Peer-reviewed version available at *Sensors* **2018**, *18*, 2724; doi:10.3390/s18082724

Article

Optimal Deployment of FiWi Networks using Heuristic Method for Integration Microgrids with Smart Metering

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Abstract: The unpredictable increase in electrical demand affects the quality of the energy throughout the network. A solution to the problem is the increase of distributed generation units which burn fossil fuels. While this is an immediate solution to the problem the ecosystem gets affected by the emission of CO2. A promising solution is the integration of Distributed Renewable Energy Sources (DRES) to the conventional electrical system, thus, introducing the concept of smart microgrids (SMG) that require a safe, reliable and technically planned two-way communication system. This document presents a heuristic based on planning capable of providing a bidirectional communication near optimal route map, following the structure of an hybrid Fiber-Wireless (FiWi) with the purpose of obtaining information of electrical parameters that help us to manage the use of energy by integrating conventional electrical system to SMG. A FiWi network is based on the integration of wireless access and optical networks. This integration increases the coverage and reliability at a lower cost. The optimization model is based on clustering techniques, through the construction of balanced conglomerates. The method is used for the development of the clusters along with the Nearest-Neighbor Spanning Tree Algorithm (N-NST). Additionally, Optimal Delay Balancing (ODB) model will be used to minimize the end to end delay of each grouping. In addition, the heuristic observes real design parameters such as: capacity and coverage. Using the Dijkstra algorithm, the routes are built following the minimum shorter path. Therefore, this paper presents a heuristic able to plan the deployment of smart meters (SMs) through a tree-like hierarchical topology for the integration of SMG at the lowest cost.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 4 July 2018 doi:10.20944/preprints201807.0078.v1

Peer-reviewed version available at *Sensors* **2018**, *18*, 2724; doi:10.3390/s18082724

Keywords: Optimization; Smart Metering; IoT; Microgrid; Heuristic; Sensor Networks

1. Introduction

Nowadays, the need to integrate modern technologies, in conventional electrical distribution systems, is of crucial importance in terms of optimization, security, confidence, reliability and energy efficiency [1]. One of the critical issues in power distribution systems, is the uncontrollable increase in demand. This is mainly due to the increase in consumers and the increasingly high dependence on electricity as a source of heat and ventilation. Therefore, these factors are enablers to significant fluctuations in the rate of consumption of electrical energy. With the increase in demand, at peak hours, there is a need for more generation plants to avoid voltage drops and the decrease in the quality of the electrical energy. As a result, institutions should encourage the Demand Side Management (DSM), which becomes viable, implementing robust bi-directional communication systems [2]. These systems need appropriate hybrid topologies to allow the communication network to provide the user with reliability and safety on the use of information [3], This approach opens a path to the existence of an intelligent electric network (IEN). An IEN is possible thanks to the use of communication to obtain data on the intrinsic components of a network (data obtained from producers to consumers). This contributes to our economic and environmental health [4]. The information obtained from the network will be collected by Smart Meters (SMs) [5] spread over the area of interest and its locations will be fixed [6]. The conventional electricity meters must necessarily be replaced by SMs, since they will be able to communicate with diverse types of electronic devices [7] distributed in the conventional network. Each SM will not only be able to receive and transmit information of electrical parameters as active and reactive power, but will also have the ability to run events, such as, reconnection, disconnection and sensing the theft of electricity supply, integration of Distributed Renewable Energy Sources (DRES) and the proper management of energetic use in each individual household. The measurements can be collected without the need to visit the facilities of the customer. This may be carried out in intervals of time of 15, 30 or 60 minutes. These measurements are the source of considerable amounts of data of energy consumption of industrial, residential and commercial customers. The analysis of these data supports analysts to improve the operation, planning, control and supervision of the conventional electric network [8,9].

1.1. Importance of the two-way communication system in smart grids It is believed that DRES play a significant role in the reduction of greenhouse gases emissions [10]. This improves the availability of the energy resource, increasing the efficiency and the quality of the supplied energy [11]. DRES is essential for the sustainability of the conventional electrical system and are part of the solution to the uncertainty of the demand load. DRES are not easy to use, as they increase the complexity of the system [12]. This document presents different methods of data collection to better understand the behavior of the electricity grid through a near optimal deployment of SMs supported with computational tools. The SMs are being implemented in the world at an increasingly rapid pace and, consequently, the analysis

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of the energy demand in individual households are receiving greater attention. This analysis gives us sufficient data to contribute in forecasting home loads and the grouping of each load profile [13].

The predicted decrease in the availability of fuels fossils, mainly due to the following reasons: a lower forming rate compared to the rate of consumption, the increase in the cost of fuel, the environmental issues related to global warming by emissions of greenhouse gases and the increase in energy demand, makes the conventional electric network topic very important for research [14–16].

The implementation of bi-directional communication technologies, low-cost and consumption leads us to integrate the concept of Smart Grid (SG) described in [17–19]. The fundamental requirements of a SG, are home automation, smart metering, automating the distribution of electrical power, controlling and enforcement of the selected standards. In an electrical network, a SG is conceived as a network that can deliver electricity in a controlled manner, from the points of generation to the active consumers [20]. In addition, SG will adjust the amount of energy generated according to the real-time demand of consumers, thus, avoiding the excess of generation and covering most of the required demand [21]. Therefore, changes in supply and demand require a more intelligent system that can handle the increasingly complex electrical network [11].

As a result, an efficient design of SGs tackles three elements: communication, control and optimization [12,18,22,23]. In this document we will put special attention to smart metering of electrical energy with the purpose of obtaining accurate information from electricity consumption and in this way run energy management processes at the lowest cost, enabling us to not only, automate the distribution in-energy, but in addition, allow us to introduce the use of DRES to SG granting enforcement and control of the system. The observance of the electrical system will allow us to know the instantaneous supply and demand with the aim of predicting energy consumption [22].

1.2. Smart Metering in Smart Cities

Smart cities are defined as urban areas which include mechanisms to monitor, understand, analyze and plan to improve the efficiency, equity, and quality of life of its citizens in real time. Therefore, motivated by the growing interest in smart cities this article reviews recent approaches and techniques needed to secure data aggregation, obtained by SMs. By introducing these new concepts there is a great potential of IEN, where households can be prosumers, that is to say, not only consumers, but also electric energy generators. Consequently, in [24]] is described the growing need for further research in the analysis of the models based on smart metering to improve the management of the energy resources in individual households, allowing the integration of SMG.

Advanced Metering Infrastructure (AMI) allows a two-way communication in which SMs must be able to send the information collected in the analysis tools and receive operating commands from the central office [25,26]. In order to avoid communication conflicts is very important to establish communication standards that allows interoperability between different electronic equipment as suggested in [12,14].

This paper proposes the implementation of a heuristic that provides a near optimal route map of SMs in a georeferenced area. The heuristic will be able to form clusters, optimize resources and draw a route map to actual parameters of capacity and coverage. This will reduce to the maximum the Free Space

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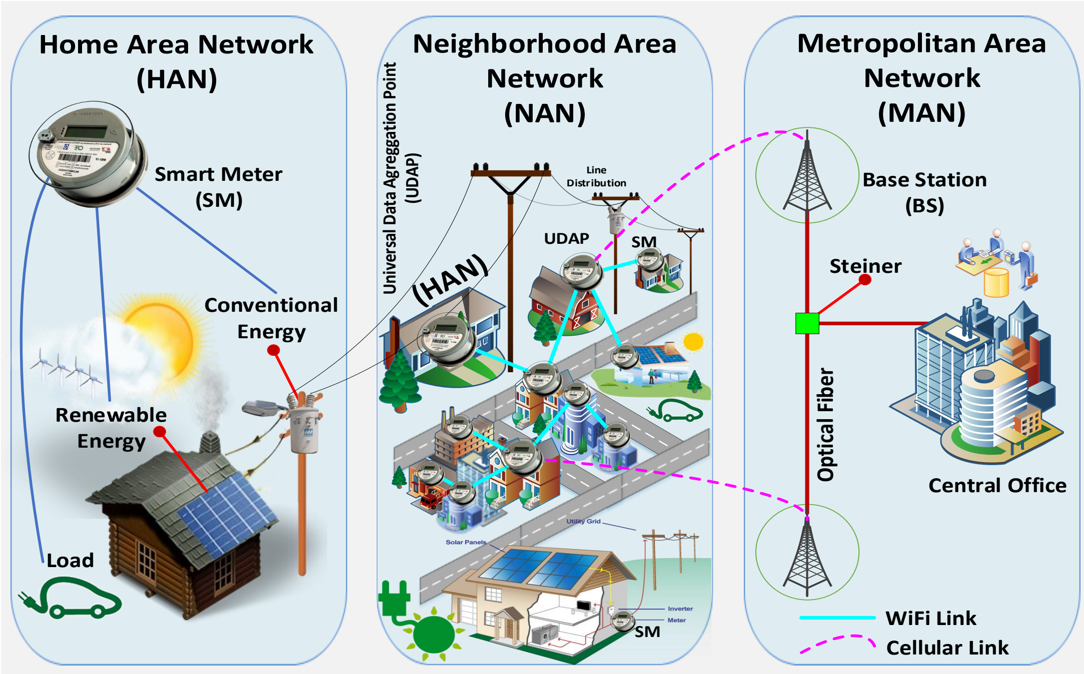
Figure 1. FiWi network architecture for the efficient integration of Smart Meters. Source: Author



Path Loss (FSPL) and decrease to the minimum the end to end delay, ensuring real-time communications for optimal operation of the FiWi network in smart cities. If there is availability of wireless technology, FSPL should be considered, in which there is a reduction in the strength of the signal by the widening of the wave front as it moves away from the transmitter, the power density decreases. Clustering is defined as the grouping of similar objects and is a key technique that is used to run the optimization processes [27–30], accepting all the options on the generation and storage of data [22]. In [28,31] there are presented examples on the advantages of the groupings: to optimize the use of bandwidth, to optimize the use of energy, to reduce overhead costs, to increase connectivity, to stabilize the network topology, to decrease delays and load balancing.

1.3. FiWi network architecture

A hierarchical clustering method using a topology type tree will be used in this work. This method is a fundamental operation in the deployment of SMs [32,33]. The paper from [34] stated that an optimal conformation of the clusters are determinants in order to minimize the end to end delays of each cluster. There are two types of hierarchical groupings: binder and divisive [35,36]. The binder method starts by placing each object in its respective cluster and then merging the groups in larger clusters, until all the objects are in a unique cluster or certain conditions are met. The divisive hierarchical grouping method is not limited to group into a balanced cluster or clusters of the same length as conventional methods of clustering do such as: k-means, k-medoids and, mean-shift [37].

K-means, k-medoids and mean-shift, are clustering algorithms that make a model for the deployment of a wireless communications network to be unpredictable. This is due to the fact that in each new iteration within the same scenario it provides diverse groups. These diverse groups need new analysis in

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each new iteration. In consequence, it affects in a negative way decision-making. Another disadvantage is that, none of them is concerned with the length of the cluster. That is, they build unbalanced clusters, which in a wireless network is unfavorable in terms of the design of the network and in terms of resource allocation in the physical and link layer. Moreover, another disadvantage of these methods is that they are not capable of group SMs through restrictions. That is to say, they are not capable of forming clusters using the binder method and only work using the divisive methods. The restrictions are necessary conditions that make the design conforms to the requirements of the network in the physical and link layers.

In the present work we will form clusters using the binder method. This is a method that allows us to balance the length of the clusters and minimize certain parameters of a communications network such as: end to end delay, FSP, and the ability to link. In the clustering techniques, the SMs are organized into groups. The regular SMs are called cluster members and a head is selected from the group tagged as Universal Data Aggregation Point (UDAP). There are three types of generated traffic: intra-cluster, inter-cluster and the existing traffic generated by base stations (BS) toward the central office [28,38–40]. These are illustrated in Figure 1 through the use of optical fiber. The members of a cluster cannot send data directly to the BSs, since, the UDAP receives data from the SMs members of the cluster, eliminates redundant data and merges the data with the objective of transmitting to their respective BSs [41].

In this section some properties of the cluster will be presented. These properties are defined by: number of clusters, size of clusters and communication inter-cluster and intra-cluster. The number of clusters to be used will depend on the capacity (size) of the gathered SMs. The communication intra-cluster involves the transmission of data from the member nodes of the cluster toward his head, known also as UDAP. It is important to mention that the communication can be either direct or through jumps and that will depend on the maximum coverage areas supported by each UDAP [42,43]. The communication inter-cluster takes place between the UDAPs and the BSs direct links or multisets depending on the area in which it is found. These can be: rural, urban or suburban. In this paper, a deployment of urban SMs is presented where it is assumed that there are not SMâĂŹs dispersion. The results show that it is not necessary the implementations of jumps between UDAPs to transmit the data to the BSs. The links intra-cluster are carried out by means of technology WIFI. The links inter-cluster are carried out by means of cellular technology, which provides large coverage areas, due to the inherent characteristics of a cellular network. That is why, it becomes unnecessary the multi jumps between UDAPs. Once data is merged in the BSs, by optical fiber, information is sent to the central office (see Figure 1), originating a FiWi network. FiWi has properties of profitability, robustness, flexibility, high capacity, reliability and is self-organized [44]. There are many challenges and open issues in the planning and functioning of the network as: the placement of UDAPs, routing, capacity, flow control, congestion, the programming and the assignation of bandwidth [45].

The properties of the UDAP allow to receive data from the SMs members of the conglomerate-Following that, merges the data and transmits the added information to the BSs. The selection of the UDAP, for each cluster uses an intelligent method based on the ODB algorithm which consists in the following steps: once the cluster is fixed using the binder method, discussed in the previous paragraphs, the algorithm searches which is the SMs that is equidistant to each of its members and at the same time

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minimizes the end to end delay of the cluster, once the SMs is identified is added as the head of the group (UDAP). An UDAP, is a SM with double availability for cellular and Wi-Fi wireless access.

This paper considers a FiWi network [46] in two stages: The first stage describes a wireless hybrid network [47,48] that articulates cellular technology and Wi-Fi to transport the information from the SMs to the BSs passing by a node of transition UDAP capable of supporting both technologies. This will ensure efficient and effective two-way communications within standardized parameters for the communication [46,49–51]. In the second stage, data is merged in the BSs using optical fiber. Following that, a backhaul will be added to transmit the information to the central offices or information management centers. In this center actions to control and monitor the final consumers and the electrical network will be taken.

In summary, we make the following contributions: 1) the proposed heuristic focuses on minimizing the data aggregation cost using a hierarchical topology capable of reducing transmission delays, contributing directly to minimize link capacity [52]. This fallouts in significant cost reduction of implementations in the physical and in the link level; 2) The mathematical optimization model considers the deployment of the FiWi network under planning and scalability over time and space; 3) The model provides a near optimal route map with georeferenced coordinates, using the haversine equation for the calculation of distances. The model is able to provide accurate data about the topology of the network and the roadmap for the hybrid near optimal communication path for the deployment in AMI; 4) The heuristic provides answers to the challenges of UDAPs placement, identification of target groups, routing, capacity, coverage and reduction of the end to end delay. Hereinafter, the paper is structured as follows.

In section 2 we describe the need to update the concept of a âĂIJconventional electric networkâĂİ with the purpose of migrating to the concept of a smart grid. Section 3 discusses the importance of AMI for optimal deployment of Microgrids. Section 4 sets out the approach to the problem. In section 5 we present the results and simulations. And finally, in section 6 conclusions are presented.

2. Conventional network and the need of smart grid

Research in the modeling of residential demand typically is focused on the monthly or yearly data averages demand and little emphasis is put on energy consumptions in a home or appliance in particular [53]. Residential consumption represents an important share of the total electricity demand, due to the exponential growth experienced throughout the world. In this context, a prediction of the energy demand of the housing industry is important as suggested in [11,22]. Consequently, a new concept is introduced: “the demand of the firm”, which refers to the ability to precisely control the individual loads always, therefore, the demand of the firm refers to load management, which means, being able to have real time and smart control of the load. In the conventional electrical system there are two types of controls, which are: cost control and direct control [22]. Cost control seeks to change the form of the load curve [54] without considering that the consumption of energy increases. This mechanism entails increasing energy prices in peak periods and then apply new rates. The direct control refers to the classic methods of load control involving the increase in energy production when the demand increases [4].

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The electricity is generated and distributed on a hierarchical network that has three different subsystems: generation, transmission and distribution. The power plants generate electricity and through transformers at substations convert electricity into high tension for the transmission. In the distribution sub-stations this high voltage electricity becomes medium voltage and is transported through the distribution network to end users. Before entering into the end users infrastructure the medium voltage becomes low tension. This scheme was maintained by a little more than a century, however, each subsystem has evolved over time at a different pace. The aggregation of data of each of the subsystems of an electric network is crucial in SG for the control, protection, automatic functioning of interrelated components and the integration of DRES in IEN [55].]. DRES are capable of functioning independently or in conjunction with the main electrical network under the concept of microgrid [56,57].

The rapid advances in automation and control generate potential benefits, such as: reducing the consumption of resources, improvements in infrastructure capacity and the coordination of the demand peaks [8,58]. This is mainly due to the introduction of the Information Communication and Technology (ICTs) [59], which has allowed the transformation of the conventional electrical network into an electrical network that ensures the productive interaction among suppliers of power, consumers and other interested parties as suggested in [11,14,60–62], Therefore, the changes in different systems, such as: generation, transmission and distribution are inevitable [12].In this way, the new control schemes will be able to cope with many uncertainties in the implementation of new sources of energy. Hence, the challenges of the power industry includes, but is not limited to: integration of DRES, improvement of the power capacity provided, environmental concerns on the conventional generation methods, the privacy of the information, the security to tackle cybernetic and physical attacks, the power systems economy, maintenance and operational costs and renewals of the network [63].

A smart electrical network should be able to motivate consumers to participate actively in the operations of the network and as suggested in [22,46,64] must be able to withstand attacks to provide a higher quality of power. For the existence of EIN is necessary a large-scale implementation of sensors and measuring instruments which have to be able to communicate with each other in order to add data from the state of the network [65]. The services of data aggregation can be structured as a tree and their goal is to merge data from various sources [21,66]. Finally, the European CommissionâĂŹs defines a smart electrical network as: “A electrical network that can integrate efficiently the behavior and actions of all the users in a framework based on rules and priorities for achieving interoperability of devices in a system of smart electrical networks” [62].

3. AMI in Microgrids

At the global level researchers are investigating on how to improve the demand management due to the great uncertainty that exists in the incremental proportions, over time of the demanded energy pattern. A topic of interest is how to improve the energy management of demand and how to introduce DRES to the conventional electrical system minimizing the impact to the ecosystem with CO2 emissions [67,68]. Therefore, introducing into the electrical sector devices capable of processing information, access the internet, adjust the energy consumption based on cost or availability depending on the preferences of consumers. All of this is part of what is called the Internet of Things (IoT). The “things” in SG include sensors [3], smart devices and the SMs [1,24,67,69]. This devices need to be interconnected in a hierarchical network with adequate levels of quality and reliability. The introduction of SG contributes to provide digital intelligence to the power system network [55]. The benefits associated with these new concepts are: adequate management of the energy resources, reduction of the interruption rates, reduction of the pollution rates in the ecosystem, reduction in the number of interruptions due to problems in the quality of power and, lower costs of operations and maintenance [1]. Consequently, one of the main benefits of SG, is the intelligent and efficient design of hybrid communication networks which take into account the congestion of the network, real-time transmission as suggested in [46,70], and the concern‘s to reduce the emissions of greenhouse gases [68].

The fast growth of data requires researchers to pay attention on how to handle these data. Therefore three definitions have to be analyzed: volume, velocity and variety. Volume refers to the large amount of data to be processed, the speed refers to the latency of data transmission and the variety refers to the different types of data that must be processed [58]. The consumers of energy resources are equipped with SMs that collect the data at real time. AMI receives all data and sends it to Meter Data Management Systems (MDMS) that controls the storage, is in charge of the analysis of data, and provides the information in useful way [71,72], In addition, through the efficient management of wireless resources, is essential to increase the life of the network [73]. AMI is not a technology, but rather a configured infrastructure that integrates a series of technologies to achieve their goals. AMI includes SMs, communication networks, MDMS, the tools to integrate the collected data of software applications platforms and interfaces [12,74]. Among the communication technologies used in this paper for extracting and transporting the information are Wi-Fi, cellular and optical fiber.

Optical fiber has dominated by being able to maintain communications over long distances, such as the metropolitan networks (see Figure 1). Additionally, it provides increased bandwidth, low transmission losses and greater tolerance to other cable access technology interference [75]. One of the disadvantages is that it requires a huge cost for a deep penetration of fiber. Therefore, the wireless access networks are a promising technology, since they provide the flexibility of low cost, increases the coverage and robustness, and are easy to implement. A disadvantage is that its bandwidth capacity is limited severely [45]. Therefore, considering the advantages of each technology it was proposed to build a hybrid network technology that includes wireless technology and optical fiber.

As a result, by using a robust system of two-way communications, AMI can provide intelligence to the conventional electrical network. Additionally, AMI can satisfy the future demand growth and can help to achieve the following: integration of DRES, dynamic operation of the network and progress of the communication standards [2].

The integration of renewable energy resources with small sources of storage leads to the concept of microgrids [72,76]. The uncontrolled integration of microgrids affects the quality of the power, among which, the more important events are the holes of voltage induced by failure defects [77]. Therefore, with the insertion of DRES, the quality of tension cannot be guaranteed if there is not a communications system to provide timely information of the state of the conventional network. To ensure the quality of tension in the network, through the integration of microgrids, the tension levels of the conventional network and the DRES must be resynchronized [78]. This resynchronization can be done by obtaining real time information of the state of the network. Therefore, the key is the integration of an adequate

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communications infrastructure that allows the aggregation of data to AMI to monitor and control the conventional electrical network so that the levels of tension, when introducing microgrids, are always known to run adequate processes of quality energy management.

Table 1 presents the model and parameters of simulation to be used in this document.

Table 1. Simulation Model and Parameter

Item	Parameter	Value
Deployment	Node density	4734 nodes/km2
	Node placement	Georeferenced
	Num. nodes per cluster	m {8, 14, 20, 27, 32}
	Coverage WiFi	r_{ds} 60 meters
	Coverage Cellular	r_{db} 1000 meters
PHY	Standard	IEEE 802.11b
	Frecuency band	2.4 Ghz
	Transmission rates	{0.5, 1, 2, 5, 11} Mbps
MAC	Standard	IEEE 802.11b
		3G, 4G, 5G
	Operation mode	*Tree*
APP	App. data length	*L* 100 bytes/packet
	Packet rate	*Lambda* {0.001, 0.01, 0.1, 0.2, 0.5} packets/sec

4. Problem Formulation

There are *n* numbers of SMs *X* for electrical energy measurements distributed in a georeferenced area A, $A(n)$. With the algorithm 1 N-NST the clusters are formed and using the algorithm 2 Optimal Delay Balancing (ODB) the SM is selected which will be come head of the group (UDAP) *Z*. Each cluster has a capacity to group until m SMs. We assume that the maximum range of bidirectional transmission of intra-cluster data is r_{ds}, and the maximum range of bi-directional data transmission of inter-cluster data is r_{db}. It is to say that any intra-cluster and inter-cluster length whose haversine distance r_{ni} and r_{ns} is within r_{ds} and r_{db} respectively, can communicate between each other. The X and Z which do not reach the maximum haversine distance allowed in a single jump, will do it with multiple jumps until being able to transmit the respective data packages. The multiple breaks are restricted by w, which is the maximum number of jumps allowed. It is worth mentioning that a SM will not be able to transmit its data directly to the BSs, therefore, the use of a node of transition UDAP (head of each group) is of vital importance to comply with that function. Since UDAP has physically two slots to hold dual wireless and cellular cards. In such a way that is able to receive the information transmitted from the access single SMs to the Wi-Fi technology and merge the information for further retransmit these data to the nearest cellular access BSs. Therefore, the allowed breaks will be done only between intra-clusters SMs or between UDAPs. Mainly to transmit the data to the closest BSs to finally send, via optical fiber, to the central office where the information will be processed.

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Table 2. Variables Used

Nomenclature	Description
x_s, y_s	Coordinates longitude and latitude respectively
n	Number of Smart Meters
A	Georeferenced Area
Z	Universal Data Aggregation Point
X	Smart Meters
m	Capacity Restriction
s	Length Cluster
k	Number of Clusters
w	Maximum number of hops allowed
C_1, C_2, C_3	Unit costs, Cellular, WiFi and optical fiber
$C_{wf}, C_{cell}, C_{fop}$	Total costs, WiFi, cellular, and optical fiber
r_{ds}, r_{db}	WiFi and Cellular coverage restriction respectively
r_{ni}, r_{ns}	Haversine distance (m) of the intra and inter cluster
$dist$	Haversine distance matrix *n x n*
d_{fop}	Distance (m) Optical Fiber

Initially, all X are candidateâĂŹs Z with a cost C_1. Once identified the clusters and the transition nodes Z the links are created at a C_2 cost. Due to that, it eliminates the need for all X are Z. This happens because, cellular links are deleted at a cost C_1 and links WiFi are added at a cost C_2 ensuring the 100% observability to the SMs deployed. Subsequently, the UDAP merges the data and send it to the BSs. Once the data is merged in the BSs it will be transmitted through optical fiber to the central office with a cost C_3 (see Figure 1). The C_1, C_2 and C_3 variables are identified as unit costs for each type of technology: cellular, WiFi, and optical fiber respectively. In addition, it should be noted that, $C_3 >> C_1 >> C_2$. Table 2 presents a summary of the variables used in the model.

In the equations 1, 2 and 3 the total costs of each technology are expressed: WiFi, cellular and optical fiber

$$C_{wf} = C_2 * \sum_{j=1}^{k} (s_j - 1) \tag{1}$$

$$C_{cell} = C_1 * k \tag{2}$$

$$C_{fop} = C_3 * dfop \tag{3}$$

Where s_j represents the length of each cluster, k is the maximum number of clusters to be deployed in the network and $dfop$ is the required distance to be used of optical fiber in the FiWi network.

In this way, the optimization problem can be expressed as follows.

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$$min\ C_{wf} + C_{cell} + C_{fop} \tag{4}$$

Sujeto a:

$$C_i \in \Re^+, \forall\, i = 1, 2, 3. \tag{5}$$

$$\sum_{s,k\ \in\ n} (s-1) + k = n,\ \forall\ s, k \in n; \forall\ n \in A(n) \tag{6}$$

$$\sum_{SM \in A(n)} SM = Z_{i,j},\ \forall\ Z \in A(n) \tag{7}$$

$$\sum_{SM \in A(n)} SM = X_{i,j},\ \forall\ X \in A(n) \tag{8}$$

$$\sum_{s \in S} S \leq\ m,\ \forall\ S \in A(n); \forall\ m > 1 \tag{9}$$

$$X = \sum_{rni_{i,j} \in r_{ds}} rni \leq r_{ds},\ \forall\ X \in A(n) \tag{10}$$

$$Z = \sum_{rns_{i,j} \in r_{db}} rns \leq r_{db},\ \forall\ Z \in A(n) \tag{11}$$

$$d_{fop} \in \Re^+, \forall\ d_{fop} \neq 0. \tag{12}$$

The equation 4 corresponds to the objective function, which consists in minimizing the costs of implementation on a FiWi network. The equation 5 necessarily asserts that there are three types of costs. The equation 6 presents a restriction of verification. In which must be satisfied that the sum of WiFi links and the sum of cellular links does not exceed the total number of SMs deployed at A, this ensures that there are no loops within the wireless network.

Algorithm 1 Nearest-Neighbor Spanning Tree: Receive (n, m, r_{ds}, w, x_s, y_s)

$dist_{i,j} = haversine(x_s, y_s)$;
while $s \leq m$ && $h \leq w$ **do**
    $flag \leftarrow 1$;
    while $flag == 1$ **do**
        for $i \rightarrow 1 : n$ **do**
            for $j \rightarrow 1 : n$ **do**
                if $h \leq w$ && $r_{ni} \leq r_{ds}$ **then**
                    $dist_{i,j} \leftarrow inf$;
                    $group_{i,j} \leftarrow find(x_{s(i,j)}, y_{s(i,j)})$;
                    $s \leftarrow length(group)$;
    $flag \rightarrow 0$;
$Send - (group)$;

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The equations 7 and 8 enables that any SM belonging to A can be an UDAP. The restriction of capacity, of the equation 9, limits the number of intra-cluster SMs that will be able to bring together each cluster. In the equationâĂŹs 10 the maximum radio allowed is restricted to give way to the existence of an intra-cluster link. In the equation 11 the maximum radio allowed is restricted to give way to the existence of inter- clusters links. And finally, in the equation 12 is expressed that the necessarily optical fiber distance must exist, guaranteeing the connectivity between the BSs, toward the central office.

Algorithm 2 Optimal Delay Balancing: Receive (group, x_s, y_s)

$num \leftarrow length(group);$

for $i \rightarrow 1 : num$ **do**

  $x_{group} \leftarrow x_s(group);$

  $y_{group} \leftarrow y_s(group);$

  $coord_{center} \leftarrow find\ center\ dough\ (x_{group}, y_{group});$

  for $j \rightarrow 1 : length(x_{group})$ **do**

    $d(j,:) \leftarrow haversine[(x_{group}j, y_{group}j), coord_{center}];$

  $udap(i,:) \leftarrow find(d == min(d));$

$Send - (udap);$

Using algorithm 1 N-NST the groupings are built under the binder method considering the capacity and coverage constraints. With algorithm 2 ODB and Dijkstra the end to end intra-cluster delay is minimized. Selecting the suitable UDAP that ensures the minimum delay at the collection of the packages of each SMs. And finally, once identified the UDAPs the cellular links are enabled toward the nearest BSs. The BSs communicate using optical fiber toward the central office following the minimum route. And finally, with algorithm 3 a solution is given to the near optimal deployment of a FiWi network used for monitoring and control of IEN that allow us to integrate SMG to the conventional electrical system.

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Algorithm 3 Generate Topology: Receive (x_s, y_s, BS_x, BS_y, r_{db}, n)

$x \leftarrow [x_s BS_x]$;
$y \leftarrow [y_s BS_y]$;
$dist \leftarrow haversine(x, y)$;
$Algorithm$ 1;
return $\rightarrow$ *group*;
used $\leftarrow$ *length*$(group)$;
temp $\leftarrow$ *group*;
while *used* $\leq$ *n* **do**
    if *index* $\neq 1$ **then**
        índex$(temp) = 1$;
        used $= sum($*index*$)$;
    for *k* $=$ *length*$(temp)$ **do**
        for *j* $=$ *length*$(temp)$ **do**
            G(*tmp(k)*, *tmp(j)*) $= 1$;
            Dijkstra inside-cluster;
            return $\rightarrow$ *path*;
$Algorithm$ 2;
return $\rightarrow$ *udap*;
for *i* $=$ *length*$(udap)$ **do**
    G(*i*, *BS*) $= 1$;
    if $r_{ns} \geq r_{db}$ **then**
        G(*i*, *BS*) $= 0$;
link udap with to the nearest BS;

5. Results

The near optimal route map, on an advanced measurement infrastructure under the concept of FiWi network allows analysts to know the state of the conventional electrical network for the optimal integration of microgrids and is presented in Figure 2. The simulation parameters are detailed in the Table 1. By having a georeferenced route map we have all the information required to run the actual deployment, and more importantly, we can account for each of the resources required for planning, implementation, economic assessing and FiWi network operability. In Figure 2 is depicted the existence of multi jumps intra-cluster, for securing the 100% of coverage of each of the SMs in the interest area. It is very important to point out that each cluster of the present document is formed with a method that is different than the conventional clustering methods (k-means, k-medoid and mean shift). The method which was developed to achieve the goals of the research, proposes the application of the algorithm 1 N-NST. Since it is capable of forming balanced clusters, subject to restrictions, allowing us to build clusters of similar lengths, contributing in this way with reliable data on each cluster. With it, is possible to make a sound planning with their respective analysis, which are part of a wireless hierarchical network

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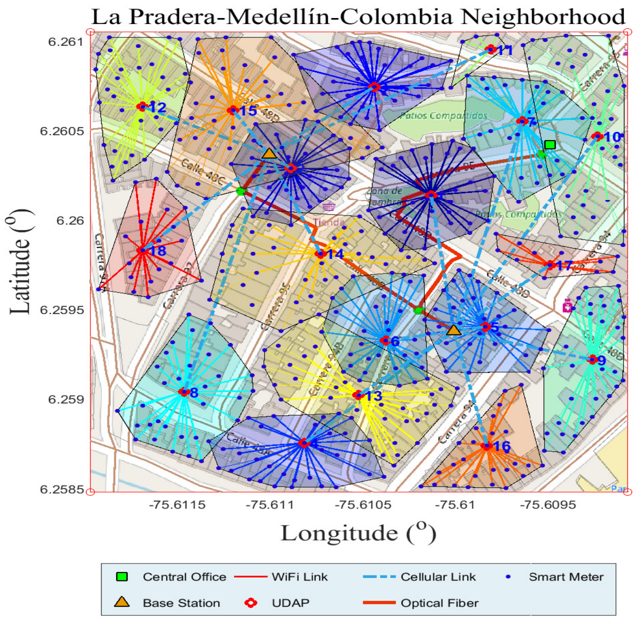
tree type. It is known that the above mentioned conventional algorithm use divisive methods to form clusters without observing the lengths of each one. Therefore, they are unpredictable and build not balanced conglomerates. In addition, they are not able to accept design parameters such as: capacity and coverage.

Figure 2. Near Optimal Deployment of SMs using FiWi network. Source: Author



In Figure 3 we can identify the near optimal route map accompanying their respective sparsity pattern matrix (spy) obtained from the binary array of dispersed adjacency of length *n x n*. Therefore, using these square matrices the binary relationships *1* and *0* are represented. Where *1* represents the existence of an edge and *0* the non-existence. For each node, which binds to an edge, is placed a *1* represented in blue in Figure 3 and in the remainder is placed a *0* represented in white color. Therefore, spy is a binary matrix that contains the information of the vertices and edges of the solution to the problem posed in this research. In this figure is proposed a scenario defined by a finite number of nodes, in which, two different criterion of selection of the UDAP is applied. The Figures 3.A and 3.B correspond to the first criteria of selection of the UDAP, that is, by the minimum distance from the closest BS to one of the SMs of the corresponding cluster. The SMs that meets this condition, will be selected as UDAP and the rest will be single access SMs to WiFi technology. The Figures 3.C and 3.D corresponds to the second criteria, which applies the ODB algorithm for the selection of the UDAP. The characteristics of the sparsity pattern matrix, in this research, are: square matrix, binary, symmetric and the inputs of the zero diagonal. If the diagonal is zero, it is because, there cannot be one edge of one vertex and toward the vertex *v*, since it will be the same vertex and is not possible to construct a graph *G(V,V)*. Therefore, a graph is defined as *G(V,A)*, where *V* is the vertex represented by SMs-UDAP and A are the edges represented by the WiFi-Cellular links that provide a link address, in such a way that a direct graph will be built. Therefore, the spy matrices in Figure 3, represent the connectivity array from a vertex *i* to a vertex *j* denoted as *Vij*. The number of nonzero elements of the spy arrays is 988 (see Figure 3) that

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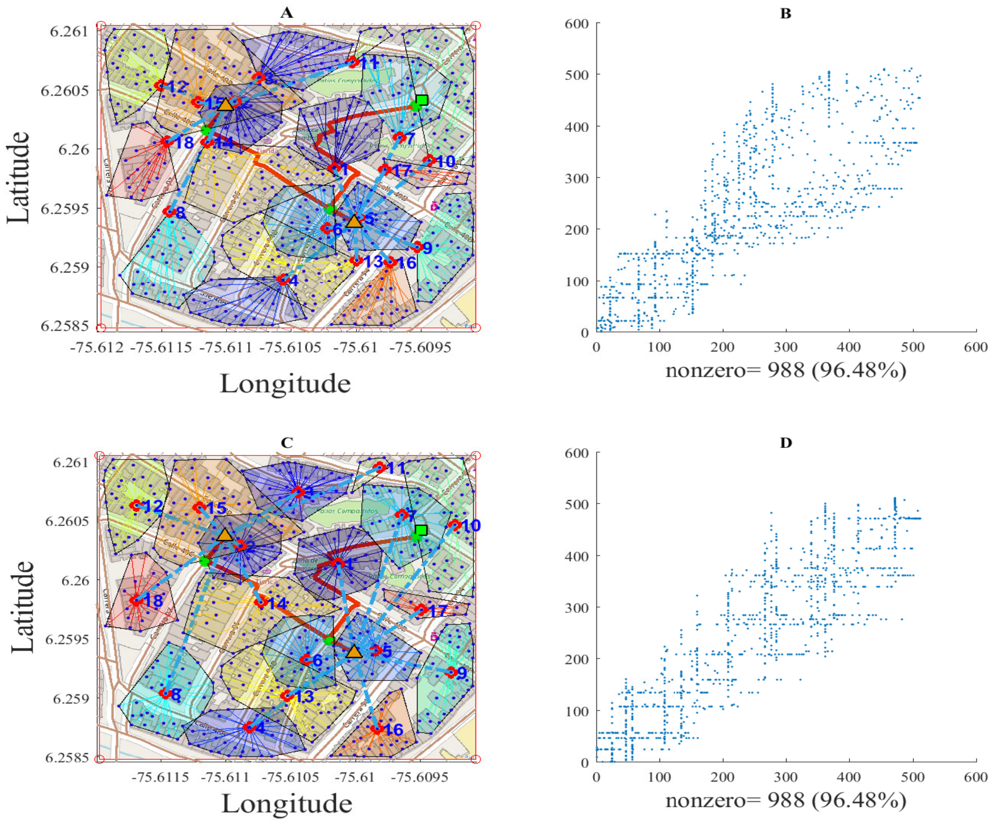
divided to 2, results in 494, which is the number of WiFi links required by the network, which represents 96.48% of use of technology with cost C_2 and 3.52% of cellular links at a cost C1 for hybrid wireless communication. If we checked in the scenario 1 on the Tables 3 and 4, we can identify that, we need 494 WiFi links and 18 UDAPs, giving as a result *n*=512, which is the number of SMs to deploy in *A(n)*. Accordingly, the number of nonzero elements of the spy arrays of Figure 3 corresponds to the set of vertices and edges V_{ij} and its respective image V_{ji} which added we have $V_{ij} + V_{ji}$, if $V_{ij} = V_{ji}$, as we refer to the same link, the resulting is $2V_{ij}$. Therefore, if we replace the required number of WiFi links from scenario 1, of the Table 3 on the previous expression, we are left with the number of nonzero elements $nonzeros = 2 * 494 = 988$, presented in Figure 3.

Figure 3. WiFi neighbor adjacency matrix *n*= 512. Source: Author



Considering the above statements, in the Figures 3.B and 3.D completely different arrays can be seen, with the same number of nonzero elements, which correspond to the binary matrices resulting from adjacency by applying different criteria for selection of the UDAP. In Figure 3.B it can be seen greater dispersion of the nonzero in the positionâĂŹs (400, 400). Comparing it with Figure 3.D, which occurs, for the existence of a greater number of jumps required to guarantee the coverage for each SMs available on the stage, therefore, the dispersion is associated with the number of hops. Consequently, the end to end delay parameters and FSPL will be increased. In Figure 3.D, through the application of the ODB algorithm, unnecessary dispersions are eliminated. Reducing to the maximum the possible utilization of jumps, to transmit data packages from the most distant SMs toward their respective UDAP, contributing

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to a significant reduction, in which an UDAP takes to add and to merge the information of its associated clusters to relay to their respective BSs. In the same way FSPL is diminished. In Figure 3 it can be determined that the SMs suitable to be selected as UDAPS by the ODB algorithm are the nearest nodes to the center of mass of each group. Thereby reducing to the maximum the average end to end delay of each group. This happens because the center of mass is equidistant to all SMs of the cluster. This decreases the average number of links that a data package must pass through to reach their respective UDAP. If the number of crossed links increases is because the SMs are far away from their respective UDAPs and require mandatory jumps to being able to transmit. This can happen because the radio coverage of the UDAP does not guarantee observability to the furthest SM. Therefore, if the number of crossed links to transmit data packages from a SMs until their respective UDAP increases, it is because in the same way different variables increase such as: the distances of transmission, jumps required and consequently end to end delay increases. Therefore, the end to end delay is directly proportional to the number of average links crossed by a data package.

In addition, through Figure 3, it is shown that the heuristics proposed is able to mutate the adjacency matrix, seeking to provide the best resulting topology to the solution of the problem. The topology will ensure a significant reduction of the average end to end delay in which the UDAPs takes to add the information of its associated clusters. Therefore, in Figures 3.C and 3.D the georeferenced near optimal deployment of SMs is shown. This serves for measurement, monitoring and control of the conventional electrical system giving rise to the possibility of an optimal data management and the integration of micro-grids to increase the reliability and quality of energy.

Figure 4. End to End Delay generated by each population increase by varying the capacity of each cluster with traffic 0.1[paq/sec], L=200 bits. Source: Author

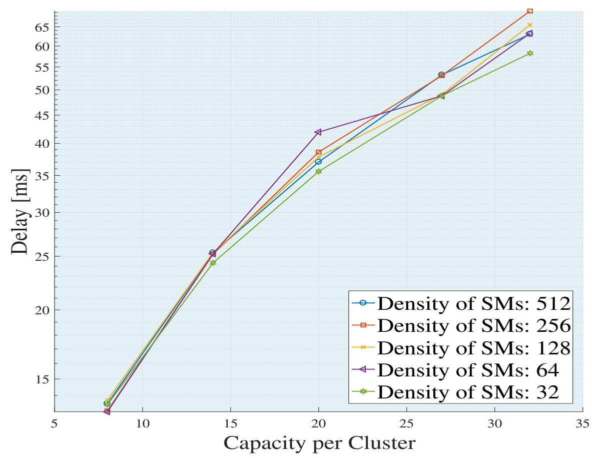

Figure 4 shows the increases in end to end delays as the capacity of an UDAP to accommodate SMs increases. This happens because, the ability to agglutinate a cluster is directly related to the number of average links that a data package must go through to transmit the package from the SMs to their respective BS. In addition, the higher the capacity of the UDAP is there may be various effects, such as: increased delay time in collecting the information, greater distances of transmission, greater number of jumps and greater chargeability of each link in the network. On the other hand, in each density of

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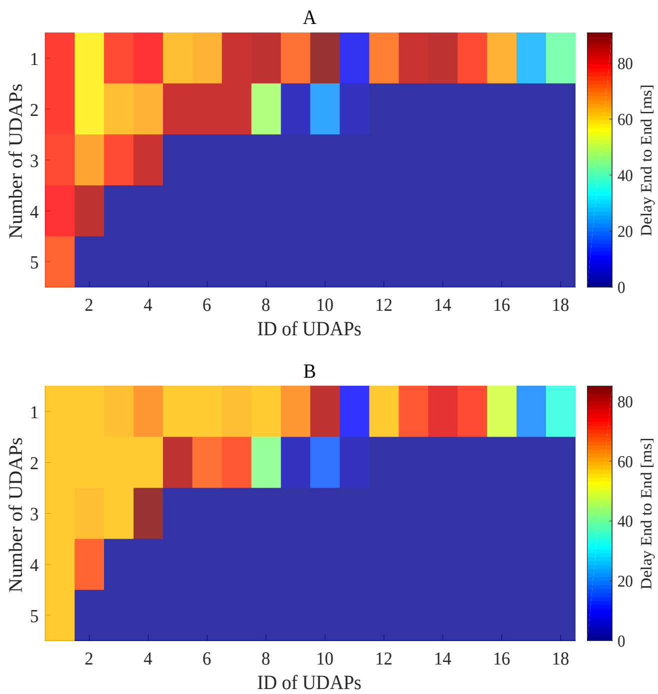
SMs the topologies of each cluster are changing, to comply with the requirements of the network, which causes and requires different routing characteristics to the extent that the density of SMs is increasing or decreasing, causing, variability in the features of each cluster and therefore the resulting topology.

Another important information that the Figure 4 provides us is: as the population increases the rate of end to end delay decreases. Corroborating what was said in the previous paragraphs. In the first two capabilities (8, 14), of Figure 4, the increase rates of end to end delay are similar. This is due to that if there is less capacity on the same stage, it is necessary to deploy more UDAPs. Building in this way clusters with SMs very nearby. As a result, if clusters are built with minimum distances, the need to transmit through multiple jumps is null. Therefore, the delay is directly proportional to the capacity-coverage of the UDAP and inversely proportional to the density of the SMs.

Figure 5. UDAPs Delay L= 200-bit/packet, Lambda= 0.1 packet/Sec. Source: Author



In the Figures 5.A and 5.B is shown the application of selection criterion 1 and 2 of the UDAP respectively. Although in Figure 5 there is a solution for each case, the difference lies in the resulting intra-cluster topologies and in the different values of end to end delay obtained by applying the different criterion of selection of the UDAP. Therefore, the topology of each group is crucial to reduce to the maximum the delays generated throughout the wireless network.

In the heat map of Figure 5.A. the first criterion of selection of the UDAP is applied, showing as a result an unbalance of times it takes an UDAP to add the total cluster information. This is because the average delay of each group is directly proportional to the average number of links traversed by each data package generated in the SMs. And as a result, the greater the number of average links traversed by each packet, the greater the delay of each group. However, the number of nodes in the group also affects the end to end delay of each group due to that if the lower the number of traffic generated data, the lower will be the delay. In the second criteria of the UDAP selection, represented in Figure 5.B, there is a trend to balance the end to end delays through the optimal routing management at intra-cluster level

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by applying the ODB algorithm and in addition reduces the time that the UDAP takes to add the data for each cluster. Following that, once data is merged, information is sent to the corresponding BSs.

Another fact of much interest, is that the heuristics tries to displace incomplete clusters with their respective UDAPs to the edges, either, because it did not comply with criteria of capacity, coverage, or the number of jumps allowed. Allowing with it, to have capacity available in these UDAPs, for the future addition of new users to the network. Therefore, through the Figure 5.B it is proved that the ODB algorithm can manage optimal intra-clusters routes and reduce the end to end delay of each group.

Table 3. Wireless WiFi network: L= 800-bit/packet, Lambda= 0.1 package/sec

Scenario	WiFi	Coverage	Distance [m]	Delay Cluster [ms]	Parameters FSPL (dB)		
#	# Links	%	Average	Average	2.4GHz	5.4 GHz	5.8GHz
1	494	100	30.12	228.26	69.63	76.68	77.30
2	245	100	30.27	192.85	69.67	76.82	77.84
3	124	100	33.44	267.65	70.54	77.60	78.20
4	62	100	31.98	258.29	70.15	77.20	77.82
5	31	100	25.52	236.95	68.19	75.24	75.86

Table 3 presents the required number of links and the computation of the analyzed variables in this document for the required wireless WiFi network. It presents five different scenarios, in which the density of SMs is varied n (512, 256, 128, 64 and 32) to be deployed in $A(n)$, thus, demonstrating, the criterion of scalability enabled by the heuristic proposed. It is known that *n* is the sum of WiFi and cellular links and can checked in the corresponding scenarios using the Tables 3 and 4. The purpose of these tables, is to quantify the necessary resources and review the behavior of the network in its different scenarios by analyzing: number of WiFi links and cellular required, coverage rates, average maximum distances of intra-cluster and inter-cluster links, average time in which an UDAP takes to add the information and the computation of FSPL considering different frequencies applicable to a wireless WiFi and cellular network. Each of these results allow us to plan the deployment of the network by observing their behavior. Considering that by the proposed heuristic, the minimum values on FSPL, end to end delay and transmission distances are obtained, providing a near-optimal solution to the planning problem exposed in this research.

As the frequency of the wireless WiFi and cellular network signal increases, also the FSPL metrics increase. This can be checked on Table 3 and 4 respectively. In general terms, the lower the frequency of transmission, the better will be the signal that will travel through the air and the objects. FSPL is used to predict the intensity of the required signals in a wireless system. In addition, in Tables 3 and 4 if we add the delays that it takes an UDAP in collecting the information of the cluster, and the delay in a cellular technology, we can estimate the average total time in which the BSs have available the data merged of each UDAP deployed in the scenario. The data of rand trip time (RTT) of Table 4, are taken from [79], which are applied in cellular technology. If we compare the Tables 3 and 4 we can see that the metrics of delays in WiFi are much greater than the metrics at cellular delays. However, the amount does not exceed the allowed delays in AMI exposed in the literature for the efficient data aggregation.

Therefore, with Tables 3 and 4 viewing at each scenarios, we can obtain the required procedures for the deployment of SMs under the configuration of an hybrid wireless network (WiFi-Cellular). Another

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fact of much interest is the length of optical fiber that communicates the BSs and the central office. In this case study is 280 meters in all scenarios, since the latitude and longitude coordinates of the BSs and central office are fixed. As a result, the heuristics has been shown to be able to provide a minimum route map, required for the planning of an hybrid FiWi network at the lowest cost while maximizing reliability and the robustness of the bi-directional communication network needed to control and supervise the conventional electrical network Allowing us by an optimal information management to integrate SMG systems that will be able to run connected to the network through an adequate synchronization and in the same way will be able to work in island mode, namely, disconnected from the system. The importance of microgrids, through an adequate two-way communication system, is that it can operate autonomous according to what the physical and economic conditions dictate.

Table 4. Wireless Cellular Network

Scenario	Cellular	Coverage	Distance [m]	Rand Trip Time [ms]			Parameters FSPL (dB)		
#	# Links	%	Average	3G	4G	5G	850MHz	1700 MHz	1900 MHz
1	18	100	84.23	70	20	5	69.55	75.57	76.53
2	11	100	59.46	70	20	5	66.52	72.54	73.51
3	4	100	55.03	70	20	5	65.85	71.87	72.84
4	2	100	68.41	70	20	5	67.74	73.76	74.73
5	1	100	66.76	70	20	5	67.53	73.55	74.52

Figure 6. A shows the metric obtained with the following characteristics: data length L=800 bits, $Lambda$ =0.1 paq/sec and, by varying the density of SMs and the capabilities of each cluster. In Figure 6.B L is kept, the density of SMs is n= 512, and lambda and capabilities are varied. In Figures 6.A and 6.B it is noted that, when the need of UDAPs decreases, the average delay of the entire wireless network increases. This happens due to the increase on the capacity of each UDAP to accommodate SMs. If the capacity to accommodate SMs of an UDAP increases and its radio of coverage is minimum, the need of multiple jumps to aggregate data from the more distant nodes to the APPU also increases. Therefore, as the multiple jumps in the cluster increase, there is also an increase in the distance of a SMs to its associated UDAP. This translates into an increased time required to add and merge the data in each UDAP. In addition, in Figure 6.A it can be seen that the average delays while maintaining the capacity, are similar in each increment of density of the deployed SMs. This is because this are partial averages of each cluster, which demonstrates that the heuristics is capable of building through appropriate topologies balanced graphs. Which in turn directly contribute to decrease technical losses on a wireless network. Therefore, the amount of required UDAPs responds to three variables in particular: Density of SMs, capacity and coverage (in terms of the technical characteristics available of the UDAP).

If we verify the behavior of the metrics in Figure 6.A, in the populations 32 and 128 with capacities of 20-27 and 27-32 respectively, there is no need to implement an UDAP since the proposed algorithm searches in each capacity increment to include (if the capacity allows it) the nodes that were not included (due to the restrictions of the problem). Thereby, completing the clusters without the need of adding UDAPs. On the other hand, in Figure 6.A it is clear that as the SMs density increases, the slope of the delays is stabilized. And this happens because, as it has a larger number of SMs, the algorithm manages to build clusters mostly balanced in terms of the following: distances, coverage radios and number

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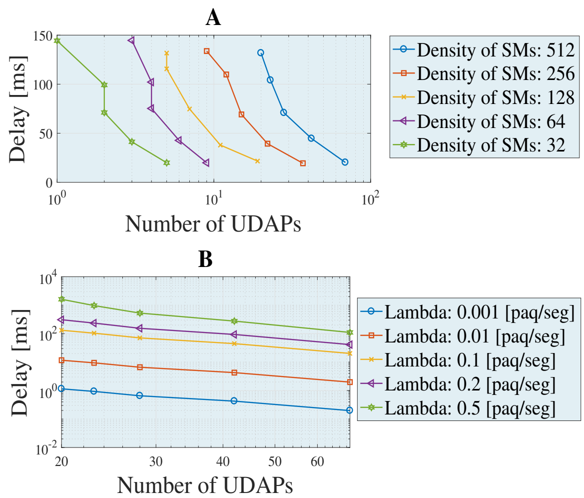
of elements for each group. Therefore, the higher the density of SMs, better results are obtained in terms of optimization due to closeness of the SMs. Therefore, when varying the capacities of an UDAP the following is modified: the topology, the average number of traversed links by package to reach its destination, the length of the cluster, the end to end delay, the link capacity and the coverage distance.

Figure 6. Delay in different scenarios. Source: Author



In Figure 6.B, are depicted significant variations in the global delay for the data aggregation as the traffic generated by each SMs is increasing. Therefore, the higher the traffic generated the greater the FiWi network delay. This is because the increase in the delay is directly proportional to the increase in capacity. If the capacity of the UDAP increases, the greater will be the length of the cluster, and therefore, the greater will be the traffic generated in each cluster. Resulting in an increase on the global end to end delays. Accordingly, the delay is directly proportional to the traffic generated by each SMs whereas, the number of UDAPs k required is inversely proportional to the capacity and coverage of the UDAP.

In Figure 7, is shown that the greater the amount of average links that a data package must go through from a SM source to an UDAP, causes increases in the delays of each scenario. This happens due to the following. If the average number of links that a data package must go through increases, is because, the package was generated by a node that is located at a greater distance than the maximum coverage radio allowed of the UDAP. That is if a node is very distant it increases global delays of the wireless network, since that data package necessarily has to carry the information through jumps, supported on the SMs of transition to bring the information to the UDAP. Each trend in Figure 7, corresponds to a different scenario. Therefore, the behavior of each trend responds to the near optimal topology in each of the cases. This heuristic is a solution to the problem of planning.

If we see the trend with n= 512, in Figure 7, we can corroborate the affirmation made in previous paragraphs. That the higher the number of deployed SMs, the best optimization results are reached. Therefore, in Figure 7 is shown that when there is a high density of SMs the average number of jumps required for the transmission of data packages is lower than in all the other cases. This is due to the

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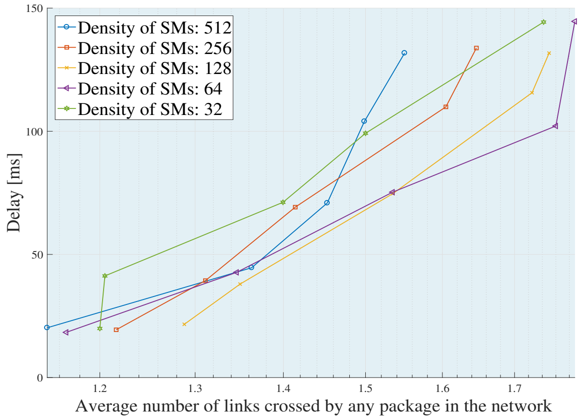
greater the number of SMs the dispersions are avoided (see Figure 3). Consequently, it translates into technical losses in a wireless network. Finally, if the average of links crossed by a package is zero, it means that the entire built network does not require multiple jumps to transmit the information from a source SM to a target UDAP.

Figure 7. Average links crossed by a data packet L=800-bit, Lambda=0.1 paq/sec. Source: Author



6. Conclusion

The heuristic proposed allows practitioners to deploy the necessary number of UDAPs for the monitoring, the supervision and the control of the conventional electrical network. Providing coverage to a number n of SMs and making possible the integration of microgrids with the conventional electrical system. In this way, final users of energy resources will be consumers and prosumers thanks to the integration of DRES. A fundamental feature of the model is that it adapts to the conditions of the required wireless network. In addition, the research carried out allowed us to determine the importance of reducing to the maximum the end to end delay of the entire network. This metric not only provides information on terms of time, but in addition, allows to comprehend and minimize the chargeability of the network and the need to allocate the capacity of the point-to-point links for its efficient operation. The model has shown to be scalable in time and space and has the following characteristics: presents finite solutions, optimizes the resources required by the FiWi network using an efficient clustering method (different to the traditional). Moreover, with the N-NST algorithm, balanced clusters can be built which are subject to real restrictions as capacity and coverage. The heuristics works with georeferenced scenarios, reducing to the maximum the aggregation delays of data of each cluster using the ODB algorithm. Furthermore, it minimizes FSPL and is a planning model of NP-Hard complexity. The complexity of the problem lies in the population density of SMs, since, in a graph with n SMs there are n^{n-2} possible trees. Therefore, the results obtained are near optimal due to the exponential increase in the complexity if there is an increase on the SMs on the scenario. Consequently, to relax the problem stop criterion are introduced. These criterion are expressed in the restrictions of the problem. The goal is that once the algorithm converges it stops providing a near optimal solution. In future works a comparative analysis will be carried out between different clustering methods. The link capacity restriction (Mbps) will be increased to decide on the topology and finally the fault tolerance will be included as well.

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