Applying DTN Routing for Reservation-Driven EV Charging Management in Smart Cities

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***Abstract*—Charging management for Electric Vehicles (EVs) *on-the-move* (moving on the road with certain trip destinations) is becoming important, concerning the increasing popularity of EVs in urban city. However, the limited battery volume of EV certainly influences its driver's experience. This is mainly because the EV needed for intermediate charging during trip, may experience a long service waiting time at Charging Station (CS). In this paper, we focus on CS-selection decision making to manage EVs' charging plans, aiming to minimize drivers' trip duration through intermediate charging at CSs. The anticipated EVs' charging reservations including their arrival time and expected charging time at CSs, are brought for charging management, in addition to taking the local status of CSs into account. Compared to applying traditionally applying cellular network communication to report EVs' charging reservations, we alternatively study the feasibility of applying 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 for reservation reporting is promisingly cost-efficient in terms of communication overhead for reservation making, while achieving a comparable performance in terms of charging waiting time and total trip duration.**

***Index Terms*—Electric Vehicle, Charging Management, Vehicle-to-Vehicle Communication.**

I. Introduction

The application of Electric Vehicles (EVs) has been recognized as a significant means to reduce CO_2 emissions and has attracted numerous attention from both academia and industries. Different from many previous works [1] addressing "when/whether" EVs should be charged while they are parking 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). Indeed, EV drivers have their individual journeys. However, inappropriate charging taking place during journeys may degrade users' Quality of Experience (QoE), as drivers prefer to reach trip destinations as soon as possible. On the one hand, drivers may not be willing to wait for a quite long time to charge their EVs. On the other hand, selecting a CS that is far away from the trip destination is undesirable as well.

However, due to the relatively long charging time, to optimally manage these requests has become a critical issue. Firstly, how to allocate an appropriate CS based on the EV's charging request will have strong impact on charging efficiency at the CS side. This is particularly the case where a grid operator deploys multiple CSs and aims to optimize (balance) the electricity utilization across them. Secondly, EV drivers can also benefit from a short charging waiting time and their trip duration (during which intermediate charging would occur), given the optimized management.

Most of previous works [2], [3] rely on a Global Aggregator (GA) to manage EVs charging in a centralized manner. Here, the GA is the system controller to monitor the CSs condition, and to implement the charging management optimization. This operation is executed when the GA receives charging requests from EVs, generally through cellular communication technologies, e.g., 3G/Long Term Evolution (LTE). Particularly, if all charging slots of a CS are occupied, any incoming EV needs to wait until one of the charging slots becomes available. Therefore, in order to achieve optimized charging performance which includes balancing the load across multiple CSs as well as minimizing charging waiting time for EVs, accurate information should be available for CS-selection decision making.

In literature, the scheme selecting the CS with the closest distance [4] and that with the minimum queuing time [5]–[7] have been studied. However, a potential charging hotspot may happen if many EVs travel towards the same CS for charging, due to that the decision just considers the local condition of CSs (e.g., availability of charging slots). In this context, it is suggested EVs should further report their charging reservations [8], including when they will arrive at their selected CSs and how long their charging time will be at there. Note that the reservation information is sent from individual EV, only if it has received the decision from the GA on where to charge. These anticipated information together with the CS local condition information, will be used to estimate the status of a CS condition in a near future.

Of course, reporting EVs' charging reservations is deemed as an auxiliary service to further improve performance. Here, 3G/LTE is applied in order not to experience delay, thanks to ubiquitous communication. However, this is costly because the reservation making is only necessary when EVs have intentions about where to charge. Driven by this, we propose to relay EVs' charging reservations via Vehicle-to-Vehicle (V2V) communication, instead of cellular network communication. This alleviates cost for transmissions over the cellular networks.

Most of the problems in Vehicular Ad hoc NETworks (VANETs) [9] arise from highly dynamic network topology, which results in the communication disruption along an end-to-end path towards destination. Here, the Delay/Disruption Tolerant Networking (DTN) [10] based routing protocols provide a significant advantage, by relying more on opportunistic communication to relay EVs' charging reservations. However, the delay due to opportunistic communication certainly has influence, on how fresh the reservation information is used for the GA to make CS-selection decisions. E.g., a decision making based on the obsolete information that is due to long delay, may mislead the EV towards the highly congested CS for charging. In this paper, we answer:

- What are the impacts of urban trip destination and the benefit to bring EVs charging reservations, on improving driver's comfort?
- How feasible and scalable is to apply V2V communication for reporting EVs charging reservations?

II. Related Work

A. Research on EV Charging Management

Most of previous works aim to determine when/whether to charge EVs, by saving charging cost to minimize peak loads and flatten aggregated demands [1]. In sharp contrary, other few works address the problem on where to charge, primarily, by minimizing the waiting time for EV charging. This can not be overlooked as it is the most important feature of a vehicle in future smart city, especially for fast charging. The works in [3], [5], [6] implement charging plans for all EVs based on the minimized queuing time. Results in [4] show that considering number of other EVs parking at the CS outperforms that considering the distance to the CS, achieves a shorter charging waiting time particularly given a high EV density. Further to these, the EV's charging reservation [8] is brought into system, in order to further improve performance.

B. Research on DTN Routing

In order to deal with the frequent intermittent connectivity due to high mobility in VANETs, the Store-Carry-Forward (SCF) mechanism in Delay/Disruption Tolerant Networks (DTNs) [10] makes opportunistic routing feasible in VANETs. The key insight is to rely on opportunistic encounter between pairwise vehicles to relay the message, and enable reliable delivery via multi-copies of message. The benchmark scheme Epidemic [11] relays a message copy to each encountered node (which does not have that message), and in theory achieves the highest message delivery ratio.

III. Preliminary

A. Assumption

In this paper, we assume each EV is equipped with Global Position System (GPS) that contains its own movement information, including current location and speed. The location of CSs are already been available through the GPS. We assume the delay for exchanging signalling between EVs and the GA is assumed to be neglected, through a reliable channel such as 3G/LTE. Therefore, an EV needs charging service can be informed by the GA, with an arrangement of CS-selection instantly.

The EV which has been informed with the selected CS for charging plan, can further report its charging reservation (including its arrival time and expected charging time at that CS) to the GA. Reporting EVs' charging reservations, as an auxiliary service, could be executed through the cellular network communication. Alternatively, EVs' reservations can be reported through the V2V communication, such that they are relayed through a number of intermediate *on-the-move* EVs. Due to the intermittency of vehicle communications caused by high mobility, the time to wait for an encounter opportunity is dominant in delay to deliver reservation.

B. System Cycle of EV Charging Management

Driving Phase: The EV is on its journey, as it is with sufficient electricity energy.

Charging Planning Phase: The EV in **Driving Phase** needs to travel towards a CS for battery recharging, by sending charging request to the GA. The GA returns the CS-selection decision back to the EV with pending request. Upon accepting the arrangement from the GA, the EV further reports its charging reservation to the GA. For example, in step 3 of Fig.1 although the reservation from EV_r (the EV requests charging service) can be normally delivered through cellular network, our effort turns to enabling a V2V manner (via EV_8) instead.

Charging Scheduling Phase: Upon its arrival at the selected CS (via the decision made in **Charging Planning Phase**), the EV will wait to be scheduled for charging, based on the First Come First Serve (FCFS) policy. This means the EV with an earlier arrival will be scheduled with a higher priority. Note that the FCFS policy has been widely applied by previous works [5]–[7] on CS-selection problem.

Battery Charging Phase: The EV is currently being charged, and will turn to the **Driving Phase** once its battery is fully charged. Now EV will resume travelling, from the CS its just experienced charging towards the trip destination.

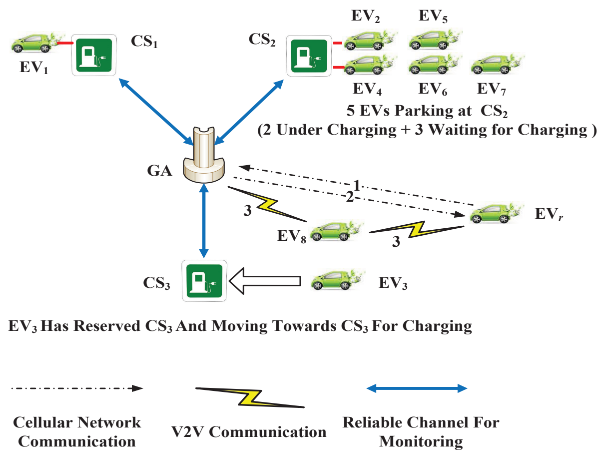


Fig. 1. An Overview of On-the-move EV Charging Management

IV. System Design

We decouple the design into three steps: Algorithm 1 details the estimation of available charging time locally at CS, upon which Algorithm 2 details the estimation of expected waiting time (with the knowledge of EVs' charging reservations). The charging reservation information is useful for the GA to predict the CS condition in the near future (e.g., as expected charging waiting time we focus), such that a potential charging hotspot could be alleviated. Then, the CS-selection is based on ranking the CS through which EV (with a trip destination, but needs charging) will experience the minimum time for its trip duration. Finally, we format the message to enable a V2V based reservation delivery via DTN routing protocol.

A. Estimating the Available Time for Charging

TABLE I
List of Notations

ATCLIST	Output list including available time per charging slot at CS
T_{cur}	Current time in the network
δ	Number of charging slots at CS
N_W	Number of EVs waiting for charging at CS
N_C	Number of EVs under charging 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}^{fin}	Charging finish time of EV
T_{ev}^{arr}	EV's arrival time at CS
T_{ev}^{tra}	EV's travelling time to reach CS
T_{ev}^{cha}	Expected charging time upon arrival of EV
S_{ev}	Moving speed of EV
S_{ev}^{max}	Maximum moving speed of EV
α	Electric energy consumed per meter
N_R	Number of EVs reserved for charging at CS
$T_{cs,d}^{min}$	Minimum travelling time from a CS to EV's trip destination

For estimating the available time for all charging slots at a CS, we consider two types of queues respectively. Those EVs which are under charging are characterized in the queue of N_C, while those still waiting for charging are characterized in the queue of N_W. As presented at line 2 in Algorithm 1, the current time in network as denoted by T_{cur} is estimated as the available charging time for each charging slot, if none of EVs is under charging. In this case, the ATCLIST containing a number of T_{cur} is directly returned. This means those charging slots of CS are currently available.

Algorithm 1 Estimation of Available Charging Time

1: **if** no EV is under charging **then**
2: add T_{cur} in ATCLIST with δ times
3: **end if**
4: **for** $(i = 1; i \le N_C; i++)$ **do**
5: ATCLIST.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: **for** $(j = 1; j \le (\delta - N_C); j++)$ **do**
9: ATCLIST.ADD(T_{cur})
10: **end for**
11: **end if**
12: sort ATCLIST with ascending order
13: **if** no EV is waiting for charging **then**
14: **return** ATCLIST
15: **else**
16: sort the queue of N_W according to FCFS
17: **for** $(k = 1; k \le N_W; k++)$ **do**
18: $T_{ev_{(k)}}^{fin} = \left(\text{ATCLIST.GET(0)} + \frac{E_{ev_{(k)}}^{max} - E_{ev_{(k)}}^{cur}}{\beta}\right)$
19: replace ATCLIST.GET(0) with $T_{ev_{(k)}}^{fin}$
20: sort ATCLIST with ascending order
21: **end for**
22: **return** ATCLIST
23: **end if**

In general, Algorithm 1 starts from processing each EV$_i$ (in the queue of N_C), where its time duration $\left(\frac{E_{ev_{(i)}}^{max} - E_{ev_{(i)}}^{cur}}{\beta}\right)$ to be fully recharged will be aggregated with T_{cur}. This sum value is as the charging finish time of EV$_i$, and it is inserted into ATCLIST. Upon the above processing for those EVs under charging, the presentation between lines 7 and 11 implies that all charging slots have not been fully occupied, because there are still $(\delta - N_C)$ slots free for charging. In this case, T_{cur} is as the available charging time for these unoccupied charging slots.

Then, Algorithm 1 will return the available time for charing per charging slot, either if the number of EVs waiting for charging is 0 as the condition stated at line 13, or a loop operation for each EV$_k$ waiting for charging has been processed as stated between lines 17 and 21.

In the latter case, the loop operation starts from sorting the queue of N_W, based on the FCFS charging scheduling order. Meanwhile, the ATCLIST containing when the charging of those EVs (in the queue of N_C) will be finished, is initialized with an ascending order. Here, the earliest available time is at the head of ATCLIST, as denoted by ATCLIST.GET(0). Normally, the charging finish time $T_{ev_{(k)}}^{fin}$ of each EV$_k$ (in the queue of N_W) will replace with ATCLIST.GET(0). At line 18, $T_{ev_{(k)}}^{fin}$ is calculated as the sum of time to start charging as denoted by ATCLIST.GET(0), and battery charging time given by $\left(\frac{E_{ev_{(k)}}^{max} - E_{ev_{(k)}}^{cur}}{\beta}\right)$. Furthermore, the ATCLIST will be sorted with ascending order once processing an EV$_k$ for each loop, such that the earliest time for charging obtained by ATCLIST.GET(0) is used in each loop. The above loop operation ends when all EV_k have been processed, and then the ATCLIST is returned at line 22.

B. Detail of EV's Charging Reservation

The reservation information is relayed from the EV which has made CS-selection decision, to the GA. This information includes the ID of selected CS, arrival time at that CS, and EV's expected charging time at there. Specifically:

Arrival Time: Based on the travelling time T_{ev}^{tra} (distance between current location of EV and selected CS, divied by EV speed) calculated from the current location of EV, to its selected CS via the shortest road path, the arrival time T_{ev}^{arr} at that CS is given by:

$$T_{ev}^{arr} = T_{cur} + T_{ev}^{tra} \tag{1}$$

Expected Charging Time: The expected charging time T_{ev}^{cha} at the selected CS is given by:

$$T_{ev}^{cha} = \frac{E_{ev}^{max} - E_{ev}^{cur} + S_{ev} \times T_{ev}^{tra} \times \alpha}{\beta} \tag{2}$$

Here, $(S_{ev} \times T_{ev}^{tra} \times \alpha)$ is the energy consumed for movement travelling to the selected CS, based on a constant α (depending on a certain type EV) measuring the energy consumption per meter.

C. Estimation of Expected Waiting Time

Algorithm 2 Expected Charging Waiting Time Estimation

1: sort the queue of N_R according to FCFS
2: sort ATCLIST returned by Algorithm 1, with ascending order
3: **for** $(i = 1; i \leq N_R; i++)$ **do**
4:     **if** $\left(T_{ev_{(i)}}^{arr} < T_{ev_{(r)}}^{arr}\right)$ **then**
5:         **if** $\left(\text{ATCLIST.GET(0)} > T_{ev_{(i)}}^{arr}\right)$ **then**
6:             $T_{ev_{(i)}}^{fin} = \left(\text{ATCLIST.GET(0)} + T_{ev_{(i)}}^{cha}\right)$
7:         **else**
8:             $T_{ev_{(i)}}^{fin} = \left(T_{ev_{(i)}}^{arr} + T_{ev_{(i)}}^{cha}\right)$
9:         **end if**
10:         replace the ATCLIST.GET(0) with $T_{ev_{(i)}}^{fin}$
11:         sort ATCLIST with ascending order
12:     **end if**
13: **end for**
14: **if** $\left(\text{ATCLIST.GET(0)} > T_{ev_{(r)}}^{arr}\right)$ **then**
15:     **return** $\left(\text{ATCLIST.GET(0)} - T_{ev_{(r)}}^{arr}\right)$
16: **else**
17:     **return** 0
18: **end if**

At the GA side, Algorithm 2 initially sorts the queue of N_R following FCFS policy, as their charging will be scheduled via this order. Here, EV_i stands for the i^{th} EV in the queue of N_R. For each $T_{ev_{(i)}}^{arr}$ earlier than $T_{ev_{(r)}}^{arr}$ (as the arrival time of EV_r), the former will involve the dynamic update of ATCLIST as returned by Algorithm 1. The purpose is to estimate when a charging slot will be available for charging upon the arrival of EV_r. Here, we denote ATCLIST.GET(0) as the earliest available charging time in ATCLIST.

- If $T_{ev_{(i)}}^{arr}$ is earlier than the earliest available time for charging as ATCLIST.GET(0), the the charging finish time of EV_i is calculated by $T_{ev_{(i)}}^{fin} = \left(\text{ATCLIST.GET(0)} + T_{ev_{(i)}}^{cha}\right)$, at line 6.
- In contrast, $T_{ev_{(i)}}^{fin} = \left(T_{ev_{(i)}}^{arr} + T_{ev_{(i)}}^{cha}\right)$ is given at line 8. This is because a charging slot has already been available before $T_{ev_{(i)}}^{arr}$.

By replacing the ATCLIST.GET(0) with each $T_{ev_{(i)}}^{fin}$, the available time for charging per charging slot is dynamically updated, until all arrival time in the queue of N_R have been processed in the loop operation. Note that the ATCLIST will be sorted with ascending order after the process of each arrival time in the queue of N_R, such that the earliest available time for charging is always at the head of this list for further calculation.

Then the arrival time of EV_r will be compared with the updated ATCLIST.GET(0). The expected waiting time is returned as $\left(\text{ATCLIST.GET(0)} - T_{ev_{(r)}}^{arr}\right)$ at line 15, if the arrival time of EV_r is earlier than ATCLIST.GET(0). Otherwise, EV_r will not experience any delay to start charging, given $\left(\text{ATCLIST.GET(0)} \leq T_{ev_{(r)}}^{arr}\right)$ at line 16.

D. CS-Selection Decision Making

Upon Algorithm 2, the total trip duration for EV_r can be calculated based on following inputs:

1) The travelling time from the current location of EV_r to the selected CS, given by $T_{ev_{(r)}}^{tra}$.
2) The duration (including the time to wait for charging given by Algorithm 2, and expected charging time $T_{ev_{(r)}}^{cha}$) staying at the selected CS.
3) The estimated minimum travelling time from the selected CS to the trip destination of EV_r, given by $T_{cs,d}^{min}$. Here, we assume that upon a fully recharged service at the selected CS, EV_r will start to travel towards its destination, with the maximum moving speed S_{ev}^{max}, e.g., speed acceleration. Therefore, $T_{cs,d}^{min}$ can be obtained by the shortest distance between that CS and trip destination, divided by S_{ev}^{max}.

Denoting the set Θ includes all CSs with their locations l_{cs}, the problem formulation is given by:

$$\arg\min_{l_{cs} \in \Theta} \left(T_{ev_{(r)}}^{tra} + \text{Expected Waiting Time} + T_{ev_{(r)}}^{cha} + T_{cs,d}^{min}\right) \tag{3}$$

The final CS-selection policy is find the CS, through which EV_r would experience the minimum value (by summarizing above three metrics).

E. Enabling V2V Communication

In order to enable the V2V communication for the delivery of EVs charging reservations to the GA, we format the message flags as follows:

- 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 message generation time is calculated since the charging reservation information is generated.
- The maximum message lifetime is the EV's travelling time towards the selected CS, since the charging reservation information is generated.
- The payload is the EV's charging reservation information.

Based on this, certain DTN routing scheme can work via above defined format, to enable the delivery of EVs' charging reservations through V2V manner.

The communication cost using V2V depends on the number of EVs N_{ev}. Whereas that using the cellular network communication, depends on the number of charging reservations N_{re}. In other words, the former is affected by the EVs density, whereas the latter is affected by the number of service requests. In case that each EV needs charging more than once, given by $N_{ev} \leq N_{re}$, we can benefit from the V2V communication enabled charging reservations reporting. Of course, fruitful contributions [10] on DTN routing can further reduce the communication cost, by means of optimal section of EVs for reservations relay. Other emerging architecture like Publish/Subscribe [9] as well as optimal caching CS information [12] can enable a distributed management manner.

V. Performance Evaluation

A. Simulation Configurations

We adopt Opportunistic Network Environment (ONE) [13], a java based simulator for evaluation. In Fig.2, the default scenario with 4500×3400 m^2 area is shown as the down town area of Helsinki city in Finland. Here, 300 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 configure two types of EVs (150 for each type), which are **Coda Automotive** [14] {33.8 kWh, 193 km, 30%} and **Hyundai BlueOn** [15] {16.4 kWh, 140 km, 50%}. Note that each EV may need to charge more than once, due to its continuous mobility. The radio coverage is set with 300m by following [6].

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 through 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.

The following schemes are compared:

- The proposed CS-selection scheme (via cellular network communication for reservation reporting), namely **Minimum Trip Duration (MTD)**.
- The proposed CS-selection scheme with V2V communication (using Epidemic [11] protocol) for delivering EVs charging reservations is evaluated as **MTD-V2V**.

Fig. 2. Simulation Scenario of Helsinki City

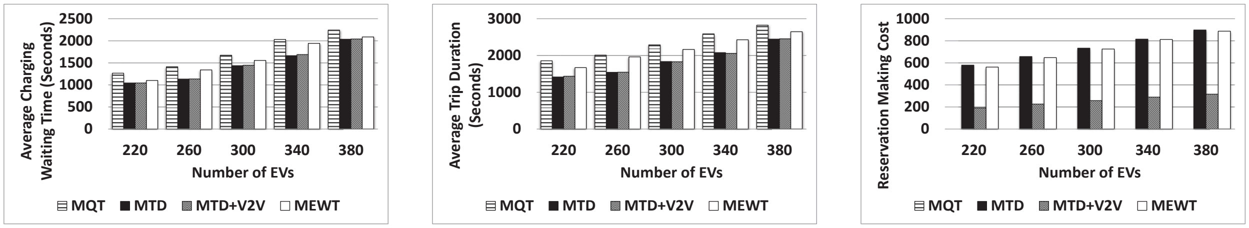
- The proposed CS-selection scheme (via cellular network communication for reservation reporting) without considering the total trip duration, namely **Minimum Expected Waiting Time (MEWT)**.
- The CS-selection scheme **Minimum Queuing Time (MQT)** (based on minimum queuing time at CS but not consider EVs' charging reservations) [6].

Evaluation metrics are as follows:

- **Average Charging Waiting Time:** The average period between the time an EV arrives at the selected CS and the time it finishes (full) recharging its battery. .
- **Average Trip Duration:** The average time that an EV experiences for its trip, through recharging service at an intermediate CS.
- **Reservation Making Cost:** For the V2V communication, the overhead is given by $\frac{\text{Number of Delivered Reservations - Number of Relayed Reservations}}{\text{Number of Relayed Reservations}}$. For the cellular network communication, it is given by the number of times to use cellular network communication for reservation reporting.

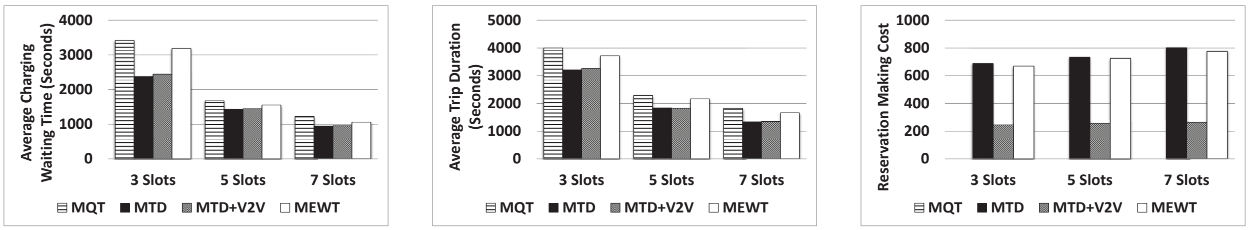
B. Evaluation Results

In Fig.3(a), Fig.3(b), Fig.3(c), MQT achieves the worst performance, due to not taking the EVs' charging reservations and their trip destinations into account for CS-selection. Since MEWT does not consider EV trip intention, it performs worse than MTD, where both of them rely on cellular link for reservation making. By comparing MTD with MTD+V2V, we observe they achieve a close performance, regarding average charging waiting time and trip duration, whereas the latter benefits from a much lower cost for reporting reservations. Note that, the former makes CS-selection decision using the instantaneous information (via ubiquitous cellular network communication), as such its charging performance is better than that via V2V (would however experience delay to report to GA). Thanks to V2V communication as well as vehicle mobility, such opportunistic communication brings comparable charging performance but with much lower cost for reservation reporting. As MQT does not involve reservation making, it experiences 0 cost.



(a) Average Charging Waiting Time (b) Average Trip Duration (c) Reservation Making Cost

Fig. 3. Influence of EVs Density



(a) Average Charging Waiting Time (b) Average Trip Duration (c) Reservation Making Cost

Fig. 4. Influence of Charging Slots

In Fig.4(a), Fig.4(b), Fig.4(c), all schemes follow similar trend given changed number of charging slots at CSs side. They all benefit from alleviated charging spot, via increased number charging slots to charge more EVs in parallel. Due to the same reason, MQT is with the worst performance, while MTD+V2V is cost-efficient in terms of reservation cost.

VI. Conclusion

In this paper, the proposed CS-selection scheme is based on the knowledge of those EVs locally parking at CSs, as well as those remotely making charging reservations. The anticipated EVs' charging reservations include their arrival time and expected charging time at selected CSs. This information is useful to coordinate EVs' charging plans take 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 shorter trip duration. We further study the feasibility of applying V2V communication to relay EVs' charging reservations. Results showed a considerable low communication cost while achieving comparable charging performance.

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