Toward Preempted EV Charging Recommendation Through V2V Based Reservation System

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***Abstract*—Electric Vehicles (EVs) are being introduced by different manufacturers thanks to their environment-friendly perspective to alleviate CO_2 pollution. In this article, the proposed EV charging management scheme enables preempted charging service for heterogeneous EVs (*depends on different charging capabilities, brands etc*). Particularly, the anticipated EVs' charging reservations information including their arrival time and expected charging time at Charging Stations (CSs), are brought for planning CS-selection (where to charge). Along with applying *ubiquitous* cellular network communication to deliver (*delay tolerant*) EVs' charging reservations, we further study the feasibility of applying *opportunistic* Vehicle-to-Vehicle (V2V) communication with Delay/Disruption Tolerant Networking (DTN) nature, due primarily to its flexibility and cost-efficiency in Vehicular Ad hoc NETworks (VANETs). Evaluation results under the realistic Helsinki city scenario show that, applying the V2V based charging reservation is promisingly cost-efficient in terms of communication overhead, while achieving a comparable charging performance to applying cellular network communication.**

***Index Terms*—Electric Vehicle, Route Planning, Charging Scheduling, Vehicle-to-Vehicle Communication, Mobility.**

I. INTRODUCTION

IN Smart Grid, the application of Electric Vehicles (EVs) [1] has been recognized as a significant means to reduce CO2 emissions with high penetration of renewables [2]. Compared with combustion engine vehicles, the travelling distance of EVs are limited by their battery volume. To address this concern, public Charging Stations (CSs) are deployed in convenient places (e.g., highway rest stops and gas stations) and places with high user centrality (e.g., parking slots around shopping mall).

Different from previous works [3]–[7] addressing "when/whether" EVs should be charged while they have been parked at homes/CSs (namely charging scheduling), our interest addresses "where" EVs should travel for charging while they are *on-the-move* during journeys (namely CS-selection). Here, an *on-the-move* EV requests charging service, needs to travel towards an appropriate CS for charging. Due to the long charging time (experienced by existing charging technologies), to optimally plan where to charge has become a critical issue. Firstly, how to allocate an appropriate CS based on EV's charging request, will have strong impact on the benefit[1] of CS. Secondly, EV drivers can also benefit from a short time to wait for charging, in terms of better Quality of Experience (QoE).

We refer to the charging system widely adopted by literature [6], [8], based on a Global Aggregator (GA) to manage each real-time EV charging request/reply in a centralized manner. Normally, the cellular network, e.g., 3G/Long Term Evolution (LTE) is applied for ubiquitous and seamless communication. The GA monitors CSs' condition (number of EVs being parked and their charging time), and implements the charging management optimization (including both charging scheduling and CS-selection). In literature, with localization and navigation solutions [9], [10], the CS-selection schemes based on the closest distance [11] and minimum queuing time [8], [12]–[14] have been studied. Nevertheless, none of them has adequately investigated the influence of preempted EV charging scheduling on actual decision making.

Regarding heterogeneities of EVs, those EVs with different types (depending on ownership, e.g., citizens and police, as well as charging capabilities, e.g., maximum battery volume and electricity consumption) are eligible for preempted charging. For example, an EV owned by military or police with emergence will preempt the charging service, prior to others (owned by citizens) already been parked [15], [16]. In this situation, an incoming EV might be scheduled for charging, prior to those already being parked at a CS. This normally happens when the incoming EV is with a higher charging priority.

Inevitably, a potential charging hotspot may happen if many EVs travel towards the same CS for charging, due to the fact that the CS-selection decision just considers CSs' local condition. In this context, it is suggested EVs should

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[1] A grid operator deploys multiple CSs, and aims to maximize their electricity utilization, e.g., attract more drivers to charge.

further report their charging reservations[2] [1], [17]–[19]. *These anticipated information together with the CS's local condition (e.g., available time for charging), will be used to estimate the congestion status of CS in a near future.* However, there is still vacancy to integrate charging reservation for preempted charging service, to balance the charging demands among CSs and particularly reduce the time that heterogeneous EVs wait for charging. Inevitably, the preempted charging scheduling strategy will introduce new design on CS-selection logic. This is because the GA must know whether a reserved EV's charging service will be preempted, and makes optimal recommendation on CS-selection.

Note that the exchange of real-time charging request/reply is delay sensitive, as EV would need to know where to charge instantly. However, reporting EVs' charging reservations (deemed as an auxiliary service), is delay-tolerant (as the essential charging recommendation system still works, even if without reservation) and independent of charging request/reply. The 3G/LTE is normally applied thanks to ubiquitous communication. However, such ubiquitous communication is costly and does not need to be anywhere and anytime, because the charging reservation is only generated when EVs have intentions on where to charge. Alternatively, the Vehicle-to-Vehicle (V2V) communication [20], [21] is receiving increasing interest, thanks to the inexpensive wireless connections and flexility of installation on vehicles. Here, envisioning for VANETs consisting of EVs, we study the feasibility to take the advantage of opportunistic V2V communication for delivery of EVs' charging reservations.

Most of the problems in VANETs arise from highly dynamic network topology, which results in communication disruption. For example, the network can be categorized as being dense in a traffic jam, whereas in suburban traffic it can be sparse. Here, the Delay/Disruption Tolerant Networking (DTN) [22], [23] routing protocols provide a significant advantage, by relying more on opportunistic communication to relay heterogeneous EVs' charging reservations. However, the delay due to opportunistic communication certainly has influence, on how accurate the charging reservations can be delivered to GA. For example, the CS-selection based on the obsolete information (due to long delivery delay), may mislead the EV towards a highly congested CS for charging.

This article addresses the impact of CS-selection on the heterogeneous EV drivers' comfort and impact of communication pattern on charging system, but not on the power grid charging scheduling (i.e., valley filling [24]). We summarize our contributions over literature works, by answering the following questions:

What is the impact of preempted charging based CS-selection? In Section IV, the proposed CS-selection scheme considers the underlying preempted charging scheduling, where the charging of incoming EVs (with a higher charging priority) may take place prior to others (with a lower charging priority) already been parked at a CS. Intuitively, the CS with the Earliest Available Time for Charging (EATC) is selected, depends on the type of EV that requests charging.

What is the benefit to bring EVs' charging reservations? We further propose a charging reservation enabled CS-selection scheme in Section V. It requires EVs (with prioritized charging nature) to further report their charging reservations to the GA (through the cellular communication). Such anticipated information from EVs (which are heading to their selected CSs), will be reported to the GA for CSs' condition estimation in the near future. The CS with the minimum Expected Waiting Time (EWT) is selected to further reduce charging waiting time.

How feasible is to apply V2V communication for delivering EVs' charging reservations? In Section VI, the EVs' charging reservations (with delay tolerance) will be delivered to the GA, through the V2V communication. The reduced communication cost and delay for delivering charging reservations, benefit from the application of Delegation Geographic Routing (DGR) [25], as our previous work on a reliable and efficient geographic DTN routing protocol.

II. RELATED WORK

A. Research on EV Charging Management

Most of previous works aim to determine when/whether to charge EVs (charging scheduling), by saving charging cost to minimize peak loads and flatten aggregated demands [3]–[7].

In contrary, a few works address the problem on where to charge (CS-selection), primarily, by minimizing the waiting time for EV charging. This cannot be overlooked as it is the most important feature of a vehicle in future smart city [26], especially for fast charging. The works in [8], [12]–[14], [27] implement charging plans for all EVs based on the minimized queuing time. Further results in [11] show that considering number of other EVs queueing at the CS, outperforms that considering the distance to the CS, to achieve a shorter charging waiting time given high EVs density. In [28], the CS with a higher capability to accept EVs' charging requests, will advertise this service with a higher frequency. While EVs sense this service with a decreasing function of their current battery level. Further to these, enabling the EV's charging reservation [1], [17]–[19] is brought into system, in order to further improve performance.

B. Research on DTN Routing

The general term on routing data is how to forward network traffic from the source to destination. Having been receiving attention, routing in VANETs is different from that in Mobile Ad Hoc Networks (MANETs) for the reasons of:

- The movement of vehicles are limited by road topology.
- The communication shortest path does not always match the physical shortest path due to heterogeneous vehicular traffic conditions on road segments.
- The frequent intermittent connectivity due to the high mobility makes the MANET routing ineffective under the VANETs scenario.

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[2] The EV's charging reservation only associates with the CS, where the EV has charging intention. This includes when it will arrive at their selected CSs and how long their charging time will be at there. If the EV does not have charging intention, both expected charging time and arrival time can not be determined, thus no charging reservation will be made. Note that the reservation information is sent from the EV, only if it has accepted the CS-selection decision from the GA.

In order to deal with the frequent intermittent connectivity due to high mobility, the Store-Carry-Forward (SCF) mechanism in Delay/Disruption Tolerant Networks (DTNs) [22] makes routing feasible in VANETs. The encounter prediction is important for routing in DTNs, where the utility metric defined in various ways is used to qualify whether an encountered node is a good relay. Given our reviews [22], [29], geographic routing protocols [25] fit well for vehicular-DTNs scenario.

C. Our Contribution

Compared to the work enables charging reservation service, a fundamental difference between our work and [18] is that, the latter assumes highway scenario where the EV will pass through all CSs. Its expected waiting time is calculated for the EV passing through the entire highway, by jointly considering the charging waiting time at a CS that the EV needs charging for the first time and that of any consequent CS before exiting the highway. In contrary, under our targeted city scenario the EV will head to a single geographically distributed CS for charging, where the expected waiting time is only in relation to that certain CS.

Previous works on CS-selection (even with charging reservation enabled [1], [17]–[19]) rarely consider the preempted EV charging scheduling (when/whether to charge), while they are just based on the First Come First Serve (FCFS) charging scheduling strategy. In our previous work [19], the performance of enabling V2V communication (flooding vs cellular network) for charging reservation under FCFS charging service has been firstly presented. Further to that, this article includes the design of preempted charging service, in line with a advanced DGR routing scheme [25] for reservation delivery. Compared to applying ubiquitous cellular network communication for auxiliary charging reservation service, applying the flexible V2V communication is also able to facilitate the driver's comfort. While, since our focus is to fundamentally minimize the charging waiting time for drivers, combining dynamically adjusted pricing [30], charging power [27], trip destination [31] could be integrated.

III. PRELIMINARY

A. Network Entities in Charging System

Electric Vehicle (EV): Each EV is with a Status Of Charge (SOC). If the ratio between its current energy and maximum energy is below the SOC threshold, EV starts to negotiate with the GA for charging planning. Additionally, upon acceptance of the decision from GA, the EV reports its charging reservation to the selected CS.

Charging Station (CS): Each CS is located at a certain location to charge EVs in parallel, with multiple charging slots. Its local condition (number of EVs already been parked at the CS and their charging time) is monitored by the GA, through reliable channel, e.g., cellular network or wired line communication.

Global Aggregator (GA): As shown in Fig. 1, the CSs' local condition (additionally, EVs' charging reservations may be needed) will be gathered. The GA behaves as centralized cloud server to make charging planning for the EV (which is below the SOC threshold) through the certain CS-selection scheme.

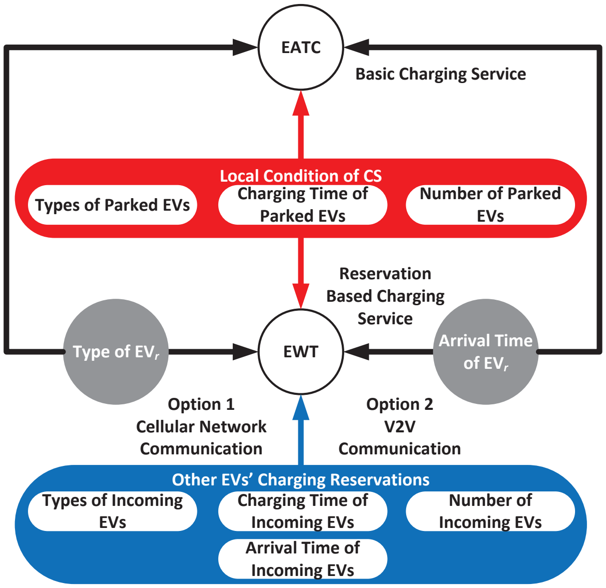

Fig. 1. Knowledge Required in Charging System

B. System Cycle of EV Charging Management

Fig. 2 describes the system cycle:

- **Driving Phase:** The EV is on journey, with sufficient electricity energy above the SOC threshold.
- **Charging Planning Phase:** The EV needs to travel towards a CS for battery recharging, by sending charging request to the GA.
  - With basic charging service, the GA replies the charging planning back to the EV, then the EV travels towards that selected CS for charging.
  - With reservation enabled charging service, upon accepting[3] the charging planning from GA, the EV responses its charging reservation to the GA. This procedure refers to **Charging Reservation Phase**.
- **Charging Scheduling Phase:** The parked EV will wait CS to schedule its charging, upon its arrival at the selected CS.
- **Battery Charging Phase:** The parked EV is being charged, will turn to the **Driving Phase** once its battery is fully charged.

C. Assumption

In this article, we assume each EV is equipped with Global Position System (GPS) that contains its own movement information, including current location and speed. The physical locations of CSs have already been labeled on digital map. We assume a seamless signallings exchange between EVs and the GA, through a reliable channel such as 3G/LTE. Therefore, the

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[3] It is omitted between Steps 2-3 in Fig. 3, as the charging planning from the GA is just a recommendation, and it is driver to make final decision.

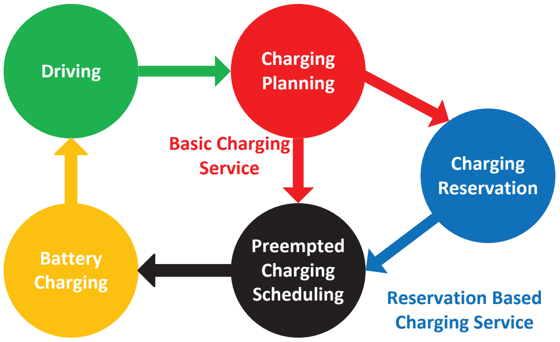

Fig. 2. System Cycle

EV (in [32], the drivers can choice their target SOC depending on own convenience, through the interaction with onboard system) needs charging service can be informed by the GA, with a charging planning instantly. Normally, EVs' charging reservations, as an auxiliary service with delay tolerant nature, could be delivered through the cellular network. Alternatively, these can be delivered in opportunistic V2V manner, through a number of intermediate *on-the-move* EVs.

The solutions to achieve trusted message exchange for EV charging use case, are to encrypt the sensitive information and hide the real identity. One development aspect of the encryption involves the light-weight and highly secured encryption algorithm, while another one is to design an efficient and scalable key management scheme.

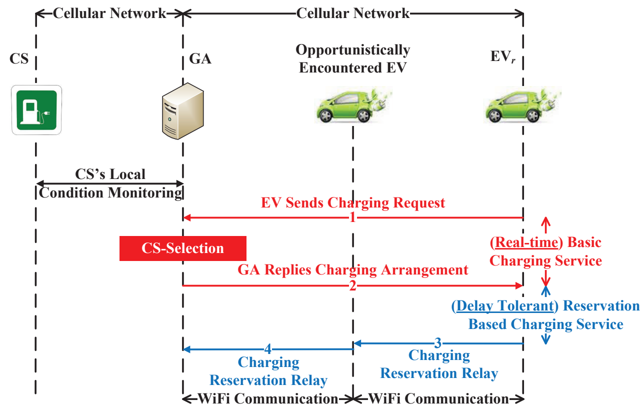

Fig. 3. Signallings for Charging System

Our contributions focus (where to charge) on the **Charging Planning Phase** and **Charging Reservation Phase**, based on a preempted charging scheduling policy (when/whether to charge) executed in the **Charging Scheduling Phase**. System signallings are illustrated in Fig. 3:

- **Step 1:** For each *on-the-move* EV needs charging, namely EV$_r$, it informs the GA about its charging request (through the cellular network).
- **Step 2:** The GA (which continuously monitors CSs local condition) compiles a list of CSs and recommends the best one (e.g., depends on CS-Selection schemes proposed in Section IV and Section V). The decision is sent back to EV$_r$ (through the cellular network).
- **Steps 3-4:** EV$_r$ further reports its charging reservation, including its arrival time and expected charging time at the selected CS. This information is normally sent through the cellular network in Section V, or the V2V communication in Section VI.

D. Preempted Charging Scheduling For Parked EVs

Our major focus is on the CS-selection (concerning where to charge). To specify the operations of the system clearly, we first present the underlying charging scheduling scheme (concerning when to charge).

Each CS ranks the charging priority of parked EVs, and applies multiple charging slots to process charging in parallel. We consider two types of EVs, which are "High Prioritized-EV (H-EV)" and "Low Prioritized-EV (L-EV)" respectively. In general, we differentiate EVs depending on their unique charging capabilities (e.g., ownership, brand, maximum battery volume and electricity consumption). A policy for their charging scheduling is given as follows:

- Those EVs with the "H-EV" type are normally scheduled prior to those with the "L-EV" type, regardless of their arrival time at a CS. This policy guarantees a preempted charging service for those "H-EVs". *Note that H-EVs (either been parked or just arrive) can preempt L-EVs (parked but have not being charged).*
- Regarding those with the same type, they are prioritized based on the the First Come First Serve (FCFS) order, such that the one with an earlier arrival time is scheduled with a higher priority. Note that the FCFS is commonly applied by most previous works for charging planning [17], [18].

E. CS-Selection Objective

To simply the solution, all CSs are equipped with the same charging slots δ, and charging power β. Based on above descriptions, we further introduce the following notations to facilitate problem formulation concerning the charging waiting time:

- $\gamma_{l_{cs}}$: Number of EVs with common charging intention at a CS.
- $\omega_{l_{cs}}$: Average waiting time for each EV plans charging at CS.
- $\mathcal{W}$: Total waiting time for all EVs in network.

And we have to:

$$\text{Minimize } \mathcal{W} = \sum_{l_{cs} \in N_{cs}} \gamma_{l_{cs}} \times \omega_{l_{cs}} \tag{1}$$

Here, note that $\gamma_{l_{cs}}$ is a decreasing function of N_{cs}. This is because that a larger number of N_{cs} CSs enables a small $\gamma_{l_{cs}}$ EVs distributed at each CS. Furthermore, $\omega_{l_{cs}}$ is related to $\gamma_{l_{cs}}$, δ, and β. This is reflected by the fact that, a large number of $\gamma_{l_{cs}}$ EVs with common charging intention at a CS, inevitably increases their average charging waiting time at this CS. Of course, both a fast charging power β and more number of charging slots δ will reduce such time.

In order to achieve the minimum waiting time for EVs allocated at N_{cs} CSs, $\gamma_{l_{cs}} \times \omega_{l_{cs}}$ should be equal among all CSs, as an ideal situation given in [18]. Since all CSs share the same β and δ, we obtain $\gamma_{l_{cs}} = \mathcal{F}(\frac{1}{N_{cs}})$, and $\omega_{l_{cs}} = \mathcal{F}(\frac{\gamma_{l_{cs}}}{\delta \times \beta})$ to achieve the minimum charging waiting time. Particularly, by considering the preempted charging for heterogeneous EVs (e.g., L-EV, H-EV), $\omega_{l_{cs}}$ needs be reconsidered for the case that the H-EV may preempt the L-EV for charging.

IV. CS-SELECTION IN BASIC CHARGING SERVICE

TABLE I
LIST OF NOTATIONS

N_C	Number of EVs under charging at CS
N_W	Number of EVs waiting for charging at CS
T_{cur}	Current time in the network
LIST	Output including available time per charging slot at CS
δ	Number of charging slots at CS
E_{ev}^{max}	Full volume of EV battery
E_{ev}^{cur}	Current volume of EV battery
β	Charging power at CS
T_{ev}^{arr}	EV's arrival time at CS
T_{ev}^{fin}	EV's charging finish time at CS
T_{ev}^{tra}	EV's travelling time to reach CS
T_{ev}^{cha}	EV's expected charging time at CS
S_{ev}	Moving speed of EV
α	Electric energy consumed per meter
N_R	Number of EVs reserving for charging at CS, sorted with FCFS charging scheduling order
N_R^p	Number of EVs reserving for charging at CS, sorted with preempted charging scheduling order

A. Estimation of Earliest Available Time For Charging (EATC)

The decision on where to charge only considers those EVs which are parked at CSs. Shown in Fig. 1, the CS with the minimized EATC, reflects the minimum time for an incoming EV to wait for charging. The calculation of the earliest available time for charging is illustrated in Algorithm 1, via the flow chart in Fig. 4.

Here, we define two types of queues. Those EVs under charging are characterized in the queue of N_C, while those still waiting for charging are characterized in the queue of N_W. In special case as presented at line 2 in Algorithm 1, the current time in network as denoted by T_{cur}, is estimated as the earliest available charging time, if all charging slots are unoccupied. Such case means the CS is currently available for charging.

Starting from line 4, the time duration $\frac{E_{ev(i)}^{max} - E_{ev(i)}^{cur}}{\beta}$ to fully recharge the battery of each EV$_i$ (in the queue of N_C), will be summated with T_{cur}. The summation of these two value reflects when the charging for EV$_i$ will be finished. Furthermore, this summation will be added into LIST, which reflects that a charging slot will be available at $\left(\frac{E_{ev(i)}^{max} - E_{ev(i)}^{cur}}{\beta} + T_{cur}\right)$, recall that $\left(\frac{E_{ev(i)}^{max} - E_{ev(i)}^{cur}}{\beta}\right)$ is the time to fully recharge EV$_i$.

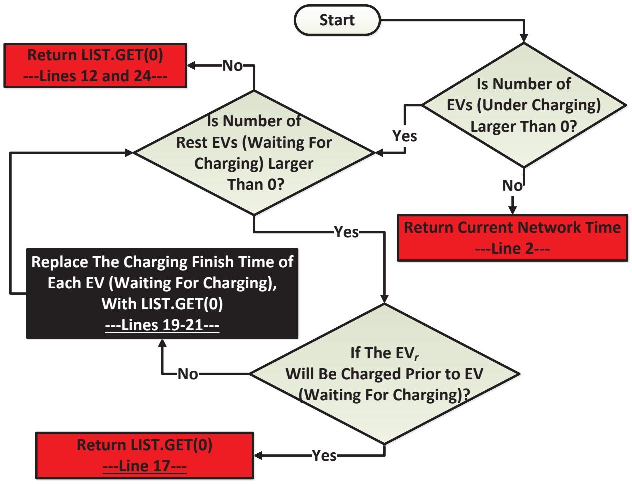

Fig. 4. Flow Chart of Algorithm 1

Algorithm 1 Estimation of EATC

```
 1: if no EV is under charging then
 2:     return $T_{cur}$
 3: end if
 4: for ($i = 1$; $i \leq N_C$; $i++$) do
 5:     LIST.ADD$\left(\frac{E_{ev(i)}^{max} - E_{ev(i)}^{cur}}{\beta} + T_{cur}\right)$
 6: end for
 7: if ($N_C < \delta$) then
 8:     add $T_{cur}$ in LIST with ($\delta - N_C$) times
 9: end if
10: sort LIST with ascending order
11: if no EV is waiting for charging then
12:     return EATC = LIST.GET(0)
13: end if
14: sort the queue of $N_W$ according to preempted charging scheduling policy
15: for ($j = 1$; $j \leq N_W$; $j++$) do
16:     if ((LIST.GET(0) > $T_{ev(r)}^{arr}$)$\cap$(EV$_j$ is "L-EV")$\cap$(EV$_r$ is "H-EV")) then
17:         return LIST.GET(0)
18:     else
19:         $T_{ev(j)}^{fin}$ = LIST.GET(0) + $\frac{E_{ev(j)}^{max} - E_{ev(j)}^{cur}}{\beta}$
20:         replace LIST.GET(0) with $T_{ev(j)}^{fin}$ in LIST
21:         sort LIST with ascending order
22:     end if
23: end for
24: return EATC = LIST.GET(0)
```

Upon the above process, the following presentation between lines 7 and 9 implies that not all charging slots are fully occupied, because there are still $(\delta - N_C)$ charging slots available for charging. In this context, T_{cur} is thus estimated as the available charging time for those unoccupied charging slots.

Here, Algorithm 1 will return the EATC, either if there is no EV waiting for charging (the condition at line 11), or a loop operation for each EV$_j$ (in the queue of N_W) waiting for charging has been processed (between lines 15 and 23).

In the latter case, the loop operation starts from sorting the queue of N_W, based on the preempted charging scheduling. Meanwhile, the LIST in relation to those EVs under charging is sorted with ascending order, where the earliest available charging time is at the head of LIST. Therefore, we denote LIST.GET(0) as the first value in LIST:

- In particular, since EV$_r$ (the *on-the-move* EV needs charging service) with the "H-EV" type, could preempt charging prior to those parked EV$_j$ (in the queue of N_W) with the "L-EV" type, the EATC is returned at line 17, given:

$$((\text{LIST.GET(0)} > T^{arr}_{ev(r)}) \cap (\text{EV}_j \text{ is "L-EV"}) \cap (\text{EV}_r \text{ is "H-EV"})) \tag{2}$$

  Above condition as highlighted at line 16, implies that the arrival time of EV$_r$ is earlier than the LIST.GET(0), meanwhile the processed EV$_j$ (in the queue of N_W) is with the "L-EV" type. As such, the charging of parked EV$_j$ will be preempted by the incoming EV$_r$.
- Apart from the above special case, the operation at line 19 calculates the charging finish time $T^{fin}_{ev(j)}$ of each EV$_j$, and replaces this value with LIST.GET(0). Upon the above, the LIST will be further sorted with ascending order, such that LIST.GET(0) is updated for further calculation.

The above loop operation ends when all EV$_j$ have been processed, then the EATC (the first value in LIST) is returned at line 24.

B. Performance Evaluation

We adopt Opportunistic Network Environment (ONE) [33], a java based simulator for evaluation. In Fig. 5, the default scenario with 4500×3400 m^2 area is shown as the down town area of Helsinki city (Fig. 6) in Finland. Here, 240 EVs with [2.7 $\sim$ 13.9] m/s variable moving speed are initialized in the network. The configuration of EVs follows the charging specification {Maximum Electricity Capacity (MEC), Max Travelling Distance (MTD), Status Of Charge (SOC)}. We differentiate two types of EVs, which are:

- **Coda Automotive**[4] {33.8 kWh, 193 km, 30%} for 120 L-EVs.
- **Hyundai BlueOn**[5] {16.4 kWh, 140 km, 50%} for 120 H-EVs.

As such, EVs are differentiated by their brands throughout our simulation. Note that each EV may need to charge more than once, due to its continuous mobility.

Here, the electricity consumption for the Traveled Distance (TD) is calculated based on $\frac{\text{MEC}\times\text{TD}}{\text{MTD}}$. Besides, 7 CSs are provided with sufficient electric energy and 5 charging slots throughout entire simulation, using the fast charging rate of 62 kW. If the ratio between its current electricity energy and maximum volume is below the value of SOC, an EV would travel towards a decided CS for charging. Here, the shortest path towards CS is formed considering road topology.

All incoming EVs are scheduled based on the preempted charging policy, as detailed in Section III-D. Since the charging request/reply between EVs and the GA is through the cellular network communication, the CS-selection decision is made instantly based on the assumption stated in Section III-C. Three CS-selection schemes are evaluated for comparison:

- **Closest Distance (CD):** The GA selects the CS which is the closest (in terms of travelling distance) to the EV sends charging request [5].
- **Minimum Queueing Time (MQT):** The GA selects the CS which is with the minimum queueing time [17], which does not consider the preempted charging into CS-selection.
- **Proposed-1:** The GA selects the CS with the minimum value of EATC (calculated in Algorithm 1).

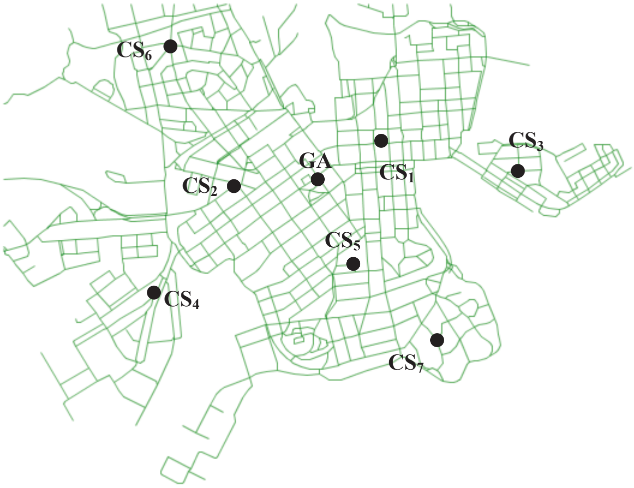

Fig. 5. Simulation Scenario of Helsinki City

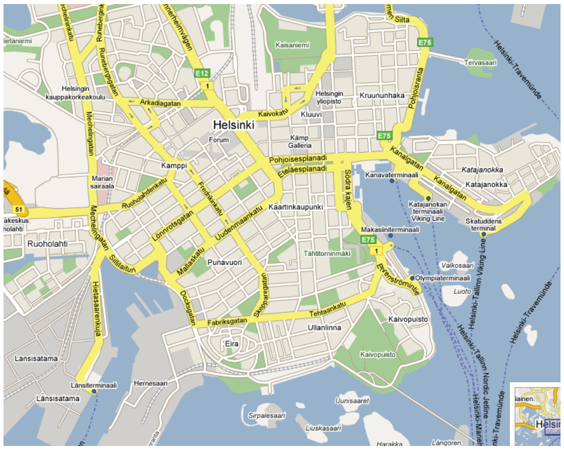

Fig. 6. Google Map of Helsinki City

Results are plotted with average value based on 10 runs, where evaluation metrics are as follows:

- **Average Waiting Time:** As the metric at the EV side, the average waiting time measures the average period, between the time that H-EVs/L-EVs arrive at the selected CSs and the time they finish recharging batteries.
- **Number of Charged EVs:** As the metric at the CS side, the number reflects the total number of fully charged L-EVs/H-EVs.

Results in Fig. 7(a), Fig. 7(b), Fig. 7(c), Fig. 7(d) show that if with 7 charging slots equipped at each CS, all schemes benefit from a great improvement on the charging performance. This is because that the charging congestion at CSs is alleviated, thus most incoming EVs will be charged without waiting for a long time. For most of the case, the MQT

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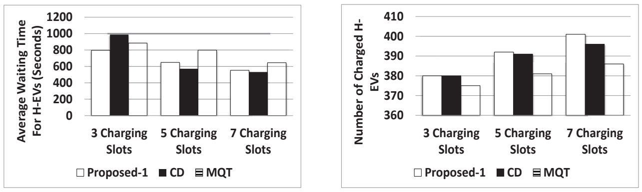
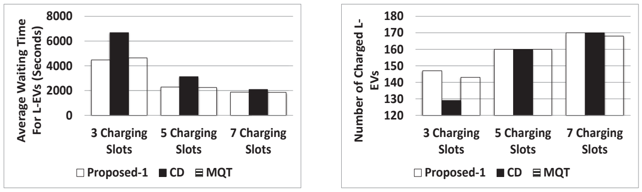
[4] www.codaautomotive.com.

[5] wikipedia.org/wiki/Hyundai BlueOn.



(a) Average Waiting Time for H-EVs (b) Number of Charged H-EVs



(c) Average Waiting Time for L-EVs (d) Number of Charged L-EVs

Fig. 7. Influence of CS-Selection Schemes

outperforms CD only in congested cases (3 and 5 charging slots per CS), which follows the outcome in [11]. In spite of this, as Proposed-1 takes the underlying preempted charging scheduling policy for CS-selection into account, the former achieves the best performance.

V. CS-SELECTION IN RESERVATION BASED CHARGING SERVICE (CELLULAR NETWORK COMMUNICATION)

In this section, each EV further reports its charging reservation to the GA. The charging reservation is useful for the GA to predict the CS condition in the near future, e.g., as the Expected Waiting Time (EWT) shown in Fig. 1, such that a potential charging hotspot could be alleviated. Here, the CS with the minimum EWT is selected for EV$_r$ (the EV needs charging service). Major computation logic is illustrated through Algorithm 2 and Algorithm 3.

A. Charging Reservation

The charging reservation generated from the EV (e.g., EV$_r$) which is travelling towards the selected CS, is defined in TABLE II. It is reported via the cellular network in this section. Specially:

TABLE II
CHARGING RESERVATION

Charging Reservation				
EV ID	EV Type	Selected CS	Arrival Time	Expected Charging Time
EV$_2$	L-EV	CS$_3$	3060s	730s

⟨EV ID⟩: The ID of EV which needs charging, and it has been replied with the selected CS.

⟨EV Type⟩: Either with "L-EV" or "H-EV" type.

⟨Selected CS⟩: Where the EV will travel for charging.

⟨Arrival Time⟩: Based on the travelling time T^{tra}_{ev} calculated from the current location of EV to that CS via the shortest road path, the expected arrival time T^{arr}_{ev} is given by:

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

Here, the detour issue is not considered.

⟨Expected Charging Time⟩: we denote T^{cha}_{ev} as the expected charging time upon that arrival, where:

$$T^{cha}_{ev} = \frac{E^{max}_{ev} - E^{cur}_{ev} + S_{ev} \times T^{tra}_{ev} \times \alpha}{\beta} \tag{4}$$

Note that $S_{ev} \times T^{tra}_{ev} \times \alpha$ is the amount of electric energy consumed for travelling, where S_{ev} is the EV speed and α is the energy consumption per meter.

One concern is to address the uncertainty from EVs' charging reservations, this is mainly due to road traffic congestion that delays EVs' arrival at their reserved CSs. One feasible solution is to apply a reservation updating mechanism to dynamically adjust decision triggered by changed charging reservations. As investigated in [31], the impact of such reservation updating will finally turn to a saturation point to prevent any subsequent decision change.

B. Estimation of Expected Waiting Time (EWT)

The estimation of EWT at a CS depends on two cases:

- **Case-1:** In the first case detailed by Algorithm 2 with flow chart illustrated in Fig. 8, we consider that incoming EV$_r$ (only with the "H-EV" type), has chance to get preempted charging upon its arrival, prior to those "L-EVs" already been parked at a CS.
- **Case-2:** In the second case detailed by Algorithm 3 with flow chart illustrated in Fig. 9, we consider that EV$_r$ (regardless of its type) will be charged, either if all EVs (parked at a CS) have been charged, or there is no other EV being scheduled.

1) Case-1: Initially, EV$_r$ is added into the queue of N_R, meanwhile these parked EVs (in the queue of N_W) are sorted with preempted charging priority. Algorithm 2 then starts from finding those EVs (in the queue of N_W), by referring to the operations in Algorithm 1. In particular, if the number of EVs (in the queue of N_C or N_W) is 0, the EWT is returned by Algorithm 3 (case-2) at lines 6 and 16 respectively.

Initially, the LIST containing the time slot (about when the charging of those EVs in the queue of N_C) will be finished, is sorted with ascending order at line 14. The motivation behind this is to obtain the earliest available time for charging, as denoted by LIST.GET(0). Before processing each EV$_j$ (in the queue of N_W) waiting for charging, those EV$_k$ (in the queue of N_R) which have made reservations are initially checked at line 19. This considers the case that, the EV$_k$ with the "H-EV" type and an earlier arrival time $T^{arr}_{ev_{(k)}}$ than LIST.GET(0), would be charged prior to EV$_j$.

The preempted charging happens only when EV$_j$ is with the "L-EV" type. In this context, given the condition:

$$((\text{EV}_k \text{ is ``H-EV''}) \cap (\text{EV}_j \text{ is ``L-EV''}) \cap (\text{LIST.GET(0)} > T^{arr}_{ev_{(k)}})) \tag{5}$$

at line 20 in Algorithm 2, we have:

- Algorithm 2 will directly return the EWT given by (LIST.GET(0)$-T^{arr}_{ev_{(r)}}$) at line 22, only if the EV$_k$ (being processed in current loop) is the EV$_r$ (the on-the-move EV needs charging).
- Otherwise, from lines 24 to 27, the charging finish time $T^{fin}_{ev_{(k)}}$ of those EV$_k$ (other than EV$_r$) will be replaced

Algorithm 2 Estimation of EWT Case-1$\langle$LIST, $N_R\rangle$

```
1: add EV$_r$ into the queue of $N_R$
2: sort the queue of $N_R$ according to FCFS order
3: sort the queue of $N_W$ according to preempted charging scheduling order
4: if no EV is under charging then
5:     add $T_{cur}$ in LIST with $\delta$ times
6:     return Estimation of EWT Case-2$\langle$LIST, $N_R\rangle$
7: end if
8: for $(i = 1; i \leq N_C; i++)$ do
9:     LIST.ADD$\left(\frac{E^{max}_{ev_{(i)}} - E^{cur}_{ev_{(i)}}}{\beta} + T_{cur}\right)$
10: end for
11: if $(N_C < \delta)$ then
12:     add $T_{cur}$ in LIST with $(\delta - N_C)$ times
13: end if
14: sort LIST with ascending order
15: if no EV is waiting for charging then
16:     return Estimation of EWT Case-2$\langle$LIST, $N_R\rangle$
17: end if
18: for $(j = 1; j \leq N_W; j++)$ do
19:     for $(k = 1; k \leq N_R; k++)$ do
20:         if ((EV$_k$ is "H-EV") $\cap$ (EV$_j$ is "L-EV") $\cap$ (LIST.GET(0) $>$ $T^{arr}_{ev_{(k)}}$)) then
21:             if (EV$_k$ equals to EV$_r$) then
22:                 return EWT = LIST.GET(0) $- T^{arr}_{ev_{(r)}}$
23:             else
24:                 $T^{fin}_{ev_{(k)}}$ = LIST.GET(0) $+ T^{cha}_{ev_{(k)}}$
25:                 replace the LIST.GET(0) with $T^{fin}_{ev_{(k)}}$
26:                 sort LIST with ascending order
27:                 record EV$_k$ into DELETESET
28:             end if
29:         end if
30:     end for
31:     remove EVs recorded in DELETESET, from the queue of $N_R$
32:     $T^{fin}_{ev_{(j)}}$ = LIST.GET(0) $+ T^{cha}_{ev_{(j)}}$
33:     replace the LIST.GET(0) with $T^{fin}_{ev_{(j)}}$
34:     sort LIST with ascending order
35: end for
36: return Estimation of EWT Case-2$\langle$LIST, $N_R\rangle$
```

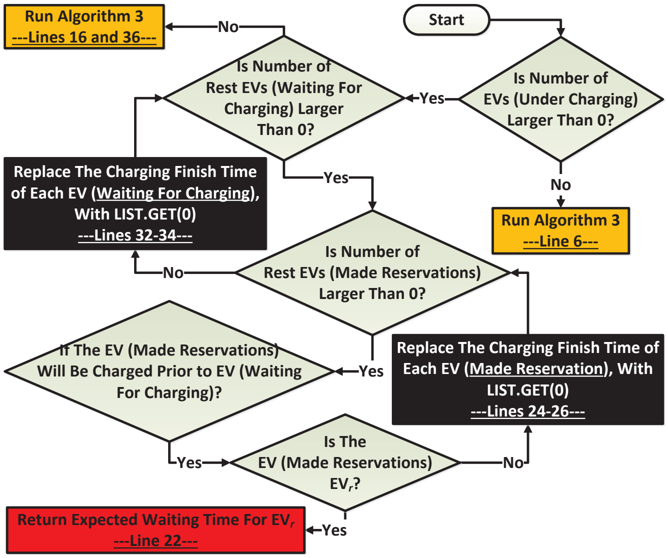


Fig. 8. Flow Chart of Algorithm 2

with LIST.GET(0). This implies the preempted charging of EV$_k$ takes place earlier than EV$_j$. Upon processing each EV$_k$ in current loop, the LIST will be further sorted with ascending order, in order to obtain the updated LIST.GET(0) in next loop. Besides, at line 31, this given EV$_k$ (which involves the updating of LIST) will be removed from the queue of N_R, since its charging has already been scheduled.

Unless the above loop operations related to EV$_k$ have been processed, those EV$_j$ waiting for charging will be processed. This implies that the charging of EV$_j$ will be started, once any EV$_k$ (meets the condition at line 20) has been charged. Here, the charging finish time $T^{fin}_{ev_{(j)}}$ also involves LIST update (between lines 32 and 34), until the charging of the last EV$_j$ (in the queue of N_W) has been scheduled. Finally, at line 36, Algorithm 3 is applied, if the charging of EV$_r$ has not been scheduled in previous steps.

2) Case-2: Previously, the inputs of Algorithm 3 including LIST and the queue of N_R, have already been updated by Algorithm 2. It is highlighted that the input N_R excludes those incoming "H-EVs" (which got preempted charging prior to those parked "L-EVs" at a CS, processed at line 31 in Algorithm 2).

Algorithm 3 Estimation of EWT Case-2$\langle$LIST, $N_R\rangle$

```
1: insert all EVs (in the queue of $N_R$) into $N^p_R$
2: sort the queue of $N^p_R$ according to preempted charging scheduling order
3: for $(i = 1; i \leq N_R; i++)$ do
4:     for $(j = 1; j \leq N^p_R; j++)$ do
5:         if ((LIST.GET(0) $> T^{arr}_{ev_{(j)}}$) $\cap$ (EV$_i$ is "L-EV") $\cap$ (EV$_j$ is "H-EV") $\cap$ (EV$_i \neq$ EV$_j$)) then
6:             if (EV$_j$ equals to EV$_r$) then
7:                 return EWT = LIST.GET(0) $- T^{arr}_{ev_{(r)}}$
8:             else
9:                 $T^{fin}_{ev_{(j)}}$ = LIST.GET(0) $+ T^{cha}_{ev_{(j)}}$
10:                replace the LIST.GET(0) with $T^{fin}_{ev_{(j)}}$
11:                sort LIST with ascending order
12:                record EV$_j$ into DELETESET
13:            end if
14:        end if
15:    end for
16:    remove EVs recorded in DELETESET, from the queues of $N_R$ and $N^p_R$
17:    if (EV$_i$ is not EV$_r$) then
18:        if (LIST.GET(0) $> T^{arr}_{ev_{(i)}}$) then
19:            $T^{fin}_{ev_{(i)}}$ = LIST.GET(0) $+ T^{cha}_{ev_{(i)}}$
20:        else
21:            $T^{fin}_{ev_{(i)}} = T^{arr}_{ev_{(i)}} + T^{cha}_{ev_{(i)}}$
22:        end if
23:        replace the LIST.GET(0) with $T^{fin}_{ev_{(i)}}$
24:        sort LIST with ascending order
25:    else
26:        if (LIST.GET(0) $> T^{arr}_{ev_{(r)}}$) then
27:            return EWT = LIST.GET(0) $- T^{arr}_{ev_{(r)}}$
28:        else
29:            return EWT = 0
30:        end if
31:    end if
32: end for
```

At line 1 of Algorithm 3, we insert the rest of those EVs (in the queue of N_R from Algorithm 2), into a newly defined queue N^p_R. Those EVs (in the queue of N^p_R) will be sorted, following the preempted charging scheduling described in

Section III-D. This is different from those in the queue of N_R following the FCFS order.

For each loop, those EV$_j$ (in the queue of N_R^p) with the "H-EV" type and an earlier arrival time than LIST.GET(0), will be charged prior to EV$_i$ (in the queue of N_R) with the "L-EV" type. As such, at line 5, given the condition:

$$((\text{LIST.GET(0)} > T^{arr}_{ev_{(j)}}) \cap (\text{EV}_i \text{ is "L-EV"}) \cap (\text{EV}_j \text{ is "H-EV"}) \cap (\text{EV}_i \neq \text{EV}_j)), \tag{6}$$

we have:

- At line 7, the EWT will be returned as (LIST.GET(0) $-$ $T^{arr}_{ev_{(r)}}$), if EV$_j$ in the current loop is EV$_r$. Note that Algorithm 3 considers that EV$_r$ was not scheduled for charging, through Algorithm 2.
- At line 9, alternatively the charging finish time $T^{fin}_{ev_{(j)}}$ of those EV$_j$ (other than EV$_r$) will be replaced with LIST.GET(0). This means that the charging of EV$_j$ will take place earlier than EV$_i$.

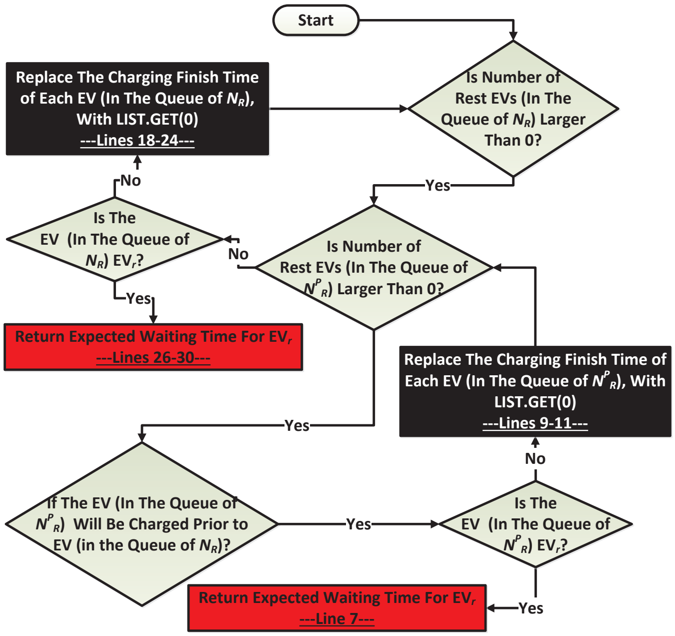


Fig. 9. Flow Chart of Algorithm 3

From lines 9 to 12, upon processing each EV$_j$, the LIST will be sorted and updated with ascending order. Besides, the given EV$_j$ (which involves the updating of LIST), will be removed from the queues of N_R and N_R^p respectively, as presented at line 16. This is because the EV$_j$ has been already taken into account for the estimation of EWT. Note that both EV$_j$ (in the queue of N_R^p) and EV$_i$ (in the queue of N_R) are those EVs made reservations, however they are placed into queues sorted with different orders. As such, any EV$_i$ mapping to EV$_j$ that is excluded from line 16, will be skipped for the loop operations at line 3 and 4 respectively.

Further to above, from line 17, EV$_i$ in the current loop will then be processed, once the loop operations between lines 5 and 15 have been finished. This means that the charging of EV$_i$ can only be scheduled, once any EV$_j$ (meets the condition at line 5) has been charged. Here, the arrival time of EV$_i$ (other than EV$_r$) will be compared with LIST.GET(0):

- In one case, given (LIST.GET(0) $> T^{arr}_{ev_{(i)}}$), the charging finish time $T^{fin}_{ev_{(i)}}$ of EV$_i$ is calculated by ($T^{fin}_{ev_{(i)}} =$ LIST.GET(0) $+ T^{cha}_{ev_{(i)}}$) at line 19. This means that the charging slot has not been available upon the arrival of EV$_i$, thus the time to start charging EV$_i$ is LIST.GET(0).
- In another case, we have ($T^{fin}_{ev_{(i)}} = T^{arr}_{ev_{(i)}} + T^{cha}_{ev_{(i)}}$) at line 21, where the time to start charging EV$_i$ is $T^{arr}_{ev_{(i)}}$. This implies that there is an available slot free for charging upon the arrival of EV$_i$, because of (LIST.GET(0) $\leq T^{arr}_{ev_{(i)}}$).

Then the $T^{fin}_{ev_{(i)}}$ will be further replaced with LIST.GET(0), similar to the LIST updating as previously mentioned.

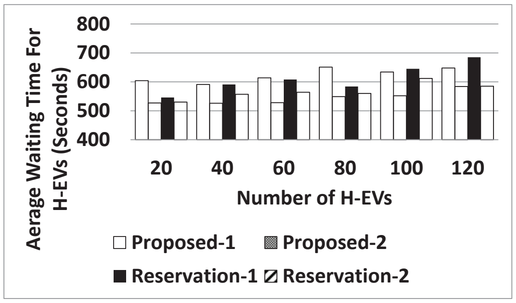
Finally, Algorithm 3 will return the EWT once the EV$_i$ in current loop equals to EV$_r$. Then the arrival time of EV$_r$ will be compared with the earliest available time for charging as given by LIST.GET(0). Here, either (LIST.GET(0) $- T^{arr}_{ev_{(r)}}$) or 0, is calculated as the expected waiting time for EV$_r$ at lines 27 and 29. This mainly depends on whether a charging slot will be available, upon the arrival of EV$_r$.

C. Performance Evaluation With Number of H-EVs

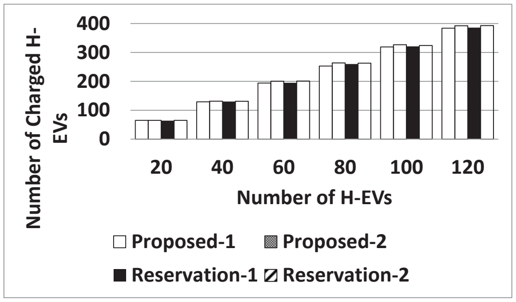
Based on the same scenario in Fig. 5, the proposed scheme **Proposed-2** enabling charging reservation via cellular network, is compared with **Reservation-1** [17] and **Reservation-2** [1]. All of them are based on the underlying preempted charging service (for charging scheduling). Note that, these compared two CS-selection schemes do not consider preempted charging policy, although they enable charging reservation service. Throughout the simulation, we fix the number of L-EVs, but only vary the number of H-EVs.

In Fig. 10(a), the Proposed-2 achieves a shorter average waiting time for H-EVs, than the Proposed-1. This is because the former estimates the EWT considering EVs' charging reservations, thus the CS condition can be predicted in a near future. With this knowledge, the Proposed-2 is able to alleviate potential congestion at CSs, by arranging EVs to travel towards lightly congested CSs for charging (meaning they will experience a shorter waiting time). Due to the same reason, the Proposed-2 also charges more H-EVs, than the Proposed-1 in Fig. 10(b). Concerning those L-EVs with a lower charging priority, their average waiting time is increased in Fig. 10(c). This is because more L-EVs will be delayed for charging, either if there are still H-EVs locally parked at CSs, or the arrival time of incoming H-EVs is earlier than the time to start charging L-EVs. Particularly, the number of charged L-EVs is decreased in Fig. 10(d), since more H-EVs will be charged with a higher priority, where the Proposed-2 outperforms Proposed-1.

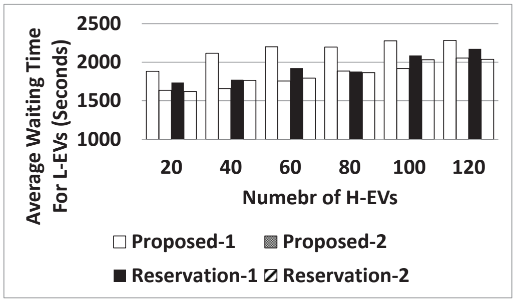
Compared with the literature works [1], [17], their performance related to H-EVs is fluctuated. This is because their CS-selection intelligences do not consider the preempted charging scheduling policy in Section III-D. As such, the CS-selection schemes in above two compared literature works treat CS-selection for H-EVs and L-EVs equally, but still outperform the Proposed-1. This claims the benefit of bringing EVs' charging reservations for CS-selection.



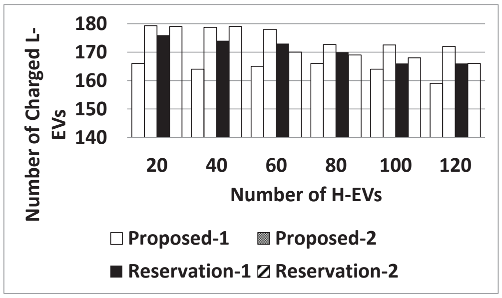
(a) Average Waiting Time for H-EVs



(b) Number of Charged H-EVs



(c) Average Waiting Time for L-EVs

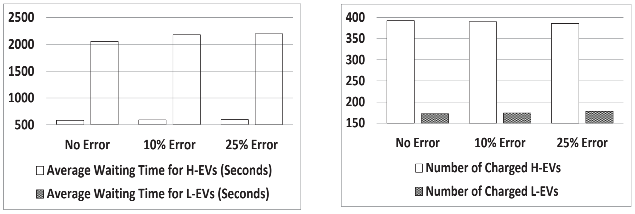


(d) Number of Charged L-EVs

Fig. 10. Influence of H-EVs

D. Performance Evaluation With Error of Charging Reservation

Following Section V-A, in case of traffic uncertainty that results in the inaccurate arrival, this situation is also in line with changed expected charging time, because any changed arrival time will correspond to changed energy consumption for driving. Fig. 11(a) and Fig. 11(b) show the results due to error of EVs' arrival time included in reservation with respect to the average waiting time, which also affects the expected charging time upon arrival at CS. It is observed that a larger error slightly degrades the performance between H-EVs and L-EVs, in terms of number of charged EVs and also increase of the charing waiting time. This implies the stability of our proposed CS-selection scheme.



(a) Average Waiting Time for H-EVs/L-EVs (b) Number of Charged H-EVs/L-EVs

Fig. 11. Influence of Arrival Time Error

VI. ENABLING V2V COMMUNICATION IN RESERVATION BASED CHARGING SERVICE

In this section, we study the feasibility of applying the V2V communication for EVs' reservations reporting, other than that using cellular network communication in Section V.

A. Applying DGR for EV Charging Management

In DGR [25], the routing decision making is based on geometric utility, calculated as the remaining time to approach stationary destination (e.g., GA). This metric considers the distance between a given EV and the GA, EV moving speed and moving direction of that EV. It is recorded as an additional flag in date message, to compare with the utility of any encountered EV. Ideally, a faster EV with a closer distance to the GA, meanwhile with a smaller relative angle between its moving direction and geometric distance to the GA, is selected as a better relay for next hop. Also, DGR intelligently relays data message depends on its lifetime, such that an emergent data message will be delivered in a fast way. Due to limited space in this article, details of DGR design and analysis of its theoretical properties could be referred to [25].

Of course, applying a larger radio range for the V2V communication, improves both the communication and charging performance. This is because a large communication range brings much inter-encounter between EVs, while a faster charging reservation delivery (thanks to V2V communication) enables a fresher information used for making CS-selection decision. However, the interference from medium access contention will be a major concern, if EVs are with large radio coverage range. Here, the DTN based communication technique DGR facilitates a short range opportunistic communication, thanks to the high mobility of EVs.

B. Data Message Formatting

Particularly, the lifetime of data message containing an EV's charging reservation, depends on the travelling time from the location of that EV to its selected CS. This time is calculated, since the time slot that EV has been informed by the GA with the selected CS. In other words, a short message lifetime is set, if the EV will need to reach its selected CS in a short time. Such a emergent delivery is driven by DGR, where the message format is illustrated by Fig. 12:

Destination	Source	Charging Reservation Information	Generation Time	Maximum Lifetime	Flag Used By DGR	Security Usage

Fig. 12. Charging Reservation Message Structure

- The message destination is the GA.
- The message source is the EV (e.g., EV$_r$ needs charging service while has received the CS-selection decision from the GA) which makes charging reservation.
- The charging reservation information follows the definition in TABLE II.
- The message generation time is calculated since the charging reservation information is generated.
- The maximum lifetime is the EV's travelling time towards the selected CS, since the charging reservation information is generated.
- An additional flag is defined to record the historical utility value, as used by DGR for routing purpose.
- Security must be considered since releasing the detailed EVs' charging reservation information will pose security challenge. Here, it is advised to digitally sign the reservation message, as such any intermediate EV relaying this message can not modify it.

Recall that we consider the message relay procedure for EVs' charging reservations only, as an auxiliary service to further improve the charging performance. Thus the communication for charging request/reply is still through the cellular network communication, to seamlessly guarantee the compulsory service. Here, the reservation message for "H-EV", is transmitted prior to that for "L-EV". This guarantees the preempted charging service, where the reservations for "H-EVs" should be delivered with a higher priority. Extension could involve increased EVs' heterogeneity for charging management, further to "H-EVs" and "L-EVs" as we investigate in this article.

C. Analysis

DGR relies on multiple copies to guarantee reliable message delivery, we provide a general analysis on flooding based delivery probability (DP), as:

$$DP = 1 - (1 - P_R)^R \tag{7}$$

where R is the number of copies including the original message (containing an EV's charging reservation) in the network. Meanwhile, P_R is the probability that each copy is delivered along an independent routing path, before message expiration deadline. The equation (7) calculates the probability that at least one of the R message copies is delivered to the GA. Here, we observe that a larger value of P_R and R increase the message delivery probability.

It has been shown that a number of popular mobility models as well as more realistic, synthetic models are based on (approximately) exponential encounter characteristics. Particularly, realistic VANETs mobility models have already shown an exponential encounter rate between vehicles [34], and has been adopted by previous works addressing opportunistic communication [25]. According to [35], the replication redundancy R when the network size grows large, is presented as:

$$R = \frac{E}{1 + (E-1)e^{-\beta E t}} \tag{8}$$

where t is the current time in the network, and E is the total number of EVs. Note that the condition $(t > 0)$ holds true for the nature that a network is active, meaning no message generation or nodal movement will start given $(t = 0)$. Besides, $(\beta = \frac{1}{T})$ as the encounter rate, is inverse to the inter-meeting time T.

Concerning the message lifetime, equation (7) is converted as:

$$DP = 1 - \left(1 - \left(\frac{\text{Initial Message Lifetime} - t}{\text{Initial Message Lifetime}}\right)\right)^{\frac{E}{1+(E-1)e^{-\frac{Et}{T}}}} \tag{9}$$

Here, with a large value of E:

$$DP \approx 1 - \left(1 - \left(\frac{\text{Initial Message Lifetime} - t}{\text{Initial Message Lifetime}}\right)\right)^{e^{\frac{Et}{T}}} \tag{10}$$

Authors in [36] have derived an approximated form for T, where $T = 0.5Z\left(0.34 \ln Z - \frac{2^{M+1} - M - 2}{2^M - 1}\right)$ is related to network size Z and nodal transmission range M.

It is observed that given an initial message lifetime, the delivery probability is increased by using more message copies as well as diffusing them fast. This requires a small T which is inherently associated to larger transmission range M. Also, a large number of EVs E to help relaying information is also beneficial to high DP.

D. Discussion

Concerning the communication performance, the delivery overhead when using the V2V communication depends on the number of EVs (as explored in [22]). Whereas the delivery overhead when using the cellular network communication depends on the number of charging reservations. In other words, the former is affected by the EVs density, whereas the latter is affected by the number of service requests.

Here, we denote the number of EVs as E, while the number of charging reservations as C. Referring to [25], the delivery overhead $\mathcal{H}_{DGR}$ when using the DGR routing scheme to relay EVs' charging reservations is scaled between $[O(\sqrt{E}), O(E))$, while that $\mathcal{H}_{EP}$ when using the Epidemic routing scheme [35] is $O(E)$. Besides, the delivery overhead $\mathcal{H}_{CNC}$ when using the cellular network communication is $O(C)$. Note that the condition $(C \geq E)$ holds true for the assumption that each EV will need to charge more than once. Therefore, we have:

$$\mathcal{H}_{DGR} < \mathcal{H}_{EP} \leq \mathcal{H}_{CNC} \tag{11}$$

As the EV would need multiple times charging in long term, using the cellular network communication to report EVs' charging reservations will inevitably suffer from a higher overhead than the V2V communication. This is particularly the case when concerning the long term popularity of EVs.

Delivering EVs' charging reservations is with a delay tolerant nature. This is because after the reservations are delivered by the GA, in future the CS-selection decision is made only when there will be a charging request from an *on-the-move* EV. This makes the application of opportunistic V2V communication feasible and cost-efficient to deliver EVs' charging reservations, as evaluated through following case study. In spite that we propose a comprehensive centralized system in this article, the effort towards a decentralized system via vehicle cloud networking [37] could be of future interest.

E. Performance Evaluation

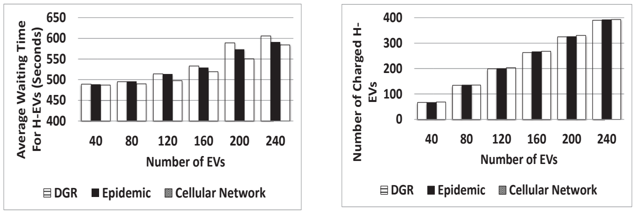
1) Configuration: Following the above analysis, we here provide feasibility study on applying V2V communication for relaying EVs' charging reservations. The V2V communication is configured with 100m transmission range and 4 Mbit/s. The performance evaluation is based on the same scenario as configured in Section IV, where the GA is located in Fig. 5. The following schemes are evaluated for comparison:

- **DGR:** Based on Proposed-2, where the EVs' charging reservations are relayed via DGR [25] routing protocol.
- **Epidemic:** Based on Proposed-2, where the EVs' charging reservations are flooded in network [19].
- **Cellular Network:** The Proposed-2 in Section V.

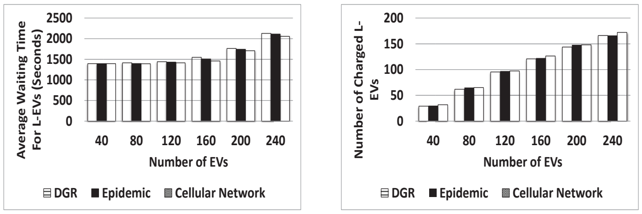
We further define three metrics regarding the communication performance:

- **Reservation Delivery Ratio:** It is given by the ratio between the number of reservations delivered and the total number of reservations generated.
- **Average Reservation Delivery Latency:** It is given by the average time spent for reservations delivery from EVs (knowing where to charge) to the GA.
- **Reservation Delivery Overhead:** Following the definition in [22], the cost in terms of V2V communication is given by $\frac{\text{Number of Delivered Reservations - Number of Relayed Reservations}}{\text{Number of Relayed Reservations}}$ [25], as the number of times to use V2V communication for reservations delivery. For the cellular network communication, it is given by the number of times to use cellular network communication for reservation reporting.

2) Influence of EVs Density: Here, we vary the EVs density, e.g., 40 EVs means there are 20 H-EVs and 20 L-EVs in network. Since a large number of EVs increases the encounter opportunities, the delivery ratio and delivery latency are improved in Fig. 13(a) and Fig. 13(b) respectively. Note that using the cellular network communication does not yield any delivery latency, since we assume the delivery is instantaneous following the assumption in preliminary. In contrast, using the DGR and Epidemic routing schemes to opportunistically relay EVs' charging reservations, suffer from an extra delivery latency, due to that the contemporaneous end-to-end connectivity between EVs and GA does not always exist. Here, since Epidemic always floods messages, its delivery latency is lower than that of DGR. This is because that the possibility that one of the message copies will be delivered, is increased by flooding more message copies. On one hand, using the DGR routing scheme to relay EVs' charging reservations maintains a smoothly increased delivery overhead, as compared to that using the Epidemic routing scheme and the cellular network communication in Fig. 13(c). On the other hand, using the cellular network communication suffers from a huge overhead, even compared with that using the flooding based Epidemic routing scheme.



(a) Average Waiting Time for H-EVs (b) Number of Charged H-EVs



(c) Average Waiting Time for L-EVs (d) Number of Charged L-EVs

Fig. 14. Influence of EVs Density on Charging Performance

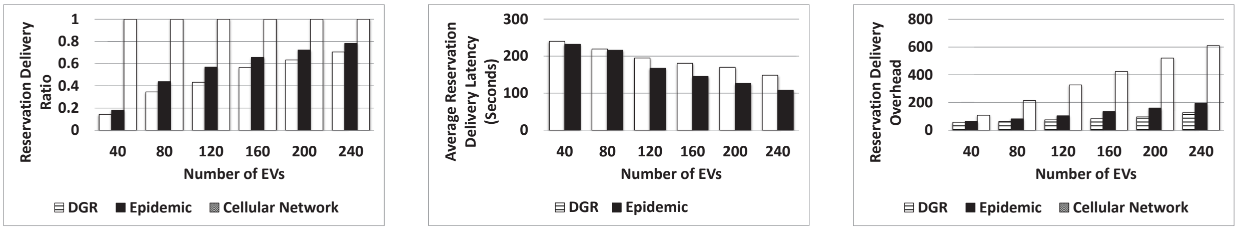
However, the evaluated schemes achieve close performance, in case of increased EVs density, in Fig. 14(a), Fig. 14(b), Fig. 14(c) and Fig. 14(d) respectively. Note that using the cellular network communication achieves the best performance, due to instantaneously delivering EVs' charging reservations, as compared to the case using the opportunistic V2V communication.

3) Influence of V2V Transmission Range: We observe that using DTN routing schemes to relay EVs' charging reservations benefits from an increased transmission range, in Fig. 15(a), Fig. 15(b) and Fig. 15(c). Such increase leads to a higher encounter opportunities among EVs, thus charging reservations will be delivered most likely, while delivery latency is reduced. In spite of achieving the highest delivery ratio and without yielding additional delivery latency, using the cellular network communication suffers from the highest delivery overhead. In Fig. 15(c), contributed by DGR, the communication overhead is dramatically reduced compared to that using Epidemic.

We next turn to the charging performance shown in Fig. 16(a), Fig. 16(b), Fig. 16(c) and Fig. 16(d). It is observed that using the cellular network communication achieves the best performance, since EVs' reservations are obtained by the GA instantaneously. The performance when using Epidemic to relay EVs' charging reservations, is with the trade-off between a better performance and higher delivery overhead.

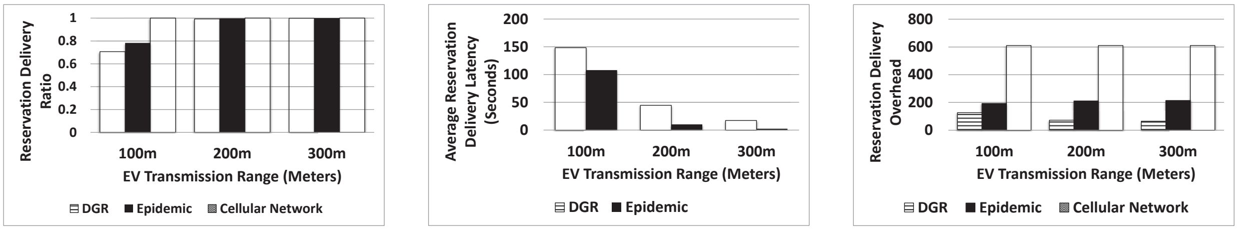
VII. CONCLUSION

In this article, the proposed CS-selection scheme minimizes the charging waiting time for heterogeneous EVs (with preempted charging service). It is based on the knowledge of those EVs locally parked at CSs as well as those remotely making charging reservations. The anticipated EVs' charging



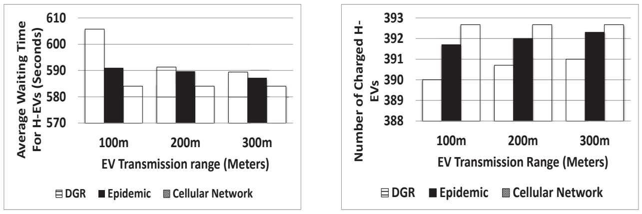
(a) Reservation Delivery Ratio (b) Average Reservation Delivery Latency (c) Reservation Delivery Overhead

Fig. 13. Influence of EVs Density on Communication Performance

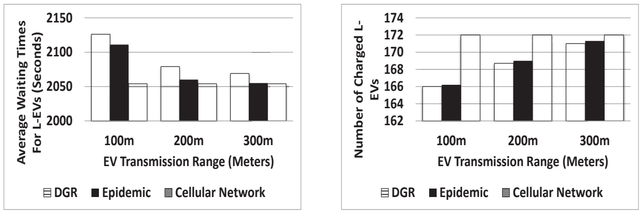


(a) Reservation Delivery Ratio (b) Average Reservation Delivery Latency (c) Reservation Delivery Overhead

Fig. 15. Influence of EV Transmission Range on Communication Performance



(a) Average Waiting Time for H-EVs (b) Number of Charged H-EVs



(c) Average Waiting Time for L-EVs (d) Number of Charged L-EVs

Fig. 16. Influence of EV Transmission Range on Charging Performance

reservations include their arrival time and expected charging time at selected CSs. This information is useful to coordinate EVs' charging plans taking place in a near future. The advantage of our proposed scheme has been evaluated under the Helsinki city scenario, in terms of a shorter charging waiting time as well as higher number of EVs attracted for charging. We further study the feasibility of applying V2V communication (with DTN nature) to relay EVs' charging reservations. Results have shown a considerable low communication cost while achieving comparable charging performance.

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