A Two-Way Communication Scheme for Vehicles Charging Control in the Smart Grid

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***Abstract*— The smart grid is a new concept of electricity supply operation and management that will enable consumers and utilities to better control the electricity usage. This is possible because of the two way electricity and information communication between all nodes in the grid. For Electric Vehicles (EVs) travelling on the road, and because of the necessary battery charging times, there is a need for wireless communication between the EVs and the Electric Vehicle Supply Equipment (EVSEs) (charging stations) to discover the availability and make pre-reservations of charging time slots. In this paper, we introduce a new communication protocol between EVs and EVSEs that allows a reliable reservation process. The scheme, called Reliable Broadcast for EV Charging Assignment (REBECA) processes information about electricity usage in EVSEs and allows to reserve charging time slots for vehicles. REBECA also takes into account balancing energy usage between EVSEs while minimizing the latency time of EVs. Simulations results show the effectiveness of REBECA scheme.**

Index Terms—Electric vehicle, broadcast, charging process, electrical vehicle supply equipment, grid.

I. INTRODUCTION

The National Institute of Standards and Technology (NIST) [1] fixed six key priority functionalities of the Smart Grid: advanced metering infrastructure, demand response, electric vehicles (EVs), wide-area situational awareness, distributed energy resources and storage and distribution grid management. The smart grid must provide also the following key functionalities: a higher efficiency in electricity usage and reliable two-way end-to-end communications with short latency time. For EVs energy supply management, achieving these functionalities means maintaining a good and balanced capacity utilization of Electrical Vehicle Supply Equipment (EVSEs) on the road, and reducing the latency time of EVs in the grid. The following question then arises "How can EVs latencies be minimized while balancing capacity utilization of EVSEs?"

In this paper, we propose a scheme called Reliable Broadcast for EV Charging Assignment (REBECA). We believe that how messages are exchanged between EVs and EVSEs and how decisions are taken by the EVs to select the appropriate EVSE during the charging process has a major influence on the performance of the smart grid architecture for serving electric vehicles on the road. Two key performance parameters have been considered in this work. First, there is the latency time for a vehicle to be served. Latency time is defined as the time a transmitting vehicle on the road requests to be served, up until the time the service has been completed. Second, there is the efficiency of the required service. Our scheme REBECA is able to determine how many EVs can be efficiently served by a number of EVSEs without increasing the probability of overload on EVSEs or latency time on EVs (see Simulations results section).

Along with the REBECA protocol, we propose three algorithms to highlight the intimate relationship between the EVSEs power balancing and the latency time of the EVs. First, we propose a random access allocation algorithm, called RAA to search for a feasible/initial charging process solution of the proposed model. RAA chooses an EVSE location randomly among the set of available EVSEs. The second algorithm is called Best Access Allocation (BAA), in which the EV selects the EVSE with the smallest free slots which are able to contain the EV demand. The last algorithm named Power Balancing Access Allocation (PBAA) takes into consideration the power balancing between EVSEs to keep a minimal variance of electricity usage between them while providing a short latency time for EVs and then guarantees service efficiency. Our contribution can be summarized as illustrated in Fig.1, where REBECA scheme establishes robust broadcast communication between different equipments in the grid and it makes use of three algorithms (detailed in section III.D) to mainly show how it is important to take into account trade-offs between power balancing (between EVSEs) and latency time of EVs.

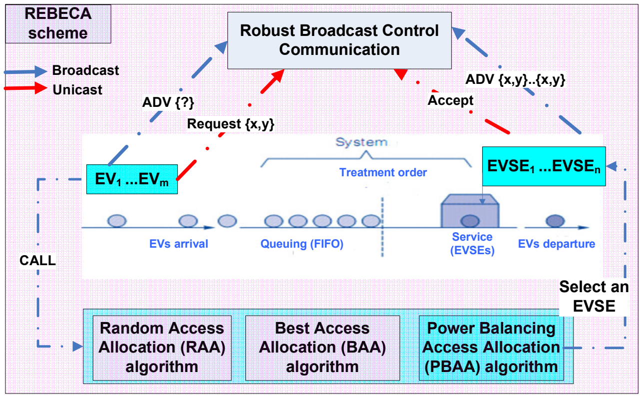

Fig.1. REBECA scheme

The remainder of the paper is organized as follows. Section II presents briefly the related work in the field. Section III proposes our scheme named REBECA and presents a mathematical formulation of the keys parameters. Section IV evaluates the proposed algorithms via extensive simulations. Finally, Section VI concludes the paper.

II. RELATED WORK

Although some existing schemes based on high speed two-way communication between all EVs and centralized controllers could allow distribution power centers to run almost in their full capacity, the service efficiency is still challenging due to real-time reliance upon communication networks. The authors in [2] tackle this issue by controlling EV start time charging. However, in their proposed scheme, they assume that all EVs chargers consume the same amount of power which is not feasible in real life.

Several researchers observe the potential increase in EVs as an opportunity to utilize the on-board battery storage in an interactive way to provide two-way energy flows to buffer time-variable renewable [3-4] or to grant supplementary services such as frequency regulation [5].

In [3], the authors claim that EV battery charging can be managed to increase the supply of regulation service. Thus, it could both control its cost and alleviate distribution network congestion. They assume that an EVSE is already selected by EV owners to manage EV charging power. For that, they equip EVs with a smart interface that measures in real-time statistics and the EVSE recovers information from each EV smart interface, controls battery charging in real-time, and communicates with the grid operator who provides information on low voltage feeder specific unused capacity available for EV battery charging. Nevertheless, these assumptions are not reasonable, because as we demonstrate in this paper, the selection of EVSE during the charging process is very important and influences the grid performance in terms of latency time and electricity use.

In the project of the California Air Resources Board and the California Environmental Protection Agency [5], N. Brooks evaluated the practicality of EVs providing a grid additional service called regulation. It is worth noting that this study focuses on one specific service. Particularly, regulation is well appropriate to battery EVs and it involves fast-response alterations in power above and below a “baseline”. They demonstrate that with the “baseline” set at zero power, the power fluctuations above and below zero average out to approximately zero net energy over time. Consequently, EVs battery state of charge would vary in the short term, but would not become discharged over time. However, the communication difficulties prominent in this project are not considered in the work.

In our study, we present in details the broadcast communication in the REBECA scheme (see next section). Because of the necessary battery charging times for EVs, the latter need to know the status of an EVSE (for example, empty slots available, all slot for vehicle are being used for a certain duration, etc…) prior to heading to its location. There is then a need for wireless communication between the EVs and the EVSEs to discover the availability and make pre-reservations of charging time slots. The REBECA communication protocol between EVs and EVSEs allows a reliable reservation process. The scheme processes information about electricity usage in EVSEs and allows to reserve charging time slots for vehicles. REBECA also takes into account balancing energy usage between EVSEs while maximizing the power utilization and minimizing the latency time of EVs.

III. REBECA OVERVIEW

A. *Deployed architecture*

In the upcoming next years where tens of thousands of EVs will be connected to the grid performing one or multiple services, it is almost certain that the grid operator will not want to contract with each individual EV. Instead, the grid operator will want to have control over the power utilization of intermediary entities, called EVSEs that would manage the interactions between the grid operator and the connected EVs in a region. To the grid operator, the EVSE will be source of controllable power charging process and a good source of regulation electricity use. The grid operator and EVSE would communicate over a secure data link of the same type used to communicate with existing sources of regulation. The EVSE would receive power management commands from the grid operator and thus allocates the required power out to the connected EVs. A graphic of such system architecture is illustrated in Fig. 2. Since the charging times of vehicle batteries are long (tens of minutes for the fastest charging stations), it his highly advisable that a reservation process takes place prior to an EV heading to the EVSE. In this work we consider that EVSEs and EVs use wireless communication such as WIFI or Wireless Mesh Networks (WMNs) [6] to exchange such information, and we present a reliable two-way communication protocol between EVs and EVSE to ensure the reservation process as shown in the sub-section III.B.

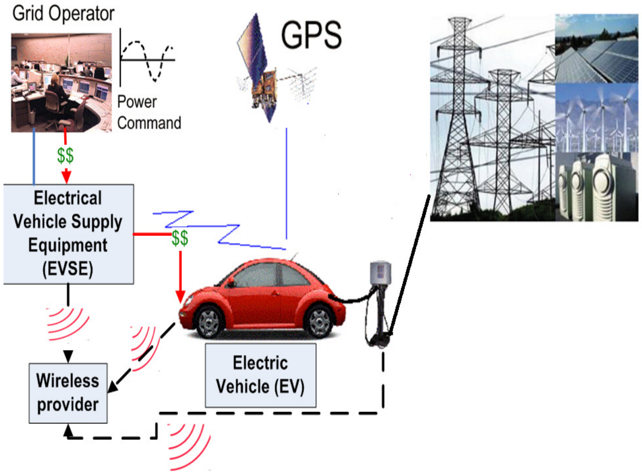

Fig.2. Architecture of an electric vehicle (EV)-based grid power management on an electrical vehicle supply equipment (EVSE)

Table I shows the notations used throughout the paper.

TABLE I. NOTATIONS PARAMETERS

P_0	Unit power
τ	Unit time
x_i	Duration units
y_i	offset
P_{EV_i}	Power of vehicle EV_i
P_{EVSE_j}	Power of $EVSE_j$
D	Latency time of EV
a	Arrival time
S	Service time
λ	Average rate of arrival rate of EVs
W	Waiting time
μ	Average rate time of departure of EVs
$D_{predefined}$	A threshold QoS value of maximum accepted latency time in our REBECA scheme

B. *Broadcast communication in REBECA*

In the following, an example of the EVs charging process using the RAA algorithm (see section III.D) is described in Fig.3 and the messages exchanged between EVs and EVSEs during the broadcast two-way communication are detailed in the diagram sequence shown in Fig.4.

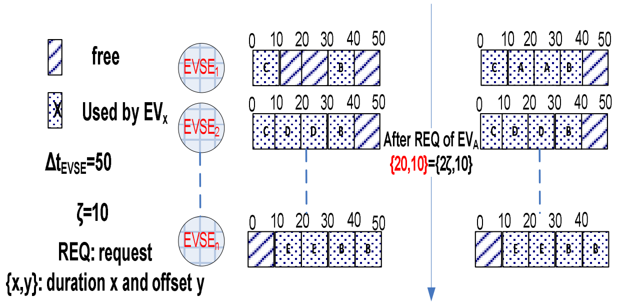

Fig.3. An example of dynamic adjustment of electricity use on EVSEs using RAA algorithm

The procedure of duration x and offset y negotiation is illustrated by means of a simple example. Fig.3 depicts part of a grid network, and we focus on N EVSEs and an EV request which are in the same region. Assume that there some charging slots that are being used in EVSEs as shown in Fig.3. These are advertised by each EVSE as a set of couples {x,y}. RAA chooses an EVSE location randomly among the set of available EVSEs. Then, in this example, EV$_A$ will select the random available duration among the set of feasible EVSEs, e.g., in Figures 3-4, it chooses the EVSE$_1$ since the free duration ({20, 10}, {10, 40}) are bigger than the demand of EV$_A$ {20, 10}.

To better understand the allocation process, Fig.4 presents the sequence diagram between a set of EVSEs and a set of EVs in a region assuming that all are in the range of each other using wireless communication e.g., WMNs. As can be seen, EV$_A$ sends an advertisement with a broadcast to all EVSEs in the range of communication {?} (we mean by ? that EV$_A$ asks its neighboring EVSEs about their corresponding values of x: duration and y: offset) to discover the charging occupation of the EVSEs. Then the EVSE$_{1\dots}$ EVSE$_n$ advertise their power consumption as {x: duration, y: offset}. For example EVSE$_1$ advertises ({10, 0}, {10, 30}), which means the slots {20, 10} and {10, 40} are available. Since the demand of EV$_A$ is equal to 20 and in this example we use the RAA algorithm, EV$_A$ sends an unicast request expressed as {20, 10} to EVSE$_1$ asking for 20 duration from offset 10. So, EVSE$_1$ responds by an “accept message” updates its power utilization by a broadcast message to all neighbors (EVs) in the range.

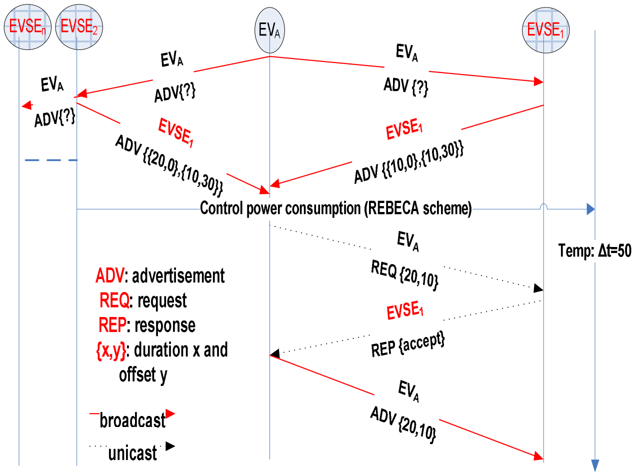

Fig.4. Sequence diagram of power discovery messages between EVs and EVSEs based on the example illustrated in Fig. 3.

C. *REBECA analysis*

Using arguments from queuing theory and statistical analysis [7], we seek to maximize power utilization, to balance power between EVSEs and to minimize latency time (D) of EVs. A simple queuing system M/M/1 is shown in REBECA scheme (see Fig. 1). EVs arrive randomly at an average rate of λ. Upon arrival, they are served without delay if there are available y offset and x duration {x,y} in selected EVSE. They are made to wait in the queue until it is their turn to be served. Once served, they are assumed to leave the system with average rate time μ. We will be interested in determining such quantities as the time service S of EV in the system, the time an EV spends in the system D, the time spent waiting in the queue w.

In the queuing system M/M/1, the number of arrivals EVs in interval time, for a Poisson distribution with rate λ and the time between successive arrivals, is exponentially distributed with μ and independents of the past.

Let a be the EV arrival time,

$$D=a+S+\begin{cases} W & \text{if waiting is recurred} \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

The total demand in EVSE at time t is expressed by the following equation:

$$\mathrm{EVSE} \geq \sum_{\mathrm{i}} \mathrm{EV_i} \tag{2}$$

Where

$$\mathrm{EV_i} = \{\mathrm{x_i}, \mathrm{y_i}\} \tag{3}$$

We express the time unit deployed in a time interval by:

$$\tau = \frac{e_0}{P_0} \tag{4}$$

D. *REBECA Scheduling Algorithms*

As described in section I, each EV selects an EVSE according to three algorithms RAA (see Algorithm I) or BAA (see Algorithm II) or PBAA (see Algorithm III). The two first algorithms are inspired from the literature [8] while the third algorithm is a new scheme used by REBECA.

The problem of placing demands of EVs within Δt interval time resembles that of memory or file system management [8], which is well known in operating systems literature. Nevertheless, the existing schemes such as FIFO, best fit, or worst fit, rely on the ability of reorganizing page allocation by moving memory chunks. We demonstrate in this paper (see simulation results section) that using algorithms based on FIFO or best fit is not enough to maximize the power utilization for all EVSEs while minimizing the latency time of EVs. So, we start by describing how we adapt these later two algorithms in our context before to display the PBAA algorithm which is more practicable and we compare it to existing approaches based respectively on random and best access.

In RAA, an EV simply selects the first EVSE that satisfies its demand by exchanging broadcast messages as shown in Fig.4, i.e., it chooses the location randomly among the set of feasible EVSEs expressed by:

$$\{x_{first}, y_{first}\} = random\{x_i, y_i\} \tag{5}$$

The intuition behind this process is that, by choosing locations randomly, we expect that at light and medium loads, the variance power between EVSEs will be reduced.

In the BAA algorithm, an EV selects the smallest free location $\{x_{best}, y_{best}\}$ which is able to contain a demand EV of x duration and y offset{x, y}, i.e.

$$\{x_{best}, y_{best}\} = \arg_{\{x_{best}, y_{best}\}} \min\{x_i - x\} \tag{6}$$

The rationale behind BAA algorithm is that having small gaps in the Δt may lead to power capacity wastage.

Next, we propose a new algorithm called PBAA to compare a set of eligible available power on EVSEs with RAA, BAA and PBAA, which selects the free location while keeping minimum variance between power EVSEs utilization.

Algorithm I. Random Access Allocation : RAA

```
Input: $P_0, e_0, P_{EV_i}, x_i, y_i, P_{EVSE}, a, \tau$;
Output: $P_{EVSE} - \sum_i P_{EV_i}$; $D$;
1 Initial power assignment ( $P_{EVSE_0}$ ); /* is randomly chosen */
2 ADV $EV_i$ {(),()…}; /* Advertisement to know available units */
3 ADV $EVSE$ {( $x$ , $y$ )…} /* Advertisement of available units in $EVSE$; where $x$ is the duration and $y$ is the offset*/
4 REQ $EV_i$ to $EVSE$ /* Request (Unicast) based on randomly selection of $EVSE$ */
5 RESP $EVSE$ to $EV_i$ /* Response (Unicast) */
6 $P_{EVSE} - \sum_i P_{EV_i}$; $D$; ;
  Go to steps 2 and 3; /* Update power charging status */
7 If waiting time is recurred
  then
      $\tau = e_0 / P_0$;
      $W = (y_{EV} - y_{EVES}) \times \tau$ ;
      $D = a + S + W$ ;
  Else $D = a + S$ ;
  Endif;
```

Algorithm II. Best Access Allocation: BAA

```
Input: $P_0, e_0, P_{EV_i}, x_i, y_i, P_{EVSE}, a, \tau, \varepsilon$ : small value
Output: $P_{EVSE} - \sum_i P_{EV_i}$; $D$;
1-3 same as RAA;
4   If $P_{EVSE} - \sum_i P_{EV_i} < \varepsilon$ then select $EVSE$;
5-7 same as RAA;
```

Algorithm III. Power Balancing Access Allocation: PBA

```
Input: $P_0, e_0, P_{EV_i}, x_i, y_i, P_{EVSE}, a, \tau$;
Output: $P_{EVSE} - \sum_i P_{EV_i}$; $D$;
1   Same to RAA;
2   Advertisement of $EV_{ik}$ {( $x_i, y_i$ ),()…}; /*Gather statistic information about a set k of vehicles $EV_i$ */
3   Set ={ $P_{EV_i}$ , $i = 1..\max(queue)$ };
4   Compute $Min(COV[P_{EVSE} - P_{EV_i}])$ ; then assign units of $EV_i$ to EVSE;
5-7 same as RAA;
```

IV. SIMULATION RESULTS

The evaluated topology is illustrated in Fig. 2 with parameters in Table II. Simulations results are produced using Matlab. Simulation results are averaged over enough runs to reach a confidence of 95%.

TABLE. II. SIMULATIONS PARAMETERS

τ	0.1
Number of EVs	100
Number of EVSEs	5
λ , μ	1
$D_{predefined}$	100 units

Fig.5 illustrates the latency time (D) of EVs using respectively RAA, BAA and PBAA algorithms with the same broadcast communication procedure while increasing the number of arrival EVs in the system. Our proposed PBAA algorithm reduces the latency time efficiently and it outperforms the existing approaches RAA and BAA by 16%, 13% resp.

We then distinguish between low, medium and high network load conditions (EV number).

In light load conditions (1-18EVs), corresponding to a low number of power requests, where the power on EVSEs is almost the same since the number of EVs is small, the three algorithms provide almost similar latency of EVs.

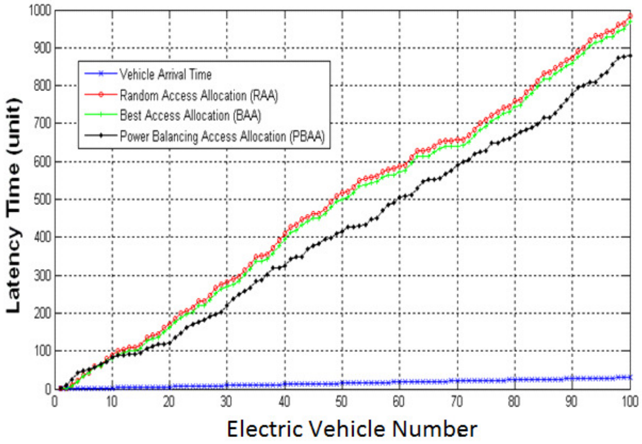

Fig.5.Latency time vs. network load

In medium load conditions (18EVs-40EVs), corresponding to a medium number of power requests, PBAA outperforms resp. RAA and BAA by 23% and 20%. However, in high load conditions (41EVs-100EVs), PBAA algorithm reduces the latency by 13% and 11% resp. We conclude that PBAA outperforms the other schemes in both medium and high load conditions but particularly for the medium load scenarios provide shorter latency times for EVs.

TABLE.III. QOS OF REQUIRED SERVICE WITH DIFFERENT SCHEMES

Satisfied EV ($D \le D_{predefined}$)	Low load (e.g., 10 EVs)	Medium load (e.g., 50 EVs)	High load (e.g., 90 EVs)
Number of unsatisfied EVs	3 (RAA) 2 (BAA) 1 (PBAA)	15 (RAA) 9 (BAA) 6 (PBAA)	27 (RAA) 20 (BAA) 13 (PBAA)
QoS	65% (RAA), 79% (BAA), 87% (PBAA)		

In the rest of the evaluations, we define quality of service (QoS) as the ratio of the numbers of vehicles that get serviced with a latency that does not exceed the predefined threshold, to the total number of vehicle to be serviced. Table. III shows that the proposed algorithm PBAA provides the higher QoS in terms of satisfied vehicles. With PBAA, we achieve 87% of satisfied vehicles with a latency time that is small comparatively to the predefined threshold while the other algorithms RAA and BAA provide resp. 65% and 79%. Therefore, PBAA outperforms RAA and BAA schemes by 25% and 9% resp.

These good results for PBAA are expected because; PBAA takes into account power balancing during the charging time slots assignment. Therefore, PBAA is able to avoid two cases: (1) statured EVSE and/or (2) forsaken EVSE. For the first case, such EVSE will be unable to answer and provide power to the requested EV at required time. Consequently, we conclude that the scheduling of charging time slots, as provided by our new Scheme REBECA using PBAA algorithm, is necessary to guarantee the QoS expected by the users (EVs) in terms of low service latency and reliable two-way communication.

Fig.6 shows that using PBAA algorithm the power utilization in EVSEs is well balanced in opposition to both schemes RAA and BAA. For example, for EVSE(2) and EVSE(3) the variance of power is equal to 0.3, 0.4, and 8.4 for PBAA, RAA and BAA resp. Therefore, PBAA outperforms RAA and BAA by 25% and 96% resp. and reduces efficiently the variance of power usage in different EVSEs in the system.

Moreover, we remark that using RAA and BAA algorithms, we can get very unbalanced energy usage on EVSEs. Especially, this happens with RAA scheme (e.g., power utilization of EVSE(2) and the rest of EVSEs (1,3,4,5)) as illustrated in Fig.6, which is not strange as how RAA algorithm process the charging time slots requests; it simply chooses the location randomly among the set of feasible EVSEs.

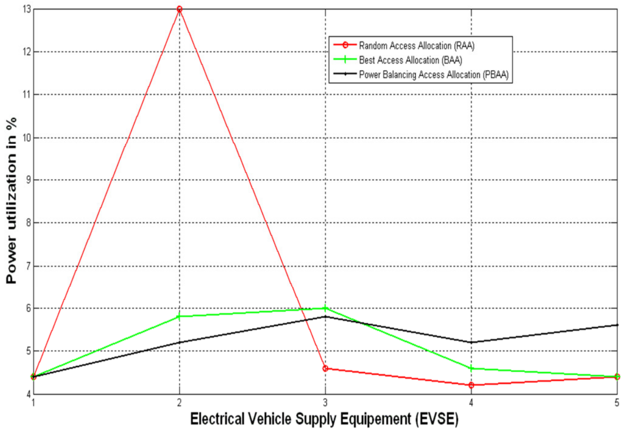

Fig.6. Power utilization in each EVSE

V. CONCLUSIONS AND FUTURE WORK

In this paper, we have presented the REBECA two-way communication protocol between EVs and EVSEs that allows a reliable reservation process of charging slots within EVSEs. REBECA was used with three reservation algorithms to determine how many EVs can be efficiently served by a number of EVSEs without increasing the probability of overload on EVSEs or latency time on EVs. Results show that the PBAA algorithm, used with REBECA, carefully dimensions demand for each EV, takes into account power balancing in EVSEs, and provides low service latency for EVs. Furthermore, we have shown that best access or power balancing algorithms are more adequate to reduce latency time than random access algorithms especially in the case of a medium and high number of vehicles that can potentially ask to be serviced.

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