Hierarchical Cloud Communication for Supply Management and Power Distribution via Wireless Mesh Network into the Smart Grid

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Abstract—**The increasing electricity demand and the additional renewable power resources have created a transition from centralized supply side management to decentralized supply and demand side management. Unfortunately, power availability is expected to be unbalanced from one area to another mainly during peak times. Actual smart grid capabilities cannot easily redistribute the power outside of a fixed area. On the one hand, cloud computing services provide a dynamic allocation of power. On the other hand, two-way communication technology is becoming an essential part of the smart grid landscape, tying between all components, from power generation, to energy transmission. In this paper, we introduce a new initiative to bring together the following two areas: two-way communication and hierarchical cloud concepts. The proposed supply management and power distribution system called *H2C-PDSM* guarantees a balanced power allocation process and reduces query latency time in the grid.**

Keywords: smart grid, Two-way communication, Cloud, management.

I. INTRODUCTION

Cloud computing is envisioned as the next generation computing paradigm which changes the way we think by decoupling components from location. Computer centers run distributed applications in an ubiquitous network access and location independent resource pooling. The cloud is much more than traditional server. It provides a shared pool of configurable computing resources that can be rapidly provisioned with minimum management effort. The cloud is composed of services accessed via the Internet. It enables hosting of pervasive applications from various users. The cloud providers own large data centers with massive computation and storage capacities. They sell these capacities on-demand to cloud users. Adding new cloud resources is usually available for end-users.

Smart Grids are large-scale electrical systems which use computers and other technology to gather information about suppliers and consumers to improve distribution of electricity. Load management is the process of balancing the supply of electricity on the network according to user demand. A fundamental challenge of the electricity infrastructure is how to be modernized to facilitate management of power demand. In fact, electric consumption increases widely according to the hour of day and the time of year mainly when peak of usage occurs. Further, electric vehicles and PHEVs (plug-in hybrid electric vehicle) add an overall load growth of energy consumption during hours of charging. Nevertheless, it is not easy to provide enough local hardware resources for important grid applications in one area. Particularly, this is expensive if the resources are from other areas. Smart Grid might adapt consumption of power to match power costs and system load. But, a reliable scheme which balances power allocation process is required to reduce cost communication and latency time to users.

Current computing infrastructure can address the resource allocation and power management challenges for smart grid. In fact, cloud concept offers flexible resources allocation and can, then, provides a scalable distribution of power with low administrative overhead. Clouds present also several benefits for the smart grid software such as the increasing grid access. Commercial cloud datacenters are built to support online access by millions of web users. Moreover, cloud data storage can scale to terabytes of data which means a flexible management of the smart grid load overtime. So, the cloud can maximize the efficiency of power distribution system.

The ***H2C-SMPD*** proposal that we describe in this paper certainly need a two-way communication infrastructure [1, 2]. Therefore, we believe that the deployment of Wireless Mesh Networks (WMNs) communication for our ***H2C-PMDS*** system enables reliable two-way communications between the connected clouds [3]. WMNs are suited to provide robust and self-healing communication between nodes and to manage more information with less cost. Further, basic user applications such as power querying and power allocation are enabled. By using over-the-air communication technologies such as WMN communication system, we ensure that user queries are routed inside the n-MiC (A Micro Cloud zone having n childs) one by the peer router in order to balance the load.

Throughout this paper, we detail a new demand management and supply distribution system for the electric grid. We outline three contributions for this proposal. Further, we might note that after a deep reading of the related literature, we believe that we are the first to present the following three contributions for smart grid research. (1) Our proposed system has a hierarchical cloud-based design where the hierarchical relation between the clouds guarantees the minimum geographic distance. A specific Minimum Spanning Tree (MSP) algorithm can be run to establish the system architecture (see section assumptions). (2) The proposed system called ***H2C-SMPD*** is able to balance power consumption with a minimum cost between the (n-1)-MiCs of the same n-MiC zone. (3) We attempt to enable fast power allocation process by reducing the transmission delay of an end user query. In order to achieve these three contributions, we suggest deploying WMN communication networks between the connected MiCs that form the global mesh MaC. A mesh router (peer router) is able to fulfill the requirements of a MiC engine such as routing requests.

This paper is organized as follows. Section II reviews and discusses related work. A description of the proposed system is shown in Section III. Analytical analyses are presented in section

IV to investigate the performance of the ***H2C-SMPD*** system. Section V evaluates the proposed algorithm via extensive experiments. Finally, Section VI concludes the paper.

II. RELATED WORK

In the context of smart grid innovation, it seems that we are the first to conduct research on geographic proximity, WMN, and cloud computing into smart grid.

Several works have highlighted the importance of two-way communication between EVs and the smart grid. One work has proposed to control EV charging start time when vehicles are already plugged-in [4]. Other researchers pointed-out to the fact that the increase in the numbers of EVs can be an opportunity to utilize their battery as a storage which can buffer time-variable renewable energy [5-6] or help in frequency regulation [7].

Several models have been developed to characterize and optimize the operation of the grid under [8-9] various conditions. The authors in [8] proposed a scheme called REBECA. The REBECA communication protocol allows a reliable reservation process once the choice of Electric Vehicle Supply Equipment has been determined. In [9], a novel multi-objective electrical vehicle (EV) Charging Slots Assignment (CSA) optimization model proposed to reserve charging time slots for vehicles. CSA model is able to balance energy usage between suppliers while maximizing the power utilization and minimizing the latency time of EVs. Both these contributions [8-9] are based on DSRC communication to provide short latency delay to electrical vehicles. However, in our study, we assume to serve two types of components Micro clouds and End users which have hierarchical connections between each other. Therefore, we believe that WMN is suitable to provide a reliable two-way communication where the hierarchical relation between the clouds guarantees the minimum geographic distance.

It worth to note that some recent research in literature [10,11] provide a smart grid testbed for demand focused energy management in end user environments. These contributions consider the typical smart grid scenario where several smart meters connected to a gateway constitute a Home Area Network (HAN), and multiple gateways connected to a Data Aggregate Unit (DAU) create a Neighborhood Area Network (NAN).

In such architecture, the gateway is responsible for transmitting the meter data periodically collected within its HAN to the DAU via vacant channels (i.e., TV White Space channels), once declared available by the geolocated database.

The TV White Space spectrum has been recently recognized by the research community as the ideal candidate to accommodate the rapidly increasing demand for wireless broadband communications in Smart Grid Networks (SGNs) via Cognitive Radio (CR) paradigm [12-13].

However, experimental studies have shown that the number of vacant channels is significantly limited in urban areas [12]. In addition, since so far there are no regulatory requirements for the coexistence among NANs operating in TV White Space spectrum, such a performance degradation can be severe.

Differently from these contributions detailed above, we develop a system that addresses the problem of load balancing in the power grid. To this to be possible, we assume a hierarchical cloud system for supply management and energy distribution into smart grid where geographic proximity between the Micro clouds is guarantees using WMN tree two-way communication.

III. H2C-SMPD SYSTEM OVERVIEW

A. Cloud-based hierarchy

We propose a novel hierarchical cloud communication system for power distribution and supply management into smart grid, named H2C-PDSM. Our system is able to route user requests as well as allocate power resources. The hierarchical clouds, called Micro Clouds (MiCs) are organized into neighbour trees and have hierarchical connections between each other. Two types of components are involved in this hierarchical structure: (a) the MiC and (b) the End User (EU). The MaC levels are called Micro Clouds (MiGs) (see Fig.1). The Macro Cloud ended with the End Users. The EUs are located behind their nearest MiCs. Each MiC provides an authoritative zone where all his connected users EUs are managed. An EU sends queries to his local MiC which forwards them, in case of lack of power, to the rest of 1-MiCs of the same 2-MiC zone.

- **Micro Cloud:** We define a Micro Cloud (MiC) as a power authoritative zone. It contains electricity generators such as wind farms or solar panels. An administration engine is responsible for the management of electricity generation, supply and demand inside the MiC. Communication with a parent MiC or a child MiC is also ensured. The level of the MiC indicates his authoritative zone. The MiC has a label identification. 1-MiC indicates a local MiC where a set of users are subscribed. Only 1-MiC zones enable user management as well as power management. The rest of the MiCs is able to route the user queries.

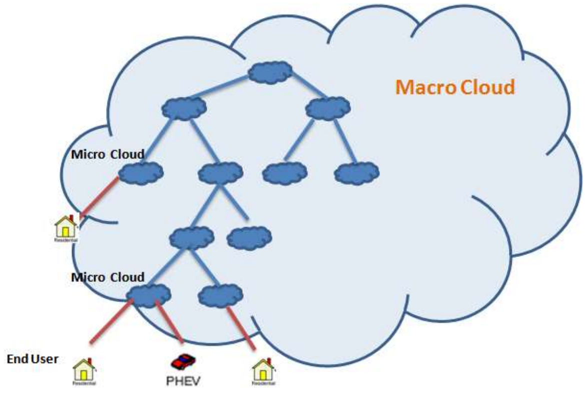


Fig.1. The hierarchical MaC system

- **Macro Cloud:** We denote the Macro Cloud (MaC) as the set of all the connected MiCs of our H2C-SMPD system. A MaC has then a tree architecture. Two-way communications inside the MaC are presented (This will be described in detail in next section). The MaC guarantees geographic proximity between all the MiCs (see the assumption section). Fast power response and real-time electricity allocation is then ensured.
- **End User:** Each power user subscribed into his nearest MiC. It has a two-way communication system with his local MiC authority.

B. Power query and power allocation

We define a power query as the process by which a power request is routed into the macro cloud and given access to electricity resources. When an EU wants to get an electricity amount L, it generates a key using his hashing function h_u. The generated key identifies the request. A packet has the following information: a key, the amount L among other elements. The packet is routed throughout the cloud hierarchy until reaching an available power resource.

When an End User EU_x wants to get electricity, it sends a query power to his local MiC. The local MiC receives the query identified by the specific generated key. Two scenarios are possible. (a) If the local MiC has enough electricity resources it will provide the user EU_x by the needed power. (b) However, in peak hours or when there is a lack of local electricity the administrative authority of the 1-MiC communicates with his 2-MiC zone by forwarding the query packet to his parent MiC.

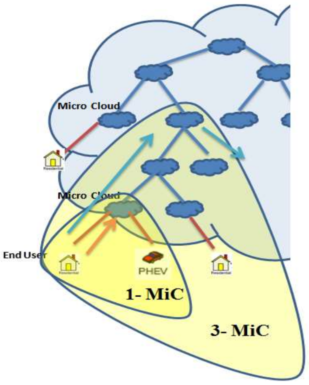


Fig.2. Queries inside 1-MiC and 3-MiC

C. *Inter/Intra-MiC Communication:*

In this work, we opt to implement WMN communication technology between the Micro-Clouds (MiCs), providing dynamic high-bandwidth networks and enabling reliability and redundancy as shown in Fig.3.

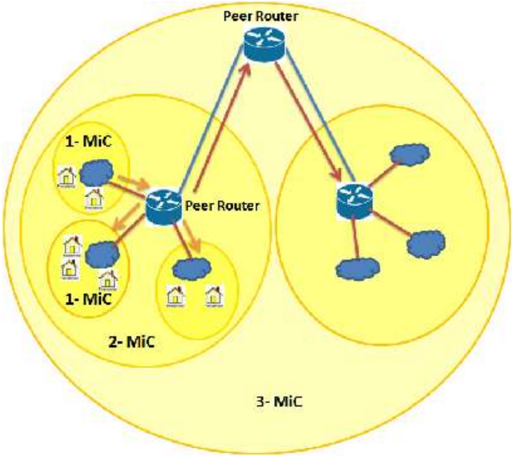


Fig.3. H2C-PDSM using WMN technology to route users query

Our motivation behind this choice is supported by the fact that the grid components communicate via a tree and we need to establish communication between parents and childs in this tree to balance the power consumption. This fact maps perfectly with WMN technology where routers route the users requests between them to form a backbone to deliver the message between users or in most cases to the gateway. In our case, we communicate different MiCs to reach the Macro cloud. Each n-MiC zone has a Peer Router which has the functionalities of a mesh router by routing the user queries. However, there are no need to establish Peer Routers in the lowest level of the tree (1-MiC zones) where End Users are directly linked to their local 1-MiC and their requests can be only forwarded to the parent MiC. Peer Routers are, then, established in the other levels of the tree to form the backbone. The routing process of the Peer Router in our H2C-PMDS system is different to a mesh router in the known WMN communication system. The main difference is that the peer router sends the requests inside the same zone, only in some cases a request can be sent to the parent, while a mesh router forwards requests to any available destination.

D. *Assumptions:*

Throughout this paper, we assume the following assumptions:

(1) A MiC zone is defined according to the following conditions:

(i) A power supply S_i is the amount of power in the zone generators. S_i might be in the range $[S_{min} \dots S_{max}]$.

(ii) The demand d_i is the predicted demand of power. d_i depends on the number of users in this zone.

(iii) The consumption rate $C_i = \frac{d_i}{s_i}$. The consumption is in the range $]0 \dots 1]$.

(2) The tree structure of our H2C-PMDS system is established by running a specific Cloud Spanning Tree (CST).

The CST algorithm defines a tree of MiCs where the distance $T_i = d_{(Peer,MiC_i)}$ between the peer router and his child MiC is minimum as possible (see Fig.4), for example $\mathrm{d}(\mathrm{M}_1, \mathrm{M}_2) > \mathrm{d}(\mathrm{M}_1, \mathrm{Router}) + \mathrm{d}(\mathrm{Router}, \mathrm{M}_2)$.

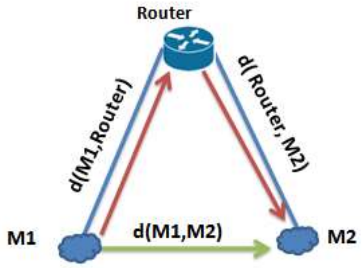


Fig.4. **H2C-PDSM** distances using a specific CST algorithm

(3) The load balancing process works level by level. It starts from the lowest level, 2-MiC zones. A peer router does not allocate power from his proper supply to his child MiCs.

(4) The MiCs are always running.

VI n-MiC LOAD BALANCING

In our study, the Micro Clouds are distributed geographically in wide area. Our aim is the discovery of an available power resources that provide the optimum physical distance as well as the minimum cost for all power allocation queries. We suppose that a n-MiC zone is unbalanced. The peer router of this zone manages k local MiCs (see Fig.2). The distance between a MiC i and the peer router R is noted T_i where $i \in \{1 \dots k\}$. We define the rate of consumption for each MiC i as follows:

$$C_i = \frac{d_i}{s_i} \mid i \in \{1 \dots k\} \tag{1}$$

The demand is represented by d_i. The available amount of power resource inside the local MiC i is represented by s_i. The process of balancing load aims to distribute the power consumption on all the MiCs of the same n-MiC zone. The load distribution process consists of three phases:

(1) information collection,
(2) decision making,
(3) power allocation.

During the collection phase, the peer router R gathers the information of load imbalance. The elected MiC has the maximum overload. The decision making phase focuses on calculating an optimal distribution schema (see the balancing algorithm); while the power allocation phase transfers the query from overloaded MiC to another one which guarantees more benefits.

A. Power distribution based on the Consumption C_i

Balancing a *n-MiC* zone means that the difference of the consumption C_i between the elected *(n-1)-MiC* and the other *(n-1)-MiCs* might be usually less than a determined parameter ε.

$$C_{max} - C_j \le \varepsilon \quad \mid \ \mathrm{j} \in \{1 \dots k\} \tag{2}$$

In this paper, we use a simple consumption-based load balancing algorithm that elects the overloaded MiC and selects the destination MiC that enables the highest allocated amount of power. Another algorithm (Alg.II) can be used by changing the destination MiC with the nearest available MiC. The details of the distributed balancing algorithm based on the consumption are illustrated as follows in Alg.I.

Alg.I : Consumption-based Load balancing algorithm

```
Input:   An unbalanced n-MiC zone;
         The number of (n-1)-MiC zones is k;
         The (n-1)-MiC zones are $M_1, M_2, \dots M_k$;
Output: A balanced n-MiC zone.

Variables:   $M_{elu}$; /*The elected MiC/Overloaded.*/
             $M_{RDV}$; /*The (n-1)-MiC where the power allocation occurs.*/
             Diff ;
             Ex; /*The allocated amount of power.*/
Constants:   $\varepsilon$
Begin
    $M_{elu}$= maximum($M_1, \dots, M_k$) ;
    $M_{min} = $ minimum($M_1, \dots, M_k$) ;
    Diff = $M_{elu}$- $M_{RDV}$;
  While (Diff> $\varepsilon$) do
    {  Ex=0;
       For each $M_i$ , $M_i \ne M_{elu}$ do
       {
           Val=$M_{min}.S * \left(\frac{M_{min}.C+M_{elu}.C}{2}\right) - M_{min}.d$
           if (Val>Ex)   then
               {
                   Ex=Val ;
                   $M_{RDV}$=$M_i$;
               }
           $d_{elu}$=$d_{elu} - Ex$;
           $d_{RDV}$=$d_{RDV} + Ex$;
           $M_{elu}$= maximum ($M_1, \dots, M_k$) ;
           $M_{min}$ = minimum($M_1, \dots, M_k$);
           Allocate (Ex, $M_{elu}$, $M_{min}$);
           Diff = $M_{elu}$- $M_{RDV}$;
       }
    }
End
```

The cost of the power distribution algorithm depends on both the rang of the crossed distance and the allocated amount of power Ex_{max}, where Ex_{max} is always the maximum possible amount of power to be allocated and $rang(T_i)$ is the order of the distance T_i of the destination MiC_i (see examples of Table.I)

$$cost_C = \sum_{iterations\ i} Ex_{max} * rang(T_i) \tag{3}$$

Table. I. Distance Classification

	MiC_1	MiC_2	MiC_3	MiC_4	MiC_5
T_i	30	10	5	13	47
$rang(T_i)$	4	2	1	3	5

B. *Power distribution basing on rang (T_i)*

The balancing schema based on minimizing the distance is defined as follows:

$$T_{elu} + T_{rdv} = Min_{i \in [1 \dots k]}(T_{elu} + T_i) \tag{4}$$

Where T_{elu} is the distance between the peer router and the overloaded MiC. T_{rdv} is the distance between peer router and the RDV MiC. The decision phase of the distributed balancing algorithm, basing on minimizing the distance T_i elects the overloaded MiC and the destination MiC that is the nearest available one. The details of this algorithm are illustrated in Alg.II.

Alg.II : Distance- based Load balancing algorithm

```
Begin
    While (Diff> $\varepsilon$) do
    {
        Ex=0;
        $M_{RDV}$ = Extraire_minimum_T ($M_1, M_2, \dots, M_k$) ;
        Ex=$M_{RDV}.S * \left(\frac{M_{RDV}.C+M_{elu}.C}{2}\right) - d_{RDV}$;
        $d_{elu}$=$d_{elu} - Ex$ ;
        $d_{RDV}$=$d_{RDV} + Ex$;
        $M_{elu}$= maximum ($M_1, \dots, M_k$) ;
        $M_{min}$ = minimum($M_1, \dots, M_k$);
        Allocate(Ex, $M_{elu}$, $M_{RDV}$);
        Diff = $M_{elu}$- $M_{min}$;
    }
End
```

The cost of the power distribution algorithm based on minimizing the crossed distance is:

$$cost_T = \sum_{iterations\ i} Ex_i * rang_{min}(T_i) \qquad (5)$$

Where Ex_i is the exchanged amount of power and $rang_{min}(T_i)$ is the order of destination MiC which is always the minimum available one.

V. SIMULATIONS RESULTS

In this section, we conduct an analytic study using Matlab to evaluate the performance of our proposed scheme, i.e., ***H2C-SMPD***.

A. Case Study:

The experimental system is configured with 5 MiCs belonging to the same 2-MiC zone. These MiCs are named $M_{1,}, M_2\,, M_3\,, M_4, M_5$. The case study inputs are supposed to be the worst case for Alg.I and the best case for Alg.II.

(1) We aim to compare between an arbitrary balanced consumption algorithm Alg.0, called AA and our proposed distribution algorithm Alg.I.

(2) We aim to compare between our proposed algorithm Alg.I and the distance-based algorithm Alg.II. The architecture design is shown in Fig.5. Our experiments measure the following parameters:

a) The balance between the MiCs;
b) The latency time of both algorithms Alg.I and Alg.II;
c) The cost of both algorithms Alg.I and Alg.II.

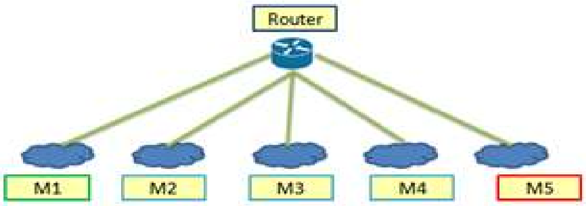
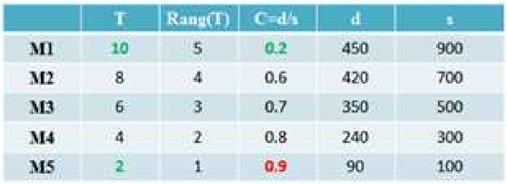


Fig.5. Case Study: 2-MiC zone design

Table.2. Case Study: Inputs and parameters



	T	Rang(T)	C=d/s	d	s
M1	10	5	0.2	450	900
M2	8	4	0.6	420	700
M3	6	3	0.7	350	500
M4	4	2	0.8	240	300
M5	2	1	0.9	90	100

As shown in Table.2, the proposed scenario has a significant relation between the load C_i and the distance T_i will be studied. The farthest MiC is the least loaded while the nearest MiC is the most loaded. In addition, the under loaded MiCs have higher supply amounts d_i than the overloaded ones. This is why it is supposed to be the worst for Alg.I and the best for Alg.II. During each experiment, the power distribution algorithms Alg.0, Alg.I, and Alg.II are run over the 2-MiC zone to balance the consumption.

B. Experiment number 1: *Alg.I vs Alg.0 (AA)*

Initially, we arbitrary distribute the power between MICs. The results of the arbitrary balanced consumption algorithm Alg.0 are shown in Fig.6.

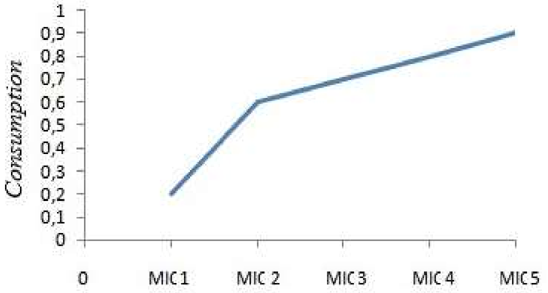


Fig.6. Consumption when using the AA scheme (Alg.0)

In the first experiment, we aim to balance the 2-MiC zone using the algorithm Alg.I. We suppose that initially Alg.0 has been run on top of the architecture to arbitrary distribute the power.

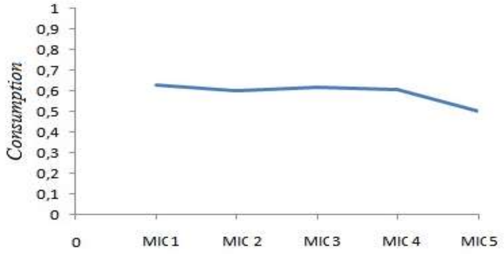


Fig.7. Consumption when using the distributed balancing algorithm Alg.I

Arbitrary distribution results of Alg.0 outline an unbalanced 2-MiC zone (i.e $C_5 - C_1 > \varepsilon$); $\varepsilon = 0.1$. We see a wide difference in the consumption rate C_i between all the MiCs $\{M_{1,}, M_2\,, M_3\,, M_4, M_5\}$. However, our distributed balancing algorithm Alg.I has a central role in balancing the MiCs (see Fig.7). The output of Alg.I is a balanced 2-MiC zone where the difference between each two consumption rates is less than ε; $C_{max} - C_{min} < \varepsilon$. The calculated cost of balancing the 2-MiC zone $Cost_c$ which is *998,5 watt/km.*

C. Experiment number 2: *Alg.II Vs Alg.I*

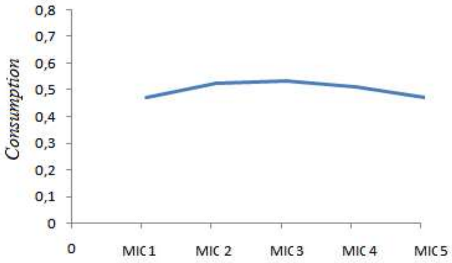


Fig.8. Consumption when using the distributed balancing algorithm Alg.II

In Experiment 2, the Alg.II algorithm is used instead of the algorithm Alg.I. The algorithm aims to redistribute the power according to the minimum crossed distance. Compared to results of Experiment 1, the balance between each two MiCs is also less than 0.1; pour $j \neq i$, $C_i - C_j < 0.05$ as shown in Fig.8

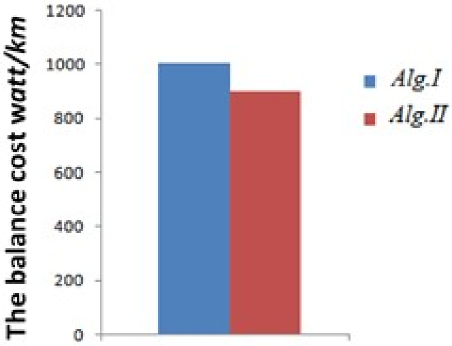


Fig.9. The balance cost of Alg.I and Alg.II

The balance cost respectively C_T of Alg.II and C_c of Alg.I is roughly *850 watt/km* and *950 watt/km* (see Fig.9). The balancing cost is, then, slightly improved, $C_T - C_c \approx 100$ *watt/Km,* which is expected because the algorithm Alg.II fits well with the chosen worst case scenario (the overloaded MiCs are the nearest that the under loaded ones) and this is not an important difference.

However, the latency time performance as shown in Fig.10 increased. So, Alg.II takes much more time to balance the Mics than Alg.I. By this result, the balancing algorithm Alg.I reduces queries latency time in the grid.

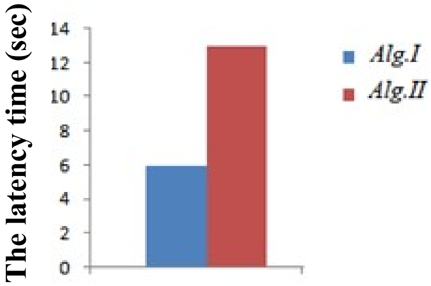


Fig.10 Latency time of Alg.I and Alg.II

VI. Conclusion

This work addresses the problem of load balancing in the power grid. A hierarchical cloud system for supply management and power distribution into smart grid called **H2C-PDSM** is proposed where geographic proximity between the MiCs is guarantees. A distributed balancing algorithm based on maximizing the allocated amount of power Alg.I is evaluated. Two experiments are carried out with defined metrics. The studied scenario is supposed to be the worst case for Alg.II and the best case for Alg.I where overloaded MiCs are near to the peer router that the under loaded MiCs. Further, the under loaded MiCs have high supply amounts than the overloaded ones. The experimental results demonstrate that Alg.I coupled with CST algorithm is suitable for H2C-PDSM load balancing. In the worst case for Alg.II, the latency time is improved and the balance cost is not high in relation with the cost of the distance based algorithm Alg.II. That is, Alg.I coupled with the CST algorithm is effective in terms of load balancing on the H2C-PDSM architecture compared to the distance based algorithm Alg.II.

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