# Towards Efficient, Scalable and Coordinated On-the-move EV Charging Management

Yue Cao, Omprakash Kaiwartya, Ran Wang, Tao Jiang, Yang Cao, Nauman Aslam and Graham Sexton

***Abstract*—Unlike traditional Internal Combustion Engine Vehicles (ICEVs), the introduction of Electric Vehicles (EVs) is a significant step towards green environment. Public Charging Stations (CSs) are essential for providing charging services for on-the-move EVs (e.g., EVs moving on the road during their journeys). Key technologies herein involve intelligent selection of CSs to coordinate EV drivers' charging plans, and provisioning of cost-efficient and scalable communication infrastructure for information exchange between power grid and EVs. In this article, we propose an efficient and scalable Publish/Subscribe (P/S) communication framework, in line with a coordinated on-the-move EV charging management scheme. The case study under the Helsinki city scenario shows the advantage of proposed CS-selection scheme, in terms of reduced charging waiting time and increased number of charged EVs, as charging performance metrics at EV and CS sides. Besides, the proposed P/S communication framework shows its low communication cost (in terms of signallings involved for charging management), meanwhile with great scalability for supporting increasing EVs' charging demands.**

## I. Introduction

IN Smart Grids, the application of Electric Vehicles (EVs) [1] has been recognized as a significant transportation option to reduce $CO_2$ emissions. However, due to the limited battery capacity and long trip distance in urban cities, EVs on-the-move are more likely to run out of energy, thus need to recharge batteries during their journeys. How to manage the charging processes to improve EV drivers' comfort, is vital to the success and long-term viability of the EV industries.

Research efforts of literature works on EV charging management focus on two use cases: The *Parking Mode* addresses the use case where EVs are parking at homes/Charging Stations (CSs), with the concerning on when/whether EVs should be charged (namely charging scheduling). The *On-the-move Mode* addresses the use case where EVs are on-the-move, with the concerning on where/which CSs they should plan for charging (namely CS-selection).

Enabling mobile and communication technologies [2], [3] are important in Smart Grids, particularly for the *On-the-move Mode* use case. Here, the decision on where/which CSs to charge involves interaction across a number of entities in network, e.g., on-the-move EVs, CSs and Global Controller (GC) which implements the sole charging management. As such, there is a necessity to design the communication infrastructure with efficiency and scalability in mind, concerning the long term introduction of EVs. Nevertheless, majority of recent literature works rely on ubiquitous cellular network communication [4], which is an expensive solution.

Corresponding author: Ran Wang (wangran@nuaa.edu.cn)

Envisioning for urban city charging scenario (by selecting a geographically deployed CS as charging plan), we aim to answer the following three questions:

- How can state-of-the-art Intelligent Transportation Systems (ITS) techniques be utilized for the on-the-move EV charging management? such as Road Side Unit (RSU), Global Position Systems (GPS), standardization of Vehicle to Infrastructure (V2I) communications. We propose a Publish/Subscribe (P/S) [5] communication framework to facilitate the fast charging service, where necessary information (e.g., charging availability of CSs, and charging reservations of EV drivers) are shared among network entities. Also, we enable light-weight computation at RSU to aggregate information for the purpose of communication cost reduction.
- Which CS should be selected by the EV driver to achieve the best driving experience (e.g., minimized charging waiting time), and how to utilize EV drivers' charging reservations (e.g., arrival time and expected charging time at their selected CSs) to coordinate charging management? We develop a distributed charging management scheme concerning EV drivers' charging reservations to coordinate their charging plans.
- How does the provisioned communication framework affect the actual charging performance (e.g., charging waiting time for EV drivers, and number of charged EVs at CSs), and is the provisioned ITS-enabled communication framework efficient and scalable? We study the influence of information publication interval, RSU and EV densities on the system-level performance.

## II. Review on EV Charging Management

### A. Parking Mode

Majority of previous works address this use case, where EVs have already been parking at homes/CSs. For a detailed survey of this use case, we recommend the readers to refer to [6]. Here, we briefly summarize these works as follows:

- Schedule and coordinate the charging/discharging of EVs, with different durations and charging/discharging rates such that power grid constraints are maintained and charging requirements of EVs are satisfied. This realizes the actual benefits brought by EVs (cleaner transportation) and eliminates the harmful impacts on the electricity network (such as voltage deviations, transformers and line saturations, increase of electrical losses, etc) [7].
- Address pricing issues in order to encourage EVs to charge during periods of off-peak hours, so that the total

demand profile of the power grid can be shaped to a nicely smoothed demand profile. And integrate renewable energy, mainly solar and wind energies into the electrical network as complimentary and clean power supply solution [1].

### *B. On-the-move Mode*

A few works have studied how to manage the EV drivers' charging plans, where they are on-the-move. Three branches have been studied:

- Route EVs (with charging event [8]) to minimize energy loss and maximize energy harvested during a trip, such that the time spent to fully recharge EVs is minimized. This would consider EV speed, as part of the efficiency of EVs results from their ability to recover some energy during deceleration.
- Where to deploy CSs (providing either plug-in charging or battery switch service [9]) such that EVs can access CSs within their driving ranges. Besides, the capabilities of CSs to handle peak demands are taken into account, due to different number of EV arrivals at different times.
- Select the appropriate CS as charging plan (or refer to where to charge). For example, to select the CS which is not highly congested [10], so as to experience a minimized charging waiting time.

## III. Provisioning of P/S Communication Framework For On-the-move EV Charging Service

In this article, we focus on the latter use case (*On-the-move Mode*), explicitly tackling where/which CSs to charge EVs. Although a few existing works have addressed the *coordinated* charging management schemes, the attention towards an *efficient* and *scalable* communication framework has not been investigated.

### *A. Centralized vs Distributed Charging Management*

In general, the EV charging management in the *On-the-move Mode* use case can be executed in both centralized and distributed manners.

- With the centralized manner, the charging management is executed by the GC or other third party who is interested in charging management. However, such a manner brings much privacy concern, as the EV status (e.g., location and ID) included in its charging request has to be released to the GC.
- The distritbuted manner benefits from a much improved privacy protection (compared to the centralized manner), where the charging management is executed by EV individually (via accessed condition information from CSs).

Necessary information needs to be disseminated to corresponding entities involved in both charging manners, in which the accuracy of information plays an important role on the charging management. For the centralized charging manner, the cellular network communication (with a ubiquitous communication range) is applied. While, heterogeneous network communications, e.g., WiFi or even Delay Tolerant Networking (DTN) nature communication [11] can be applied for the distributed management manner.

### *B. The P/S Paradigm*

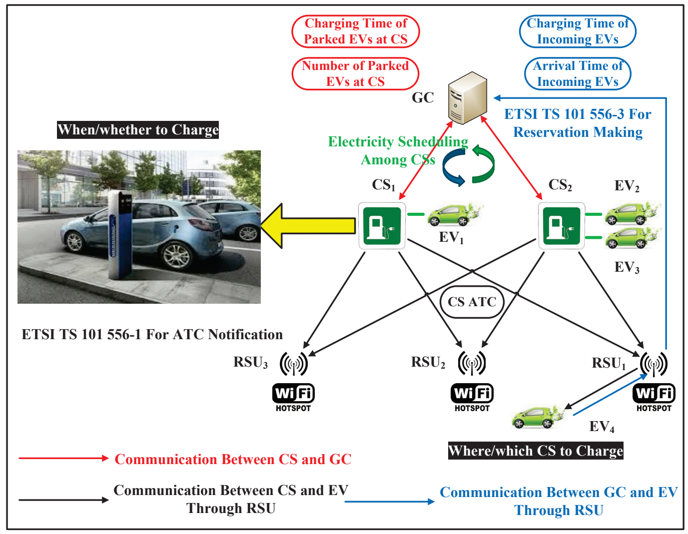


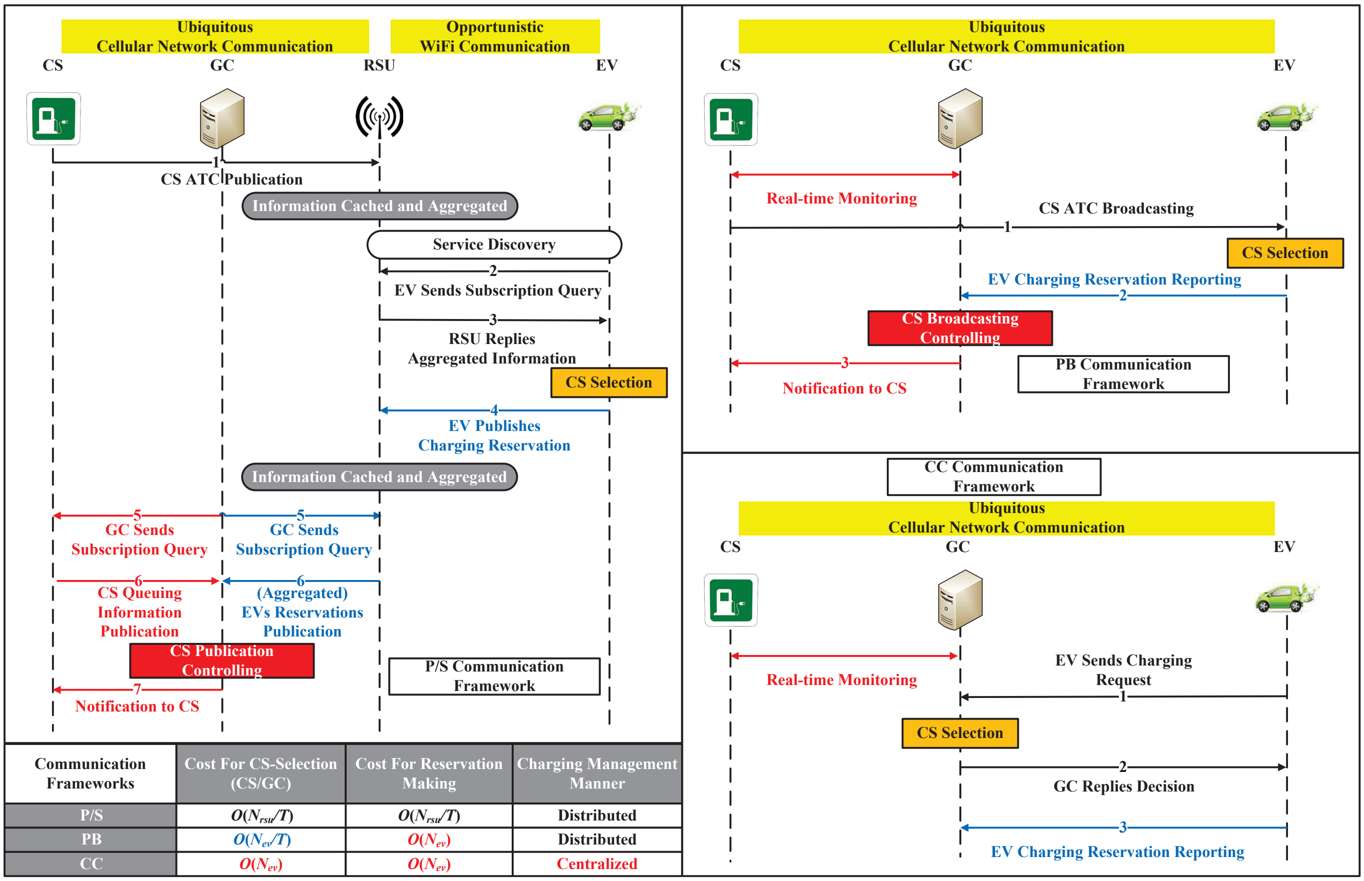

Fig. 1. Big Picture

We herein provision a Publish/Subscribe (P/S) with topic based communication paradigm, in which different stakeholders in the ecosystem including EVs, CSs, RSU and GC, can subscribe to the information of their interest. This is different from literature works relying on the point-to-point communication paradigm. In Fig.1, four network entities are involved in the system:

**Electric Vehicle (EV):** It pro-actively interacts with RSUs to access information from CSs, e.g., the Available Time for Charging (ATC) - about when the CS is available for charging an EV. Each EV is with a Status Of Charge (SOC) and implements two operations: 1) If the ratio between its current energy and maximum energy is below the SOC threshold (a value under which the EV should seek for charging), the EV starts to select a CS as charging plan (based on the accessed information from RSUs); 2) The EV which has made its individual CS-selection, is able to further make the remote reservation. Here, the reservation includes arrival time (when the EV will arrive at a CS) and expected charging time at the selected CS (how long its charging time will be).

**Charging Station (CS):** It is located at a certain location to charge EVs in parallel, via multiple plug-in chargers. Particularly, its local condition information (including number of EVs parking at a CS and their charging time) is subscribed by the GC for ATC computation. Also, each CS periodically publishes its ATC information to legitimate RSUs.

**Road Side Unit (RSU):** It is strategically deployed at a certain location, and mainly involved for two operations: 1) It bridges the information flow from CSs to EVs (for advertising CSs' ATC purpose), and that from EVs to the GC (for reservations making purpose). Each RSU is able to aggregate all CSs' ATC information, caches and publishes it when receiving a subscription query from the on-the-move EV passed by; 2) The RSU also aggregates EVs' charging reservations, that is subscribed by the GC for the ATC computation purpose.




| Communication Frameworks | Cost For CS-Selection (CS/GC) | Cost For Reservation Making | Charging Management Manner |
|---|---|---|---|
| P/S | $O(N_{rsu}/T)$ | $O(N_{rsu}/T)$ | Distributed |
| PB | $O(N_{ev}/T)$ | $O(N_{ev})$ | Distributed |
| CC | $O(N_{ev})$ | $O(N_{ev})$ | Centralized |

Fig. 2. Signalling Procedures of P/S, PB and CC Communication Frameworks

**Global Controller (GC)**[1]**:** It manages the ATC publication of all CSs in a centralized manner. The CSs' local condition and EVs' charging reservations are jointly considered, to compute and control the ATC publication of CSs. This operation is mainly involved in the *On-the-move Mode* use case.

The provisioning of P/S communication framework well supports the distributed charging management, where EVs access CSs' condition information from opportunistically encountered RSUs (shown as black color signalling) and make their individual charging managements about where/which CSs to charge when needed. Upon the CS-selection decisions have been made, EVs further publish their charging reservations, to the GC through RSUs (shown as blue color signalling). Such anticipated information associated with a CS together with the CS's local condition information, will be used by the GC to compute the ATC of that CS (shown as red color signalling).

## C. Design of Proposed P/S Communication Framework

All CSs are geographically deployed under a city scenario, and their locations are available for all EVs through their embedded GPS. Each CS is connected to all RSUs using reliable channel such as authorized cellular network communication, and periodically publishes its ATC.

Furthermore, EVs are capable of making remote reservations to the GC via the P/S system, before reaching their selected CSs.

The GC then analyzes the EVs' charging reservations together with their associated CS's local condition information, to compute and notify ATC publication of that CS. Note that, by strategically deploying RSUs (as CS-selection decision is only made when needed), there will not be an overlap between the radio coverage of adjacent RSUs.

The "ETSI TS 101 556-1" [12] standard has been defined for the on-the-move EV charging use case. Its the basic application is to notify EV drivers about the CSs' status (e.g., ATC in our charging system), such that EVs are able to select CSs for charging. In addition, the "ETSI TS 101 556-3" [13] standard enables the remote charging reservation service, from EVs to the GC. Fig.2 shows a typical procedure:

**Step 1:** Each CS periodically (with publication interval $T$) publishes its ATC to all RSUs, using its individual "*ATC_Update*" topic (defined in TABLE I). The RSU subscribes to the publications from all CSs, will aggregate and cache their ATC information.

**Steps 2-3:** Given an opportunistic encounter between pairwise EV and RSU, the EV fetches the cached information from that encountered RSU. Here, the EV is aware of an

[1] It also schedules the amount of electricity among CSs, depending on the anticipated charging demands (identified from received EVs' charging reservations). This operation is mainly involved in the *Parking Mode* use case.

TABLE I
TOPICS DEFINED IN P/S SYSTEM

| Topic | Dissemination Nature | Publisher | Subscriber | Payload |
|---|---|---|---|---|
| *ATC_Update* | One-to-Many | CS | RSUs | <CS ID, CS's ATC, publication time slot> |
| *Aggregated_ATC_Update* | Many-to-Many | RSUs | EVs | <Aggregated CS IDs and CSs' ATC, publication time slot> |
| *Charging_Reservations_Update* | Many-to-Many | EVs with charging plans | RSUs | <EV ID, arrival time, expected charging time> |
| *Aggregated_Charging_Reservations_Update* | Many-to-One | RSUs | GC | <Aggregated EVs' reservations cached by RSUs> |
| *Local_Condition_Update* | Many-to-One | CSs | GC | <CS's local condition information, including number of EVs parking at CS and their charging time> |
| *ATC_Controlling* | One-to-Many | GC | CSs | <Computed ATC of each CS> |

updated service published from RSU (through existing service discovery protocols). As such, it only subscribes to the aggregated ATC of CSs, that is published at updated time slot, using the "*Aggregated_ATC_Update*" topic. This reduces the redundant access signalling, particularly when an EV frequently encounters several RSUs in short time.

**Step 4:** The EV requiring charging service can make its own CS-selection decision on where to charge, and further publishes its charging reservation to an encountered RSU. Here, the "*Charging_Reservations_Update*" topic is applied, with the EV as publisher and RSUs as subscribers. Each RSU aggregates its received a number of EVs' charging reservations and locally caches it.

**Steps 5-6:** At the GC side, it sets two dedicated topics to collect[2] information from CSs and RSUs.

- The local condition information of CSs includes the number of parked EVs and their required battery charging time, which is accessible by sending a subscription query via the "*Local_Condition_Update*" topic.
- The GC also accesses aggregated EVs' charging reservations from all RSUs, using the "*Aggregated_Charging_Reservations_Update*" topic.

**Step 7:** The GC then computes the ATC related to each CS, and controls their publication at the next time publication interval, using the "*ATC_Controlling*" topic.

Compared to [10], we bring heterogeneous topics illustrated in TABLE I and enable light-weight computation at RSUs side. This is motivated by the recent trend of data services towards the edge of the cloud, resulting in novel architectures called "fog computing" [14] for increasing data security while reducing information access times.

## D. Other Alternative Cases

We further introduce other two alternative communication frameworks acquired for charging service, namely **Periodical Broadcasting (PB)** and **Centralized Case (CC)** also shown in Fig.2.

*1) Periodical Broadcasting (PB):* This is the extreme case without bringing RSUs, specifically:

**Step 1:** Each CS periodically (with interval $T$) broadcasts its ATC to all EVs, through cellular network communication. As such, each EV can always access ATC from CSs within interval $T$.

[2]Rather than seamless operation (realtime monitoring), such collection task is only operated when the next time slot for CSs' publication is approaching.

**Step 2:** The EV which has made the CS-selection decision, reports its charging reservation to the GC, through the cellular network communication.

**Step 3:** By continuously monitoring local condition of CSs and collecting EVs' charging reservations, the GC controls and notifies ATC of all CSs. The computation outcome will be announced at the next broadcasting time slot.

*2) Centralized Case (CC):* Concerning the PB communication framework with an extremely short interval $T$, the PB case would be equivalent to the CC.

**Step 1:** The EV needs charging service sends its request to the GC, through the cellular network communication.

**Step 2:** The GC makes CS-selection decision, based on the continuously monitored CSs' condition information and charging reservations reported from other EVs. The decision on where to charge is replied to that pending EV.

**Step 3:** The EV acknowledges this CS-selection decision, further reports its charging reservation back to the GC, also through the cellular network communication.

## E. Discussion

*1) Probability to Access Information From RSUs:* Concerning the probability $P_{p/s}$ for an EV to access aggregated CSs' ATC from at least one of $N_{rsu}$ RSUs, the above provisioned P/S communication framework shares the same analysis of that in [10], as they both rely on RSUs for information dissemination.

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

Note that $S$ is the distance between adjacent RSUs and $T$ is the publication interval (how often the information is published) of CS. Besides, $V$ is the EV moving speed while $F$ is the distance from the starting point to the first RSU. A higher $P_{p/s}$ implies that the CS's ATC should be cached before EV passing a RSU, from which it is suggested to increase radio coverage $R$, the number of RSUs $N_{rsu}$ and inter-RSUs distance $S$ (To diversely deploy RSUs); and reduce CS publication interval $T$.

*2) Communication Cost:* Furthermore, we denote $N_{ev}$ as number of EVs, the communication cost of the above three communication frameworks are given:

- In proposed P/S case, the cost at CS side for information dissemination is given by $O(\frac{N_{rsu}}{T})$, since there are only $N_{rsu}$ subscribers within each $T$ interval. Similarly, the cost for reservations making to the GC is given by $O\left(\frac{N_{rsu}}{T}\right)$, owing to the information aggregation at RSUs.

- In PB case, each CS experiences a communication cost of $O\left(\frac{N_{ev}}{T}\right)$, for broadcasting its ATC to all EVs. While, $O(N_{ev})$ is scaled for reservation reporting to the GC.
- In CC, the cost at GC side for handling EVs' charging requests and charging reservations are both $O(N_{ev})$.

Since PB case does not involve RSUs, it however relies on a ubiquitous cellular network communication and broadcasting nature. This is even more expensive than the proposed P/S case, which utilizes a short range WiFi communication with an opportunistic nature to interact with on-the-move EVs. The CC suffers from privacy concern, in which the EV status information has to be released through its charging request.

In reality, it is reasonable that $N_{rsu} \ll N_{ev}$, while the number of charging services is larger than $N_{ev}$ (meaning that each EV needs to charge more than once in long term). As such, we claim that the efficiency and scalability of proposed P/S communication framework. Having no direct communication between service providers and clients, the P/S communication paradigm also alleviates the attack surface of network entities.

## IV. On-the-move EV Charging Management Via P/S Communication Framework

### A. System Cycle of On-the-move EV Charging Management

Fig.3 describes five phases involved in the EV charging management cycle.

**Driving Phase:** The EV with sufficient energy above the SOC threshold, is travelling on the road, and can access aggregated CSs' ATC information from opportunistically encountered RSUs.

**Charging Planning Phase:** The EV reaching its SOC threshold, needs to find a CS for charging. Based on accessed CSs' ATC information, the EV locally runs the CS-selection logic.

**Charging Reservation Phase:** The EV which has made its individual CS-selection decision, further publishes its charging reservation to the GC. EVs' charging reservations are aggregated and cached by RSUs, then reported to the GC.

**Charging Scheduling Phase:** Upon arrival at the selected CS, the underlying charging scheduling concerning when to charge EVs, is based on the First Come First Serve (FCFS) order. This means that the EV with an earlier arrival time will be scheduled with a higher charging priority. Of course, further effort could be referred to contributions paid in the *Parking Mode* [6] use case.

**Battery Charging Phase:** The EV is being charged via the plug-in charger at the CS. Once it has been fully charged, the EV will resume its movement and turn to the **Driving Phase**.

### B. CS-Selection Logic

Note that, the EV might have received aggregated CSs' ATC for several times, before it reaches the threshold for making CS-selection decision. Therefore, the CSs' ATC recorded at EV side will be updated towards a more fresh value, for making accurate CS-selection decision. If all charging slots of a CS are currently occupied (meaning all plug-in chargers are connected to other parking EVs), the incoming EV needs to wait until one of them is free.

The CS-selection computed by the GC, is to find the CS through which the EV will experience the shortest charging waiting time, where the CS's ATC computation is detailed as follows:

- **Step 1:** Run at the GC side, it divides the estimation window $W$ into $D$ adjacent time slots, to primarily estimate the CS's ATC associated with each time slot[3]. Note that estimation window $W$ is initialized as the traveling time of the first EV making reservation in network.
- **Step 2:** The CS's ATC associated with a given time slot, is estimated considering the local condition of CS. This only happens when there is no EV made reservation within this time slot.
- **Step 3:** Alternatively, if there exists EVs making reservations for a CS within a given time slot, the travelling time of each EV heading to given selected CS, is compared with the existing estimation window. Upon the comparison, the larger value is updated as the new estimation window.
- **Step 4:** The reservations of those EVs with their arrival time (earlier than a given time slot), are included to estimate the CS's ATC associated with this time slot.
- **Step 5:** Once the CS's ATC associated with $D$ time slots have been calculated respectively, such integrated information will be published with interval $T$.

Note that the CS's ATC computation involved in Step 2 and Step 4 are partially referred to Algorithm 3 and Algorithm 4 in [10]. The main idea is to track the available time of each charging slot, by taking into account the charging time of EVs (in a sorted local CS queue, and also those in the queue of reservation) to charging slot. Here, denote the output of former Algorithm 3 or Algorithm 4 as $\mathcal{H}$, then the CS's ATC associated with a given time slot $\mathcal{T}$, is given by $\mathcal{T}$ (if $\mathcal{H} < \mathcal{T}$), or $\mathcal{H}$ (if $\mathcal{H} \geq \mathcal{T}$). The CS-selection decision made at EV side, is to capture the CS's ATC associated with two adjacent time slots $\mathcal{T}_i$ and $\mathcal{T}_{i+1}$, such that ($\mathcal{T}_i <$ EV Arrival Time $< \mathcal{T}_{i+1}$). Then the charging waiting time of the EV making CS-selection decision is given by $\frac{\text{EV Arrival Time} \times \mathcal{H}_{i+1}}{\mathcal{T}_{i+1}}$. In a special case where the EV arrival time is not bounded within the estimation window $W$, either the ATC associated with the first or last time slot is returned.

In former scheme [10], each CS just publishes its associated EVs reservations, to all on-the-move EVs through RSUs. Its abstract estimation on expected charging waiting time is not driven by the time window $W$, nor linking the ATC associated with each discrete time slot. Therefore, the proposed scheme in this article can capture and predict the status of CS more accurately.

## V. Case Study

We have built up an entire EV charging system in Opportunistic Network Environment (ONE) as used in [10]. In Fig.4, the scenario with 4500×3400 $m^2$ area is as the down

[3]For example, the first and second time slots are the current network time, and that plus $\frac{W}{D}$, respectively.

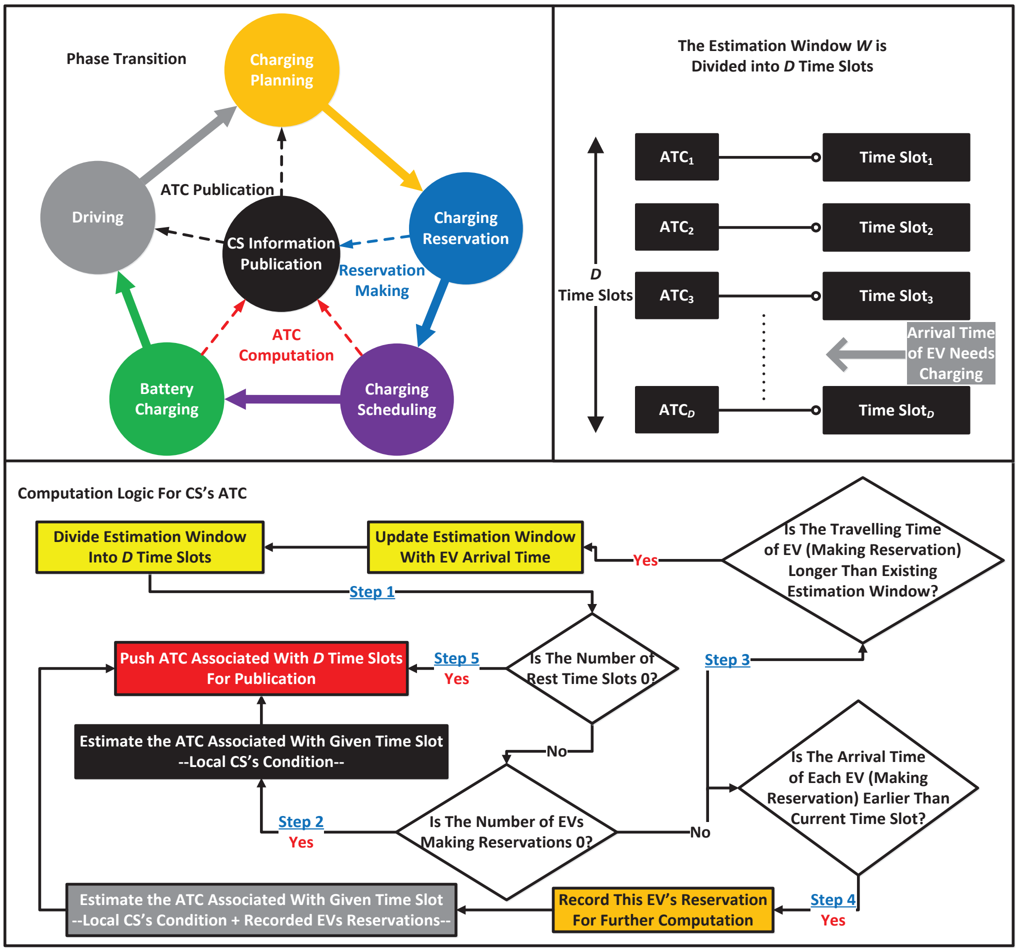



Fig. 3. System Cycle of On-the-move EV Charging Management

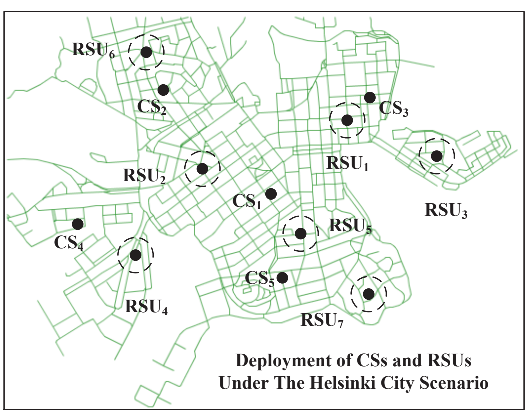



Fig. 4. Helsinki City Scenario (5 CSs + 7 RSUs Deployment)

town area of Helsinki city in Finland. The simulation time is 43200s = 12 hours. Here, 320 EVs are with $[30 \sim 50]$ $km/h$ moving speed. The configuration of EVs follows the charging specification of Wheego Whip EV in [10], and we set SOC threshold = $[24\% \sim 36\%]$ for all EVs. 5 CSs are provided with sufficient electric energy and 7 charging slots through the entire simulation, using the fast charging rate of 62 kW. The CS publication frequency is 100s by default. Besides, 100m short range radio coverage is applied for 7 RSUs and 320 EVs.

The coordinated charging management scheme proposed in Section IV is evaluated under the **P/S**, **PB** and **CC** discussed in Section III. Also, our previous work [10] is compared in distributed and centralized manners, namely **Compared-P/S** and **Compared-CC**. We are interested in **Average Charging Waiting Time** - The average period between the time an EV arrives at the selected CS and the time it finishes charging; **Number of Charged EVs** - The number of EVs have been charged at CSs side.

### *A. Influence of Communication Framework Provisioning*

In TABLE II, the decrease of CS publication frequency (from 100s to 300s) increases the charging waiting time and reduces the number of charged EVs. This implies that, by appropriately controlling the CS publication frequency, the P/S communication framework with distributed charging management manner is able to achieve a comparable charging performance to that of CC. This is because the decision on where to charge is made only when needed, while the CS's ATC publication is periodical. Note that the P/S communication framework is also deemed with a low privacy sensitivity, as compared with the CC case.

TABLE II
EVALUATION RESULTS OF CASE STUDY

| | Default (100s Frequency, 7 RSUs, 320 EVs) | 300s Frequency | 480 EVs | 3 RSUs | 12 RSUs |
|---|---|---|---|---|---|
| **Average Charging Waiting Time** | | | | | |
| CC | 2825s | 2825s | 7167s | 2825s | 2825s |
| Compared-CC | 2945s | 2945s | 7342s | 2945s | 2945s |
| PB | 2827s | 2869s | 7287s | 2827s | 2827s |
| P/S | 3164s | 3735s | 7347s | 3897s | 3125s |
| Compared-P/S | 3683s | 4355s | 7451s | 4100s | 3621s |
| **Number of Charged EVs** | | | | | |
| CC | 888 | 888 | 945 | 888 | 888 |
| Compared-CC | 876 | 876 | 940 | 876 | 876 |
| PB | 887 | 876 | 944 | 887 | 887 |
| P/S | 872 | 827 | 933 | 813 | 875 |
| Compared-P/S | 844 | 796 | 929 | 804 | 847 |
| **Number of Information Accesses From EVs** | | | | | |
| PB | 691200 | 230400 | 1036800 | 691200 | 691200 |
| P/S | 25961 | 18040 | 31326 | 15352 | 37312 |
| Compared-P/S | 79837 | 76116 | 119710 | 51715 | 117702 |
| **Number of Reservations Making to GC/CSs** | | | | | |
| CC | 939 | 939 | 1141 | 939 | 939 |
| Compared-CC | 923 | 923 | 1114 | 923 | 923 |
| PB | 925 | 919 | 1138 | 925 | 925 |
| P/S | 190 | 167 | 276 | 162 | 259 |
| Compared-P/S | 226 | 204 | 303 | 203 | 317 |

Regarding distributed charging manner, deploying a less number of 3 RSUs (by keeping $RSU_1$, $RSU_2$ and $RSU_5$) degrades charging performance. This is because that EVs less likely to encounter RSUs, as reflected by less number of accesses. However, if increasing the number of RSUs to 12 (we uniformly deploy 5 additional RSUs), the charging performance reaches saturation. This mainly depends on the deployment strategy, where the default 7 RSUs are able to bridge accurate information dissemination for all EVs. Of course, certain optimal RSUs deployment can maintain a satisfied performance.

### B. Advantage of Coordinated Charging Management

We next focus on the comparison between the CC and Compared-CC, the former achieves a shorter charging waiting time (2825s v.s 2945s) and larger number of charged EVs (888 v.s 876). This benefits from decoupling the estimation window into several discrete time slots, and then capturing two adjacent time slots (within which the EV will arrive) for making CS-selection decision making. Such a gain is also applicable for the comparison between the P/S and Compared-P/S cases.

### C. Efficiency & Scalability of P/S Communication Framework

The proposed P/S system achieves the lowest number of accesses at EV side, thanks to the service discovery operation and P/S paradigm. Regarding the cost for reservations making at GC (involved in the proposed P/S system) and CSs (involved in the Compared-P/S system) sides, result shows the advantage of former, thanks to aggregation operation at RSUs. In particular, since CC, PB and Compared-CC all require cellular network communication for reservations reporting, they suffer from a much higher cost compared to the P/S (and also the Compared-P/S) communication framework. When increasing the number of EVs from 320 to 480, the P/S system is more scalable than Compared-P/S, by experiencing the lowest cost.

## VI. DISCUSSIONS AND OPEN ISSUES

### A. Advanced System Integration

Renewable energy (e.g., solar and wind) and advanced charging technologies (e.g., battery switch and wireless charging) can be integrated into the P/S system, through which the CSs' ATC publication requires further computation. Besides, the charging price of different CSs could be integrated together with the CSs' ATC for publication, concerning the business model. Note that the high degree of semantic heterogeneity of events in large and open deployments such as smart cities makes it difficult to develop and maintain P/S system.

### B. Urban Driving Uncertainties

Given traffic accidents/jams [15], an EV within a congestion area of traffic jam has to slow down its speed, while it will accelerate its speed once leaving from the range of that traffic jam. Such variation of moving speed inevitably affects the accuracy of EVs' charging reservations. Besides, EV drivers may have their daily routes or point of interests to visit for leisure. This will affect the CS-selection, as a suboptimal charging during journey may degrade drivers' comfort.

### C. Security

Malicious business may bombard an individual EV with unsolicited product or service, e.g., attracting drivers using manipulated CSs condition information. As such, secure communication is required to ensure confidentiality, integrity and availability of information exchange between GC/CSs and EVs.

## VII. CONCLUSION

In this article, we presented an efficient and scalable P/S communication framework, to support on-the-move EV charging management in a coordinated manner. Results showed the advantage of coordinated charging management policy, in terms of reduced charging waiting time for EV drivers and increased number of charged EVs at CSs. The proposed P/S communication framework also outperformed other alternative options, in terms of communication efficiency and scalability, while with comparable charging performance. Open research issues have also been discussed.

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## Biographies

**Yue Cao** received his PhD degree from the Institute for Communication Systems (ICS) formerly known as Centre for Communication Systems Research, at University of Surrey, Guildford, UK in 2013. Further to his PhD study, he was a Research Fellow at the ICS. Since October 2016, he has been the Lecturer in Department of Computer and Information Sciences, at Northumbria University, Newcastle upon Tyne, UK. His research interests focus on Delay/Disruption Tolerant Networks, Electric Vehicle (EV) charging management, Information Centric Networking (ICN), Device-to-Device (D2D) communication and Mobile Edge Computing (MEC).

**Omprakash Kaiwartya** received his Ph.D. degree in Computer Science from School of Computer and Systems Sciences, Jawaharlal Nehru University, New Delhi, India in 2015. He is currently a Post-Doc Research Fellow at Faculty of Computing, Universiti Teknologi Malaysia (UTM), Johor Bahru, Malaysia. His research interests include Vehicular Ad-hoc Networks, Mobile Ad-hoc Networks and Wireless Sensor Networks.

**Ran Wang** is currently an assistant professor at College of Computer Science and Technology, Nanjing University of Aeronautics and Astronautics (NUAA), China and Collaborative Innovation Center of Novel Software Technology and Industrialization, Nanjing, China. He received his Ph.D. degree from School of Computer Science and Engineering, Nanyang Technological University (NTU), Singapore, in April 2016 and B.E. degree from Honors School, Harbin Institute of Technology (HIT), China in July 2011. His research interest includes resources allocation in smart grid, evolution of complex networks, network performance analysis, etc.

**Tao Jiang** is currently a Distinguished Professor in the Department of Electronics and Information Engineering, Huazhong University of Science and Technology, Wuhan, P. R. China. He received the B.S. and M.S. degrees in applied geophysics from China University of Geosciences, Wuhan, P. R. China, in 1997 and 2000, respectively, and the Ph.D. degree in information and communication engineering from Huazhong University of Science and Technology, Wuhan, P. R. China, in April 2004. From August. 2004 to December. 2007, he worked in some universities, such as Brunel University and University of Michigan-Dearborn, respectively. He has authored or co-authored over 200 technical papers in major journals and conferences and six books/chapters in the areas of communications and networks. He served or is serving as symposium technical program committee membership of some major IEEE conferences,including INFOCOM, GLOBECOM and ICC, etc.. He is invited to serve as TPC Symposium Chair for the IEEE GLOBECOM 2013 and IEEE WCNC 2013. He is served or serving as associate editor of some technical journals in communications, including in IEEE Communications Surveys & Tutorials, IEEE Transactions on Vehicular Technology, and IEEE Internet of Things Journal, etc. He is a recipient of the NSFC for Distinguished Young Scholars Award in P. R. China. He is a Senior Member of the IEEE.

**Yang Cao** is currently an assistant professor in the School of Electronic Information and Communications, Huazhong University of Science and Technology, Wuhan, P. R. China. He received his Ph.D. and B.S. degrees in information and communication engineering from Huazhong University of Science and Technology in 2014 and 2009, respectively. From 2011 to 2013, he worked in the School of Electrical, Computer, and Energy Engineering, Arizona State University as a visiting scholar. His research interests include 5G cellular networks and the Internet of Things. He has coauthored more than 30 papers in refereed IEEE journals and conferences. He was awarded the CHINACOM Best Paper Award in 2010 and a Microsoft Research Fellowship in 2011.

**Nauman Aslam** is a Reader in Department of Computer and Information Sciences, at Northumbria University, Newcastle upon Tyne, UK. He received Ph.D. in Engineering Mathematics from Dalhousie University, Canada in 2008. Prior to joining Northumbria he worked as an Assistant Professor at Dalhousie University, Canada from 2008 to 2011. Dr Nauman has extensive research experience in wireless ad hoc and sensor networks, he is a member of IEEE and IAENG.

**Graham Sexton** completed his Ph.D. at Newcastle University in 1983 on the subject of Signal Processing for Ground Probing Radar. Following this, he worked for British Telecoms Visual Telecoms research team at Martlesham Heath, where he led international video compression standardisation work. In 1989, he joined the Northumbria University, Newcastle upon Tyne, UK, where he now is the Academic Head for the Department of Computer and Information Sciences in the Faculty of Engineering and Environment. His research interests include Computer Networks and Image Processing.