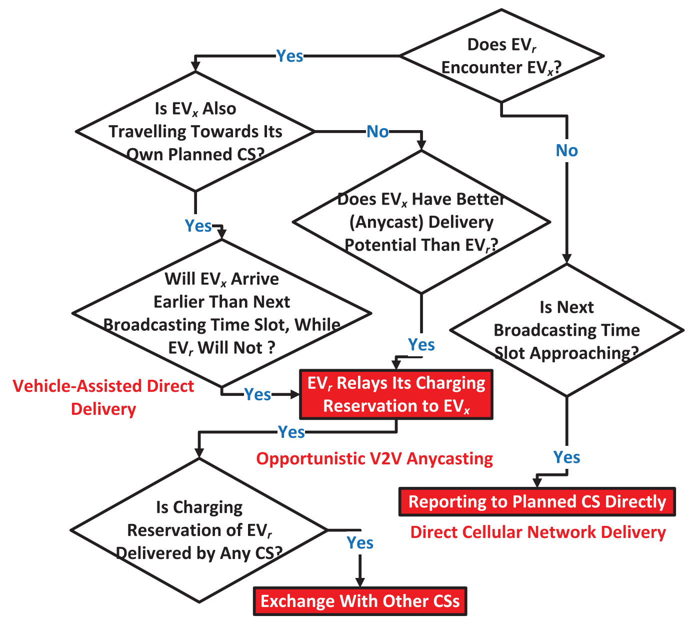



Fig. 6. Flowchart of reservation delivery.

to trigger EV$_r$ to replicate a copy of its reservation to EV$_x$. This is because the reservation from EV$_r$ is only useful[6] to predict the future status of the CS (where EV$_r$ intends to charge), given by $(T^{\text{arr}}_{\text{ev}_{(r)}} \geq (\Delta + L))$. As such, to timely deliver, the reservation of EV$_r$ bounded by $(\Delta + L)$ is facilitated by a faster mobility of EV$_x$, with $(T^{\text{arr}}_{\text{ev}_{(x)}} < (\Delta + L))$.

*2) Opportunistic V2V Anycasting:* If EV$_x$ has not been in charging planning toward its selected CS, a DTN-based anycasting scheme is applied. To estimate the delivery potential of EV$_x$, we denote the anycast probability to deliver the reservation of EV$_r$, to any one of $N_{\text{cs}}$ CSs, as $\mathcal{P}$

$$\mathcal{P} = 1 - (1 - P_{\text{cs}})^{N_{\text{cs}}}. \tag{7}$$

Here, $(1 - P_{\text{cs}})$ means the probability that the reservation is not delivered, while $P_{\text{cs}}$ is the successful probability of this event.

We propose a geocentric anycasting approach based on (7), by considering speed $S_x$, a relative moving direction toward a CS $\phi_{x,\text{cs}}$, and distance $D_{x,\text{cs}}$ between EV$_x$ and a CS (shown in Fig. 5). To qualify $P_{\text{cs}}$ bounded by $(\Delta + L)$, we further define $(H = \Delta + L - T_{\text{cur}})$ as the remaining time left to that time bound $(\Delta + L)$, where $T_{\text{cur}}$ is the current time in network.

Next, we apply our previous work, a unicasting routing scheme delegation geographic routing [19] to the EV charging use case. It utilizes $\frac{D_{x,\text{cs}} - T}{\phi_{x,\text{cs}} \times S_x}$ as the intersect time to CS, where $T$ is the V2V communication radius (also for that between EV and CS). Then, we have

$$P_{\text{cs}} = \begin{cases} \frac{H - \frac{D_{x,\text{cs}} - T}{\phi_{x,\text{cs}} \times S_x}}{H} & \text{if}(\phi_{x,\text{cs}} < \frac{\pi}{2}) \text{ and } (H > \frac{D_{x,\text{cs}} - T}{\phi_{x,\text{cs}} \times S_x}) \\ 0 & \text{else.} \end{cases} \tag{8}$$

[6] The charging reservation of EV$_r$ with an earlier arrival than $(\Delta + L)$ will not be mined by CSs for future broadcasting. This is because the reservation of EV$_r$ will be deleted by its selected CS, upon once being parked at there.

Fig. 7. Simulation scenario of the Helsinki city.

Depending on the mobility of $\mathrm{EV}_x$, the more CSs it can intersect with forwarding progress ($\phi_{x,\mathrm{cs}} < \frac{\pi}{2}$) and earlier arrival than $H$, the higher $\mathcal{P}$ will be. Further to this, an iterative optimization [19] for fast converged routing decision is implemented to reduce the communication cost involved for V2V manner to $O(\sqrt{N_{\mathrm{ev}}})$ (e.g., not select $\mathrm{EV}_x$ if it does not extensively contribute to delivery).

*3) Direct Cellular Network Reporting:* $\mathrm{EV}_r$ would switch to the cellular network, for reporting its reservation to the selected CS. This happens at the time slot approaching $(\Delta + L)$, while the reservation has not been delivered through the above two options.

## V. Performance Evaluation

We have built up an entire EV charging system in opportunistic network environment (ONE) [23], a network simulator developed for VANETs communication. In Fig. 7, the default scenario with $4500\times$ 3400 $\mathrm{m}^2$ area is shown as the down town area of the Helsinki city abstracted from Google map. Here, 300 EVs with 30–50 km/h variable moving speed and 300 m transmission range are initialized in the network. The destination of each EV trip is randomly selected from a location in the map. Particularly, once the current destination is reached, a new destination is randomly chosen again. Such a procedure is repeated until the EV reaches the SOC threshold, and then requests the BS service. The configuration of EVs follows the charging specification {MEC, max travelling distance (MTD), SOC threshold}. EVs are a type of Hyundai BlueOn as set in [13] {16.4 kWh, 140 km, 15–45%}.

Here, the electricity consumption for the traveled distance (TD) is calculated based on MEC $\times$ TD/MTD, as widely used in the literature such as [9]. All EVs' batteries are fully charged at the beginning. Besides, 7 CSs are provided with sufficient electric energy and 30 charging slots through the entire simulation, using the charging rate of 10 kW (using the constant charging power in our work can refer to many previous works on common CS-selection schemes, e.g., [10]–[12], [17]). A total of 30 fully charged batteries are initially set for each CS. This is different from previous works on demand response where the charging power is dynamically adjusted. Here, the shortest path toward CS is formed considering the Helsinki road topology.

Even if each EV reaching the SOC threshold may request a BS at different time slots due to its variable speed ranging between 30–50 km/h and initial location, the charging management is essential as some EVs need to wait for additional time for the BS, until a battery is fully charged by the CS and then becomes switchable. The following schemes are evaluated for comparison.

1) *BS:* The proposed centralized BS based CS-selection scheme in Section III-F, but does not bring EVs' reservations. This means that the queue of $N_R$ is always 0, as the EV will not report its reservation. Besides, *BS (O)* is the way to estimate batteries' availability as given in [17].
2) *Reservation-BS:* The proposed centralized CS-selection scheme, presented in Section III-F, based on the BS system, with EVs' reservations enabled.
3) *A-Reservation-BS:* The proposed decentralized CS-selection scheme, presented in Section IV, where EVs' reservations are delivered through anycasting.
4) *MQT [5]:* The centralized CS-selection scheme based on the plug-in charging technology [5], which selects the CS with the minimum queueing time.
5) *Reservation-1 [10], Reservation-2 [11]:* The *plug-in charging*-based centralized CS-selection schemes, which take EVs' reservations into account. Note that in [10], the estimation is decoupled into ten time intervals.

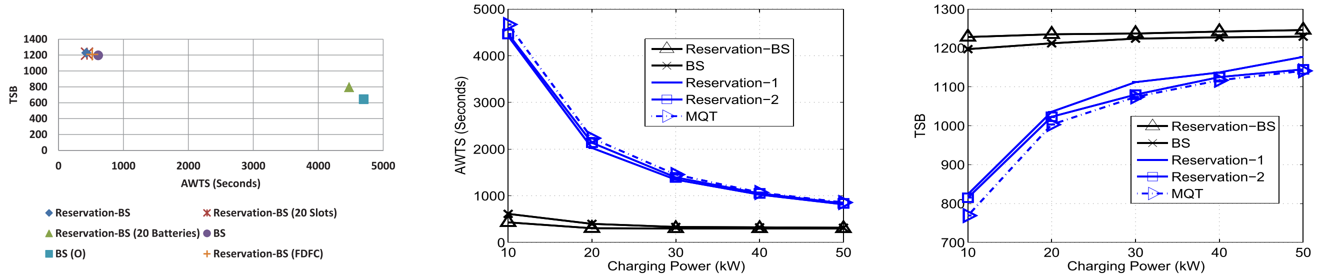
The simulation represents a 12 h duration with a $\gamma = 0.1$ s resolution. So, the EVs' positions, speeds, and energies are updated every 0.1 s, on the road or at a CS. The following performance metrics are evaluated.

1) *Average waiting time for switch (AWTS):* The average period between the time an EV arrives at the selected CS and the time it finishes BS as the performance metric at the EV side.
2) *Total switched batteries (TSB):* The total number of EVs have been switched with batteries at CSs as the charging performance metric at the CS side.
3) *Total reservations making (TRM):* The communication cost for reservation service captured through the cellular network.

### A. Influence of Charging Power

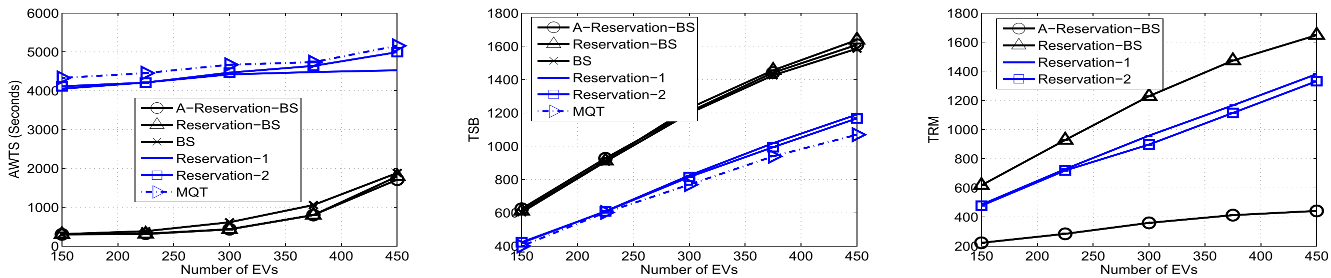
In Fig. 8(a), we observe the performance (in terms of AWTS and TSB) applying the STCF policy to charge depleted batteries, which outperforms that applying the first deplete first charge (FDFC) policy. This is because CSs will not experience a long service queue if the period for batteries cycling is reduced via STCF policy. Whereas in case of FDFC, batteries that can be fully charged in short time may be delayed for charging, due to their later depleted time from EVs. In the following evaluation, we apply the STCF policy for battery cycling.

The advantage of applying the reservation service is reflected by comparing BS with Reservation-BS. Besides, both a less number of charging slots $\delta$ and batteries $N_B$ degrade performance. This is mainly due to the lack of switchable batteries for incoming EVs. This is because as less EVs' batteries are switchable at CSs, the time for other parked EVs to wait for BS increases. Furthermore, BS (O) performs worse than BS because the proposed scheme jointly considers the expected number of switch batteries, for balancing the switchable batteries among CSs.




(a) (b) (c)

Fig. 8. Influence of charging power $\beta$. (a) AWTS versus TSB Given 10 kW charging power. (b) AWTS. (c) TSB.




(a) (b) (c)

Fig. 9. Influence of EVs' density $N_{\mathrm{ev}}$. (a) AWTS. (b) TSB. (c) TRM.

If the charging power at CSs is increased, the performance is improved, as shown in Fig. 8(b) and (c). In particular, a reservation-enabled scheme benefits more from increased charging power than other schemes. This implies that a fast charging power is able to service EVs toward a saturation, even not with the BS technology. Here, the benefit of enabling BS over a plug-in charging system is reflected by comparing "Reservation-BS" with "Reservation-1" and "Reservation-2." Particularly, we observe that those with/without reservation service enabled start to perform closely under the 50-kW case. This implies that when incoming EVs or depleted batteries can be fast recharged, the benefit of enabling EVs' reservations becomes subtle. In other words, most likely there will not be charging hotspot at CSs.

## B. *Influence of Density of EVs*

Results in Fig. 9(a) and (b) show that the BS system outperforms the plug-in system, even in the case of a lower EVs density. This is directly related to the contributions from battery cycling and the proposed CS-selection scheme. Here, both the "Reservation-BS" and "BS" perform closely given 150 EVs. This is because the initially maintained $30 \times 7 = 210$ batteries are sufficient to support timely BS without additional waiting.

As the number of EVs increases, enabling the reservation for CS-selection starts to show its benefit, by balancing the batteries switched as well as minimizing the time to wait for switchable batteries. In spite of this, the CS-selection schemes under the plug-in charging system ("Reservation-1" and "Reservation-2") still perform worse than those ("Reservation-BS" and "A-Reservation-BS") under the BS system. Here, the decentralized "A-Reservation-BS" has a slightly worse performance (a longer AWTS and less TSB), because of a periodical information broadcasting.

However, in Fig. 9(c), "A-Reservation-BS" achieves a much lower cost to deliver EVs' reservations through the cellular network compared to the centralized "A-Reservation-BS." This is due to the flexibility of V2V anycasting to deliver reservations.

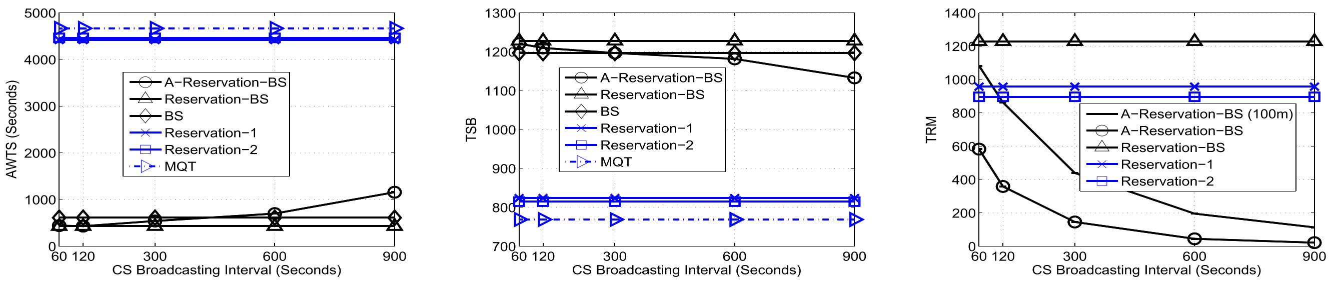
## C. *Influence of CS Broadcasting Interval*

In Fig. 10(a) and (b), we observe that infrequent CS broadcasting $\Delta$ (e.g., 900 s) degrades both AWTS and TSB under "A-Reservation-BS." This is mainly because of the obsolete information received by EVs, which leads to the suboptimal CS-selection.

Since other compared schemes function in a centralized manner, they are not affected by $\Delta$. In Fig. 10(c), if decreasing the V2V transmission range, the case "A-Reservation-BS (100 m)" suffers from much higher TRM. This is because the infrequent encounter between EVs, is unable to timely deliver reservation through anycast-driven V2V manner. As such, most of EV's reservations will be delivered through the cellular network as the back-up solution at the time of approaching the next broadcasting. With the default 300-m case (shown as "A-Reservation-BS"), such cost is dramatically reduced as more EVs' reservations can be delivered through V2V anycasting.

## D. *Future Works*

If bringing the heterogeneous BS system, the difference of information to be required from depleted battery (of the EV on-the-move) is still the required charging time of battery. Such required charging time depends on the full volume of the battery (because the charging power at CS is not changed). As this work assumes that EVs are with homogeneous batteries, future work will consider the compatibilities between heterogeneous EVs




(a) (b) (c)

Fig. 10. Influence of CS broadcasting interval Δ. (a) AWTS. (b) TSB. (c) TRM.

and batteries (e.g., each type of EV can only be switched with a certain type of battery).

Also, the battery degradation should also be taken into account for CS-selection, considering the impact of charging power and frequency, etc. For example, for the comfort of EV drivers, they may prefer to switch the battery at a CS, which fast cycles depleted batteries using a higher power. Whereas, this would bring a negative impact on the battery state of health (SOH). Therefore, investigating the tradeoff between SOH and driver's comfort is worthwhile.

## VI. Conclusion

In this paper, we investigated the BS technology to enable fast EV charging in an urban city. The system addresses the fast cycling policy to provide switchable batteries for incoming EVs. Also, EVs' reservations including arrival time and expected charging time of batteries are taken into account to estimate the future status of CSs. The CS-selection policy follows the rules to balance the number of batteries switched among CSs, and to minimize the time to wait for switch (if currently there is no battery switchable). Evaluation results under the Helsinki city scenario showed the advantage of our proposed CS-selection scheme in terms of charging performance at the EV and CS side. A decentralized system is provisioned to address some EVs' privacy concerns, which outperforms other schemes in terms of communication cost for a reservation service.

## References

[1] J. Mukherjee and A. Gupta, "A review of charge scheduling of electric vehicles in smart grid," *IEEE Syst. J.*, vol. 9, no. 4, pp. 1541–1553, Dec. 2015.

[2] E. Rigas, S. Ramchurn, and N. Bassiliades, "Managing electric vehicles in the smart grid using artificial intelligence: A survey," *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 4, pp. 1619–1635, Aug. 2015.

[3] M. Gharbaoui, L. Valcarenghi, R. Bruno, B. Martini, M. Conti, and P. Castoldi, "An advanced smart management system for electric vehicle recharge," in *Proc. IEEE Int. Electr. Veh. Conf.*, Mar. 2012.

[4] F. Hausler, E. Crisostomi, A. Schlote, I. Radusch, and R. Shorten, "Stochastic park-and-charge balancing for fully electric and plug-in hybrid vehicles," *IEEE Trans. Intell. Transp. Syst.*, vol. 15, no. 2, pp. 895–901, Apr. 2014.

[5] Y. Cao, N. Wang, and G. Kamel, "A publish/subscribe communication framework for managing electric vehicle charging," in *Proc. IEEE Int. Conf. Connected Veh. Expo*, Vienna, Austria, Nov. 2014, pp. 318–324.

[6] E. Rigas, S. Ramchurn, N. Bassiliades, and G. Koutitas, "Congestion management for urban EV charging systems," in *IEEE Int. Conf. Smart Grid Commun.*, Vancouver, BC, Canada, Oct. 2013, pp. 121–126.

[7] S.-N. Yang, W.-S. Cheng, Y.-C. Hsu, C.-H. Gan, and Y.-B. Lin, "Charge scheduling of electric vehicles in highways," *Elsevier Math. Comput. Model.*, vol. 57, no. 11/12, pp. 2873–2882, Jun. 2013.

[8] F. Malandrino, C. Casetti, C.-F. Chiasserini, and M. Reineri, "A game-theory analysis of charging stations selection by EV drivers," *Perform. Eval.*, vol. 83/84, Suppl. C, pp. 16–31, 2015.

[9] M. M. de Weerdt, E. Gerding, S. Stein, V. Robu, and N. R. Jennings, "Intention-Aware routing to minimise delays at electric vehicle charging stations," in *Proc. 27th AAAI Conf. Artif. Intell.*, Jul. 2013.

[10] Y. Cao *et al.*, "Towards efficient, scalable and coordinated on-the-move EV charging management," *IEEE Wireless Commun.*, vol. 24, no. 2, pp. 66–73, Apr. 2017.

[11] Y. Cao, N. Wang, G. Kamel, and Y.-J. Kim, "An electric vehicle charging management scheme based on publish/subscribe communication framework," *IEEE Syst. J.*, vol. 11, no. 3, pp. 1822–1835, Sep. 2017.

[12] H. Qin and W. Zhang, "Charging scheduling with minimal waiting in a network of electric vehicles and charging stations," in *Proc. ACM Int. Workshop Veh. Inter-Netw.*, Las Vegas, NV, USA, Sep. 2011, pp. 51–60 .

[13] Y. Cao, T. Wang, O. Kaiwartya, G. Min, N. Ahmad, and A. H. Abdullah, "An EV charging management system concerning drivers' trip duration and mobility uncertainty," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 48, no. 4, pp. 596–607, Apr. 2018.

[14] T. Winkler, P. Komarnicki, G. Mueller, G. Heideck, M. Heuer, and Z. Styczynski, "Electric vehicle charging stations in magdeburg," in *Proc. IEEE Veh. Power Propulsion Conf.*, Sep. 2009, pp. 60–65.

[15] F. Pan, R. Bent, A. Berscheid, and D. Izraelevitz, "Locating PHEV exchange stations in V2G," in *Proc. IEEE Int. Conf. Smart Grid Commun.*, Gaithersburg, MD, USA, Oct. 2010, pp. 173–178.

[16] X. Tan, B. Sun, and D. H. K. Tsang, "Queueing network models for electric vehicle charging station with battery swapping," in *Proc. 2014 IEEE Int. Conf. Smart Grid Commun.*, Nov. 2014, pp. 1–6.

[17] Y. Cao *et al.*, "A cost-efficient communication framework for battery switch based EV charging," *IEEE Commun. Mag.*, vol. 55, no. 5, pp. 162–169, May 2017.

[18] O. Kaiwartya *et al.*, "Internet of vehicles: Motivation, layered architecture, network model, challenges, and future aspects," *IEEE Access*, vol. 4, pp. 5356–5373, Sep. 2016.

[19] Y. Cao, Z. Sun, N. Wang, H. Cruickshank, and N. Ahmad, "A reliable and efficient geographic routing scheme for delay/disruption tolerant networks," *IEEE Wireless Commun. Lett.*, vol. 2, no. 6, pp. 603–606, Dec. 2013.

[20] M. T. Beck, M. Werner, S. Feld, and S. Schimper, "Mobile edge computing: A taxonomy," in *Proc. 6th Int. Conf. Adv. Future Internet*, Nov. 2014.

[21] Y. Cao and Z. Sun, "Routing in delay/disruption tolerant networks: A taxonomy, survey and challenges," *IEEE Commun. Surveys Tut.*, vol. 15, no. 2, pp. 654–677, Second Quarter, 2013.

[22] F. Kargl *et al.*, "Secure vehicular communication systems: Implementation, performance, and research challenges," *IEEE Commun. Mag.*, vol. 46, no. 11, pp. 110–118, Nov. 2008.

[23] A. Keränen, J. Ott, and T. Kärkkäinen, "The ONE simulator for DTN protocol evaluation," in *Proc. Int, Conf. Simul. Tools Tech.*, Mar. 2009.