International Journal of Information Management 33 (2013) 245–251

Contents lists available at SciVerse ScienceDirect

International Journal of Information Management

journal homepage: www.elsevier.com/locate/ijinfomgt

Mobile charging information management for smart grid networks

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ARTICLE INFO

Article history:
Available online 16 January 2013

Keywords:
Smart grid network
Mobile charging station
Electric vehicle
Mobile charging information management system

ABSTRACT

With today's electric charging technology, charging time of an electric vehicle (EV) is much longer than that for a gasoline vehicle, and therefore the queueing effect at an EV charging station (CS) may be serious. That is, when an EV arrives at an overloaded CS, it is likely that the EV will wait for a long time before it is charged. This paper investigates the waiting problem for EV charging. We propose a Mobile CS (MCS) management system to dynamically distribute charging pole support that reduces the waiting times of EVs incurred in a fixed CS. A Mobile Charging Information Management System (MC-IMS) is presented to describe the execution flow of the MCS service. Simulation experiments are conducted to investigate the waiting time performance for the proposed mechanism. Our study indicates that the MCS-based MC-IMS provides effective EV charging with short waiting times.

1. Introduction

Compared with gasoline cars, Electric Vehicles (EVs) provide energy-efficient transport with carbon emission reduction (Kim, 2003; Lee, 2007; Schofield, Yap, & Bingham, 2005; U.S. Fuel Economy, 2011). An important issue about EV charging is to deploy an efficient smart grid network that can effectively and conveniently charge the EVs. This Grid-to-Vehicle (G2V) issue has been intensively investigated in the literature (Verma, Singh, & Shahani, 2011). Other EV charging/discharging issues for G2V-based smart grid network have been also studied, including Vehicle-to-Grid (V2G) and Vehicle-to-Vehicle (V2V) scenarios. An EV is generally equipped with energy storage of 24–56 kWh (Nissan USA, 2012; Tesla Motors, 2011), which is about 2–5 times more than the average daily energy consumption of a household in Taiwan (Miao, 2008). V2G technology utilizes such high energy storage of EV to discharge electricity to the power grid (Su, Eichi, Zeng, & Chow, 2008). In the V2V technology, an EV can soak up the power from the battery of a specific EV that is equipped with plenty energy storage (Li, Sahinoglu, Tao, & Teo, 2010; Sahinoglu, Tao, & Teo, 2010). The V2G and V2V technologies are currently under feasibility study and trial operations (Baker, 2011; Li et al., 2010; NUVVE Corporation, 2012; Sahinoglu et al., 2010; Su et al., 2008). This paper focuses on G2V architecture that also accommodates the V2V technology.

In a smart grid network, several Fixed Charging Stations (FCSs) are deployed in geographic area such as a highway. The charging time of an EV typically exceeds 30 min with the present fast-charging technologies (Nor, 1993; Winkler et al., 2009). If an EV arrives at an overloaded FCS, it will wait for a long time before it is charged. This paper integrates G2V and V2V technologies to reduce the EV waiting time for charging. The idea is to deploy Mobile Charging Stations (MCSs) in the smart grid network, which are dynamically distributed to relieve the workload of busy FCSs. An MCS is a specific EV equipped with several fast Charging Poles (CPs). When too many EVs arrive at an FCS (specifically the number of EVs in the FCS exceeds a tolerable threshold), an MCS will be dispatched to support the FCS for relieving the charging workload. The power source of an MCS may come from the connection to the power grid at the FCS or the MCS can be equipped with limited energy storage. This paper studies the scenario of the former case. In the latter case, the MCS needs to be recharged from time to time.

Information Management System (IMS) has been utilized to support many large-scale scheduling and parallel processing applications such as aviation (Abdi & Sharma, 2007) and cryptography (Ogiela & Ogiela, 2012). In this paper, we take the advantage of the IMS approach for dispatching the MCSs. Specifically, we develop a Mobile Charging Information Management System (MC-IMS) that dynamically dispatches the MCSs to relieve the workload of FCSs. In this solution, an EV is connected to an FCS for G2V charging, and is connected to an MCS for V2V charging. Our approach distributes MCSs based on the workload information (i.e., the number of EVs in the FCS) of FCSs. We conduct simulation experiments to compare the performance between traditional FCS system and the MC-IMS in terms of the average waiting time of EVs. In this paper, the smart grid network is called an FCS network if it is only deployed with

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http://dx.doi.org/10.1016/j.ijinfomgt.2012.11.007

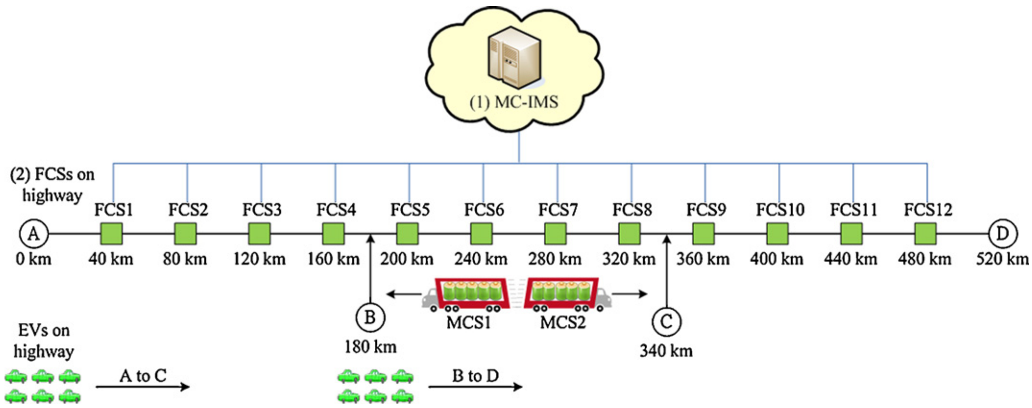


Fig. 1. The MC-IMS-based MCS Network Architecture.

FCSs (and the network only supports G2V charging). On the other hand, if MCSs are also deployed besides FCSs to be dispatched by the MC-IMS, then the smart grid network is called an MCS network (where both G2V and V2V charging are supported).

2. MC-IMS-based smart grid network

This section describes the waiting problem of EVs at FCSs. Then we describe how the MC-IMS dispatches MCSs based on the workload information of FCSs.

Without loss of generality, we consider the Taiwan-highway-like model (Taiwan Area National Freeway Bureau of MOTC, 2012) to show the MC-IMS architecture. As illustrated in Fig. 1, the length of the highway is 520 km with 12 intermediate highway rest areas. We assume that the FCSs are located at the highway rest areas (one FCS per rest area). The distance between two FCSs is 40 km.

In a smart grid network, an EV is installed an on-board unit (OBU, a GPS-based navigator). Therefore, from a digital map and GPS, the EV is aware of the locations of the FCSs. In an FCS network, when an EV travels on the high way, its OBU can select the next FCS for charging based on the local information (i.e., the current position of the EV, the remaining electricity, and the distances to the FCSs) (Imai, Ashida, Zhang, & Minami, 2008). From the local information, the OBU compiles a list of reachable FCSs, and then selects the next FCS for charging. We assume that each EV selects the farthest FCS for charging.

Since each EV selects the next FCS without considering the queueing status of FCS, the EVs may select busy FCSs. To resolve this issue, the MCSs are introduced into the FCS network and are dispatched by the MC-IMS (see Fig. 1 (1)) to support hot-spot FCS locations. An FCS (e.g., Fig. 1 (2)) requests MCS support from the MC-IMS when the number of EVs in this FCS is larger than a high threshold. Then the MC-IMS will dispatch an MCS to provide extra charging capacity to the FCS location. On the other hand, if the workload of an FCS with MCSs is under a low threshold, then the MCSs at this FCS location can be dispatched to support other hot spots.

The parameters used in this mechanism are described as follows. Suppose that there are F FCSs, and each FCS has P_f CPs. There are M MCSs, each of them has P_m CPs. The ith FCS is denoted as $f(i)$, where $1 \le i \le F$. In $f(i)$, several parameters are maintained:

- q: the queue length (the workload) or the number of EVs in the FCS
- f: a flag indicating the status of the workload, where $f = 0$ represents the light-load, $f = 1$ represents the medium-load, and $f = 2$ represents the heavy-load
- P_n: the number of CPs at an FCS's location, where $f(i) \cdot P_n = P_f + j\,P_m$ means that there are j MCSs at $f(i)$'s location
- L_R: the MCS-requesting lock, where $L_R = 0$ ($L_R = 1$) represents that the FCS can (cannot) request MCS support

To determine whether an FCS will request an MCS or donate an MCS, the criterion with a weighted factor $\alpha > 1$ is considered to indicate the workload of an FCS. An FCS is heavy-load if $f(i) \cdot q \ge \alpha f(i) \cdot P_n$. On the other hand, the FCS is light-load if $f(i) \cdot P_n - f(i) \cdot q \ge P_m$. A light-load FCS can donate MCSs if $f(i) \cdot P_n > P_f$ (i.e., there is at least one MCS at this FCS location). The parameters maintained in the MC-IMS include:

- Q_D: the donor list or the set of light-load FCSs that can donate one or more MCSs
- Q_R: the requester list or the set of heavy-load FCSs that require extra CPs

Based on the above parameters, we develop the procedures for the MCS-Dispatching mechanism to be described in the next section.

3. The procedures for the MCS-Dispatching mechanism

The procedures for the MCS-Dispatching mechanism include EV-Arrival, Request-MCS, Dispatch-MCS, Donate-MCS, Cancel-Donate-MCS, Charge-Complete, Cancel-Request-MCS, and MCS-Arrival. The details are elaborated in the subsequent subsections.

3.1. EV-Arrival procedure

When an EV arrives at $f(i)$ for charging, the EV-Arrival procedure is executed. The message flow is shown in Fig. 2 and is described as follows:

Step A.1. An EV arrives at $f(i)$, and $f(i) \cdot q$ is incremented by 1.

Step A.2. (Check if the workload of $f(i)$ changes from medium to heavy). If $f(i) \cdot q \ge \alpha f(i) \cdot P_n$ and $f(i) \cdot f = 1$, then $f(i)$ requests extra CPs from the MC-IMS with the following actions:

Step A.2.1. $f(i) \cdot f$ is set to 2.
Step A.2.2. If $f(i) \cdot L_R = 0$ (i.e., there no MCS dispatched to $f(i)$ and driving to $f(i)$'s location), then $f(i)$ invokes the Request-MCS procedure (see Section 3.2) and exits.

Step A.3. (Check if the workload of $f(i)$ changes from light to medium). Else if $f(i) \cdot P_n - f(i) \cdot q < P_m$ and $f(i) \cdot f = 0$, then the following substeps are executed:

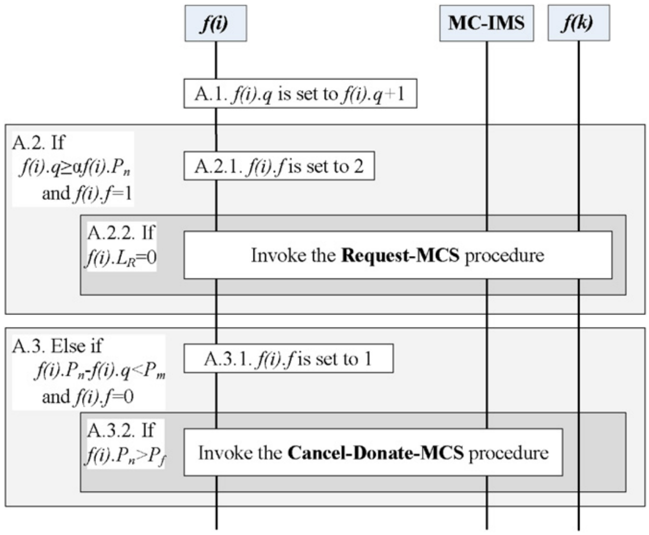


Fig. 2. The message flow of the EV-Arrival procedure.

Step A.3.1. $f(i){\cdot}f$ is set to 1.
Step A.3.2. If $f(i){\cdot}P_n > P_f$ (i.e., there are one or more MCSs at $f(i)$'s location), then $f(i)$ invokes the Cancel-Donate-MCS procedure (see Section 3.5) and exits.

Note that if $f(i){\cdot}q \le f(i){\cdot}P_n$ after Step A.1 is executed, then the EV is served by a CP immediately. Otherwise, the EV is queued in $f(i)$. When the workload of $f(i)$ changes from light to medium, if $f(i){\cdot}P_n = P_f$ at Step A.3, there is no MCS at $f(i)$'s location, and $f(i)$ does not donate any MCS to the MC-IMS.

If neither Step A.2 nor Step A.3 is executed, it means that the workload of $f(i)$ does not change when the EV arrives, and $f(i)$ needs not to interact with the MC-IMS.

3.2. Request-MCS procedure

In the Request-MCS procedure, $f(i)$ requests the MC-IMS to provide MCS support. The MC-IMS selects a light-load FCS from Q_D to donate extra MCSs. The message flow is shown in Fig. 3 and is described as follows:

Step B.1. $f(i)$ sends the Request-MCS message to the MC-IMS for MCS support.

Step B.2. Upon receipt of the Request-MCS message, the MC-IMS checks the status of Q_D.

Step B.3. If $Q_D = \Phi$ (i.e., no FCS can donate any MCS to $f(i)$), then the MC-IMS takes the following actions:

Step B.3.1. Q_R is set to $Q_R \cup \{i\}$.
Step B.3.2. The MC-IMS sends the Request-MCS-Response message with the result "Reject" to $f(i)$, and this procedure exits.

Step B.4. Else (i.e., $Q_D \neq \Phi$ and there is at least an FCS that can donate an MCS) the MC-IMS selects k in Q_D such that the distance of $f(k)$ is closest to $f(i)$.

Step B.4.1. The MC-IMS invokes the Dispatch-MCS procedure (see Section 3.3) that instructs $f(k)$ to send an MCS to $f(i)$.
Step B.4.2. Check the returned result c of the Dispatch-MCS procedure ($c \ge 0$ represents the number of MCSs remained at $f(k)$'s location after dispatching an MCS to $f(i)$, and $c < 0$ represents that no free MCS is at $f(k)$'s location).
Step B.4.3. If $c \le 0$ (i.e., $f(k)$ has medium or heavy workload), then Q_D is set to $Q_D - \{k\}$.

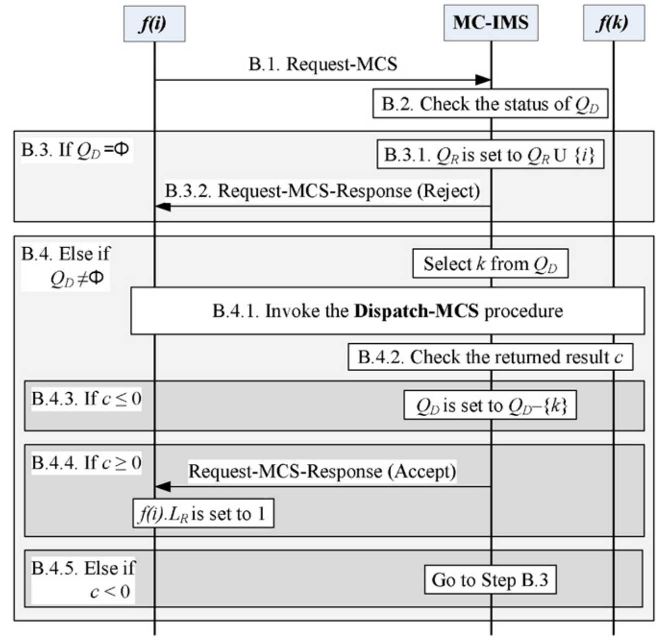


Fig. 3. The message flow of the Request-MCS procedure.

Step B.4.4. If $c \ge 0$ (i.e., an MCS has been dispatched to support $f(i)$), then the MC-IMS sends the Request-MCS-Response message with the result "Accept" to $f(i)$. Upon receipt of the Request-MCS-Response message with the result "Accept", $f(i)$ sets $f(i){\cdot}L_R$ to 1.
Step B.4.5. Else (i.e., the MC-IMS should select another FCS from Q_D to support $f(i)$) go to Step B.3.

Note that although Q_D indicates that an FCS $f(k)$ can donate an MCS at Step B.4, $f(k)$ may cancel its donation before Step B.4.1 is completed. If so, the MC-IMS must check Q_D to find another MCS donor. Therefore, Step B.4.5 may loop back to Step B.3. At Step B.4.3 and B.4.4, when $c = 0$, it means that $f(k)$ becomes medium-load after it has dispatched an MCS.

3.3. Dispatch-MCS procedure

In the Dispatch-MCS procedure, the MC-IMS dispatches an MCS from $f(k)$ to $f(i)$. In this procedure, we can use the switching technique to switch the EVs charged by the CPs of certain MCSs to the CPs of the FCS or other MCSs, and $\lfloor [f(k) \cdot P_n - \max(f(k) \cdot q, P_f)]/P_m \rfloor$ is the number of MCSs that $f(k)$ can donate (if $\lfloor [f(k) \cdot P_n - \max(f(k) \cdot q, P_f)]/P_m \rfloor \ge 1$). The message flow is shown in Fig. 4 and is described as follows:

Step C.1. The MC-IMS sends the Request-MCS message to $f(k)$. This message requests $f(k)$ to dispatch an MCS to support $f(i)$.

Step C.2. Upon receipt of the Request-MCS message, $f(k)$ checks its workload.

Step C.3. If $\lfloor [f(k) \cdot P_n - \max(f(k) \cdot q, P_f)]/P_m \rfloor \ge 1$ (i.e., $f(k)$ can donate at least one MCS), then $f(k)$ dispatches an MCS to $f(i)$ and $f(k){\cdot}P_n$ is set to $f(k){\cdot}P_n - P_m$.

Step C.4. If $\lfloor [f(k) \cdot P_n - \max(f(k) \cdot q, P_f)]/P_m \rfloor = 1$ (i.e., the status of $f(k)$ will become medium after it donates the MCS), then $f(k){\cdot}f$ is set to 1.

Step C.5. $f(k)$ sends the Request-MCS-Response message with the status code $c = \lfloor [f(k) \cdot P_n - \max(f(k) \cdot q, P_f)]/P_m \rfloor$ to the MC-IMS.

At Step C.3, $f(k){\cdot}P_n$ is decreased by the amount P_m. Therefore, at Step C.5, $c < 0$ represents that no free MCS is at $f(k)$'s location, $c = 0$ represents that exactly one free MCS is at $f(k)$'s location, $c > 0$

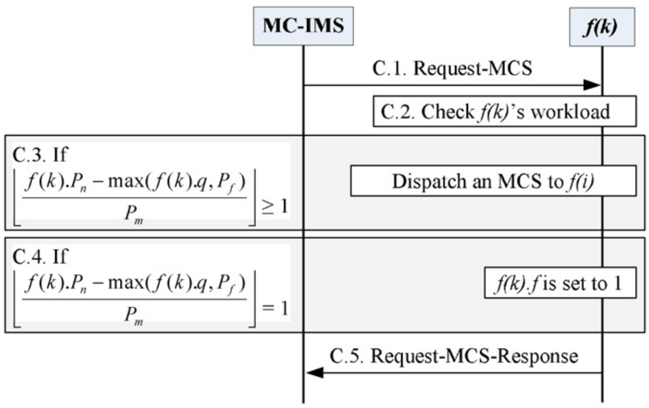


Fig. 4. The message flow of the Dispatch-MCS procedure.

represents that more than one free MCSs are at $f(k)$'s location, and $f(k)$ has dispatched an MCS for $c \geq 0$.

3.4. Donate-MCS procedure

In the Donate-MCS procedure, $f(i)$ informs the MC-IMS that $f(i)$ can donate MCSs. The message flow is shown in Fig. 5 and is described as follows:

Step D.1. $f(i)$ sends the Donate-MCS message to the MC-IMS.

Step D.2. Upon receipt of the Donate-MCS message, the MC-IMS checks the status of Q_R.

Step D.3. If $Q_R = \Phi$ (i.e., no FCS needs extra CPs), then Q_D is set to $Q_D \cup \{i\}$.

Step D.4. Else (i.e., $Q_R \neq \Phi$ and there is an FCS that needs extra CPs) the MC-IMS selects k from Q_R.

Step D.4.1. The MC-IMS invokes the Dispatch-MCS procedure (see Section 3.3) that instructs $f(i)$ to send an MCS to $f(k)$.
Step D.4.2. The Dispatch-MCS procedure returns the result c to the MC-IMS.
Step D.4.3. If $c \geq 0$ (i.e., $f(i)$ has dispatched an MCS to support $f(k)$), then the MC-IMS sets Q_R to $Q_R - \{k\}$ and sends the Dispatching-Notification message to notify that an MCS is dispatched and driving to $f(k)$. Upon receipt of the Dispatching-Notification message, $f(k)$ sets $f(k) \cdot L_R$ to 1.

Step D.5. The MC-IMS sends the Donate-MCS-Response message to $f(i)$.

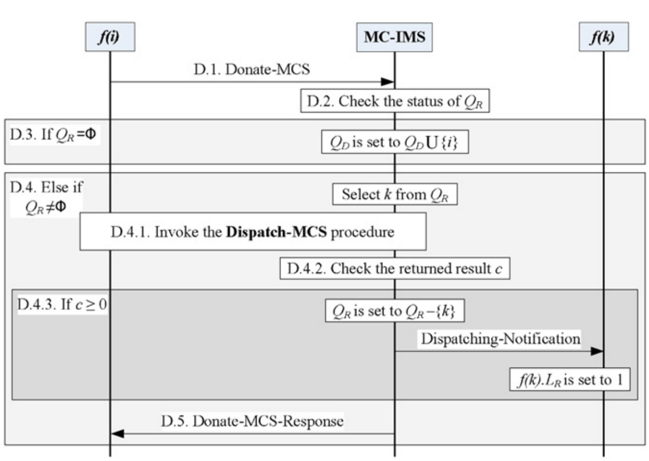


Fig. 5. The message flow of the Donate-MCS procedure.

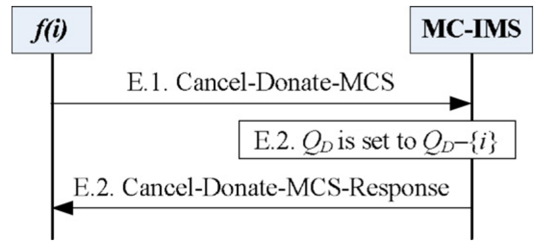


Fig. 6. The message flow of the Cancel-Donate-MCS procedure.

After Step D.4.2, if $c < 0$ (i.e., $f(i)$ cannot donate any MCS to support $f(k)$), the MC-IMS takes no action.

3.5. Cancel-Donate-MCS procedure

In the Cancel-Donate-MCS procedure, $f(i)$ informs the MC-IMS to cancel the previous donation. When this procedure is executed, it means that after the FCS decided to donate an MCS, its workload has been increased, and the FCS can no longer keep its promise (and therefore has to cancel the donation). The message flow is shown in Fig. 6 and is described as follows:

Step E.1. $f(i)$ sends the Cancel-Donate-MCS message to inform the MC-IMS that $f(i)$ will not release any MCS.

Step E.2. Upon receipt of the Cancel-Donate-MCS message, the MC-IMS sets Q_D to $Q_D - \{i\}$ and sends the Cancel-Donate-MCS-Response message to inform $f(i)$ that the donation is canceled.

3.6. Charge-Complete procedure

When an EV completes its charging from $f(i)$, the Charge-Complete procedure is executed. The message flow is shown in Fig. 7 and is described as follows:

Step F.1. An EV completes its charging from $f(i)$, and $f(i) \cdot q$ is decremented by 1.

Step F.2. (Check if the workload of $f(i)$ changes from medium to light). If $f(i) \cdot P_n - f(i) \cdot q \geq P_m$ and $f(i) \cdot f = 1$, then the following substeps are executed:

Step F.2.1. $f(i) \cdot f$ is set to 0.

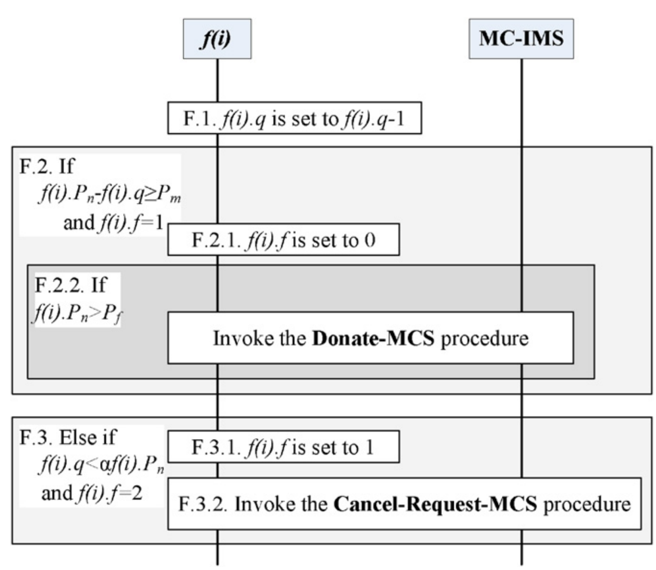


Fig. 7. The message flow of the Charge-Complete procedure.

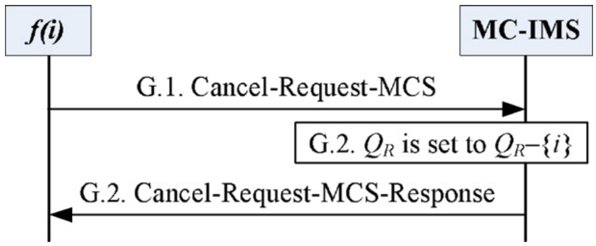


Fig. 8. The message flow of the Cancel-Request-MCS procedure.

Step F.2.2. If $f(i){\cdot}P_n > P_f$ (i.e., there are one or more free MCSs at $f(i)$'s location), then $f(i)$ invokes the Donate-MCS procedure (see Section 3.4) and exits.

Step F.3. (Check if the workload of $f(i)$ changes from heavy to medium). Else if $f(i){\cdot}q < \alpha f(i){\cdot}P_n$ and $f(i){\cdot}f = 2$, then $f(i)$ informs the MC-IMS that it no longer requests for MCS support with the following actions:

Step F.3.1. $f(i){\cdot}f$ is set to 1.
Step F.3.2. $f(i)$ invokes the Cancel-Request-MCS procedure (see Section 3.7) and exits.

Note that when the workload of $f(i)$ changes from medium to light, if $f(i){\cdot}P_n = P_f$ at Step F.2, there is no MCS at $f(i)$'s location, and $f(i)$ needs not to interact with the MC-IMS.

If neither Step F.2 nor Step F.3 is executed, it means that the workload of $f(i)$ does not change. In this case, $f(i)$ needs not to interact with the MC-IMS.

3.7. Cancel-Request-MCS procedure

In the Cancel-Request-MCS procedure, $f(i)$ informs the MC-IMS to cancel the previous Request-MCS command sent from $f(i)$. When this procedure is executed, it means that after the FCS decided to request an MCS, its workload has been decreased, and the FCS no longer requests for MCS support (and therefore has to cancel the previous request). The message flow is shown in Fig. 8 and is described as follows:

Step G.1. $f(i)$ sends the Cancel-Request-MCS message to inform the MC-IMS that $f(i)$ will not request extra MCSs.

Step G.2. Upon receipt of the Cancel-Request-MCS message, the MC-IMS sets Q_R to $Q_R-\{i\}$ and sends the Cancel-Request-MCS-Response message to inform $f(i)$ that the request is successfully canceled.

3.8. MCS-Arrival procedure

When an MCS arrives at $f(i)$ to provide extra CPs, the MCS-Arrival procedure is executed. The message flow is shown in Fig. 9 and is described as follows:

Step H.1. An MCS arrives at $f(i)$ to provide extra CPs. $f(i){\cdot}P_n$ is set to $f(i){\cdot}P_n + P_m$, and $f(i){\cdot}L_R$ is set to 0.

Step H.2. (Check if the workload of $f(i)$ is still heavy). If $f(i){\cdot}q \geq \alpha f(i){\cdot}P_n$, then $f(i)$ invokes the Request-MCS procedure (see Section 3.2) and exits.

Step H.3. (Check if the workload of $f(i)$ changes from medium to light). Else if $f(i){\cdot}P_n - f(i){\cdot}q \geq P_m$ and $f(i){\cdot}f = 1$, then $f(i)$ can donate MCSs with the following actions:

Step H.3.1. $f(i){\cdot}f$ is set to 0.
Step H.3.2. $f(i)$ invokes the Donate-MCS procedure (see Section 3.4) and exits.

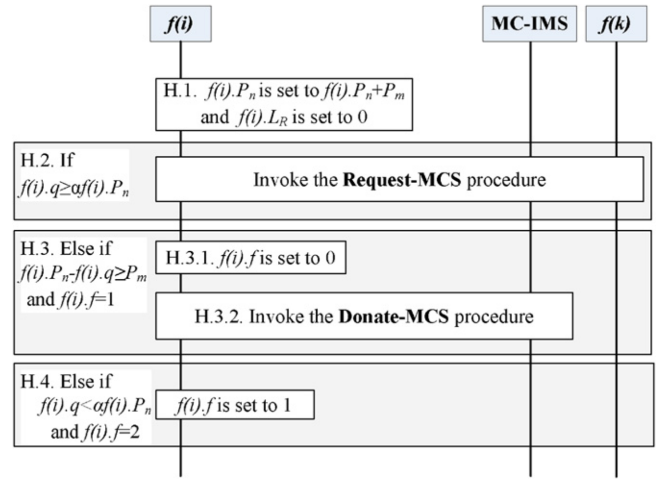


Fig. 9. The message flow of the MCS-Arrival procedure.

Step H.4. (Check if the workload of $f(i)$ changes from heavy to medium) Else if $f(i){\cdot}q < \alpha f(i){\cdot}P_n$ and $f(i){\cdot}f = 2$, then $f(i){\cdot}f$ is set to 1.

If none of the steps in Step H.2, Step H.3, and Step H.4 is executed, it means that the workload of $f(i)$ is still medium or still light. In this case, $f(i)$ needs not to interact with the MC-IMS.

4. Performance evaluation

We develop an event-driven simulation model (Gan & Lin, 2007) to compute the output measures for the FCS and the MCS networks. Based on the simulation experiments, this section compares the performance of these two networks. In our simulation experiments, the speed of an EV is uniformly distributed between 60 km/h and 100 km/h, which are the lower and the upper speed limits of TNE1, respectively. The initial power of an EV is uniformly distributed between 25% and 100% (the value 25% is the minimal required power for an EV to drive to the nearest FCS). A fully-charged EV can last for 160 km (e.g., when an EV travels for a trip longer than 160 km in the highway, it must be recharged at the FCSs), and the time for an EV charging from 0% to 100% is 30 min. Each EV is charged to 100% at an FCS, and the charging time is linearly proportional to the amount of charged energy. We simulate 1,000,000 EV arrivals. For the FCS workload indication, the weighted factor α is set to 1.5.

The input parameters in the simulation experiments are the EV arrival rate (λ), the number of FCSs (F), the number of CPs at each FCS (P_f), the number of MCSs (M), and the number of CPs on each MCS (P_m).

The major output measure in this paper is the average waiting time W for an EV before it is charged at an FCS location.

Without loss of generality, there are two types of EV traffic patterns: In the first pattern, the EVs drive from point A to point C as illustrated in Fig. 1. In the second pattern, the EVs drive from point B to point D. The length of each path is 340 km. Note that the paths (A, C) and (B, D) have an overlapping segment (B, C) that covers four FCSs (i.e., from FCS5 to FCS8). The EVs arrivals are a Poisson process with the rate λ ranging from 1.02 to 1.06, which is about 8.5–8.8% of the average vehicle traffic of Sijhih at Taiwan National Expressway 1 (TNE1) in southward direction (i.e., for every minute, there are 12 car arrivals, and among them, 1.02–1.06 are EVs) (Ministry of Transportation & Communications, 2011). Each EV selects the farthest FCS for charging. When an EV enters an FCS and then is served by a CP, we collect its waiting time at the FCS location (i.e., the time that the EV waits for charging).

We assume that there are 12 FCSs, and each FCS has 20 CPs in the FCS network (i.e., the total number of CPs is 240). There are M

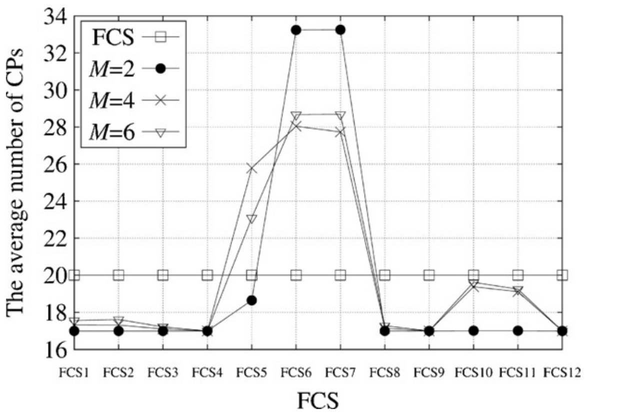


Fig. 10. The CP distribution among the FCS locations ($\lambda = 1.04$; FCS network: $F = 12$, $P_f = 20$, $M = P_m = 0$; MCS network: $F = 12$, $P_f = 17$, $M \times P_m = 36$).

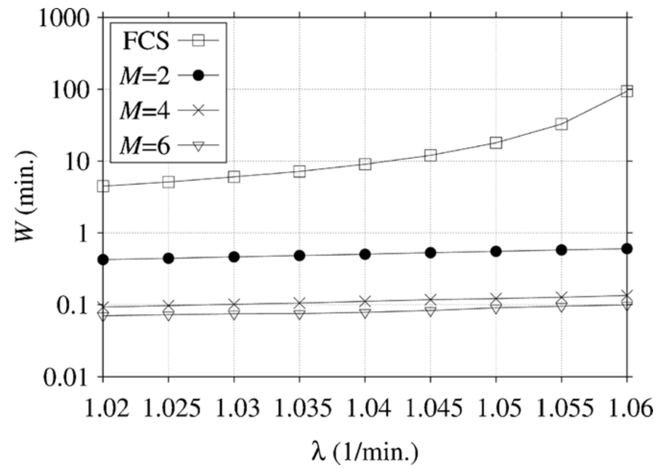


Fig. 11. The W performance (FCS network: $F = 12$, $P_f = 20$, $M = P_m = 0$; MCS network: $F = 12$, $P_f = 17$, $M \times P_m = 36$).

MCSs and each MCS is equipped with P_m CPs. The speed of an MCS is set to 90 km/h, which is the upper speed limit of large truck on TNE1. To make a fair comparison, the total number of CPs in the MCS network is also set to 240 in the following simulations (i.e., $F \times P_f + M \times P_m = 240$, where F is fixed to 12).

Fig. 10 compares the CP distribution between the FCS network and the MCS network. Note that in the FCS network, every FCS has 20 CPs (see the □ line). In the MCS network, we allocate 15% of total CPs to 2, 4, and 6 MCSs respectively (i.e., each MCS has 18, 9, and 6 CPs, respectively) and the arrival rate λ is fixed to 1.04. Since the overlapping segment (B, C) covers FCS5 to FCS8, it is more likely that the hot spots occur in these four FCSs. Fig. 10 shows that FCS5 to FCS7 receive more extra CPs that will mitigate workloads of the hot spots. The MCS network can distribute CPs flexibly since the mobile CPs can be donated to the hot-spot FCSs and effectively reduces the queueing effect in these FCSs.

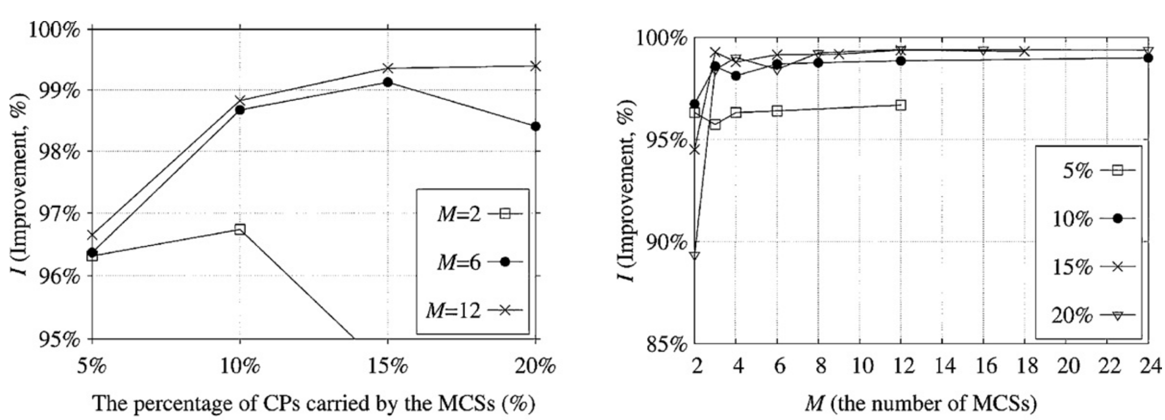
Fig. 11 compares the average waiting time W between the FCS network and the MCS network, where the total number of CPs is fixed to 240. In this simulation experiment, the EV arrival rate λ ranges between 1.02 and 1.06. We allocate 15% of total CPs to 2,4, and 6 MCSs, respectively. Intuitively, W increases as λ increases. In the FCS network, if λ is small, W increases slowly as λ increases. When $\lambda > 1.05$, W increases fast as λ increases since the queueing effects of the hot spots are intensified with the high EV arrival rates. On the other hand, the MCS network can effectively distribute the CPs to the hot spots (i.e., FCS5 to FCS7) to reduce the queueing effect of these FCSs (see Fig. 10). Therefore, the W values in the MCS network increase insignificantly for all λ values, and are much lower than those in the FCS network. The advantage of the MCS network over the FCS network becomes very significant when traffic load is heavy.

Let W_F be the W for the FCS network, and W_M be the W for the MCS network. Then the improvement of W by the MCS network over the FCS network can be defined as:

$$I = \frac{W_F - W_M}{W_F} \quad (1)$$

Fig. 12(a) shows the waiting time improvement I for the various percentagesof CPs carried by the MCSs, where the total number of CPs is fixed to 240, and we consider the scenarios where 5%, 10%, 15% and 20% of CPs are equipped on MCSs in the experiments. The EV arrival rate λ is fixed to 1.04. Clearly, when the percentage of mobile CPs is fixed, the improvement I of the waiting time increases with the number of the MCSs M.

Fig. 12(b) shows the waiting time improvement I as the function of MCS number. Compared to the FCS network, the improvement of W performance is significantly improved by the MCS network with 10% mobile CPs allocated to the MCSs; that is, allocating a small amount of CPs to MCSs can obtain significantly performance improvement. Thus if the budget for building an MCS network is limited, and the MCS network operator would like to reduce



(a) Effect of the percentage of CPs carried by the MCSs

(b) Effect of the number of MCSs

Fig. 12. The improvement I where 5–20% CPs are mobile ($\lambda = 1.04$; $F \times P_f + M \times P_m = 240$, e.g., in the 5% case, $F = 12$, $P_f = 19$, and $M \times P_m = 12$).

the waiting times of EVs, then allocating 10% CPs to MCSs is an appropriate choice. Furthermore, the improvement I increases insignificantly after $M > 6$. Thus for better MCS investment, the operator can limit the number M to less than 6 to save the operating costs and still efficiently reducing the waiting times of EVs.

5. Conclusions

This paper proposed two types of smart grid networks for an EV charging: the Fixed Charging Station (FCS) and the Mobile Charging Station (MCS) networks. The FCS network only utilizes fixed charging stations. The MCS network combines FCSs with mobile charging stations dispatched by a Mobile Charging Information Management System (MC-IMS). The simulation experiments are conducted to investigate the waiting time performance for these smart grid networks. Our experiments indicated that the MCS network has better waiting time performance than the FCS network. The advantage of the MCS network over the FCS network becomes very significant when the EV arrival rate is large.

In this paper, every FCS location has infinite waiting capability. In the future, we will extend our study to consider FCS locations where the parking spaces are limited.

Acknowledgements

This paper was supported in part by the ITRI/NCTU JRC Research Project, the ITRI Advanced Research Program under B301EA3300, B301AR2R10, and B352BW1100, under C352BW1100, C301EA 3600, and C301AR2D10, ICL/ITRI, NSC 100-2221-E-009-070, Chunghwa Telecom, IBM, Arcadyan Technology Corporation, Nokia Siemens Networks, Department of Industrial Technology (DoIT) Academic Technology Development Program 100-EC-17-A-03-S1-193, the MoE ATU plan, and the Technology Development Program of the Ministry of Economic Affairs (MoEA TDP), Taiwan.

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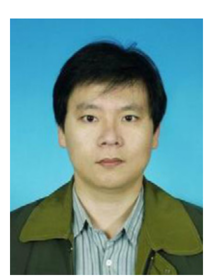

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