Optimal Positioning of GPRS Concentrators in Smart Grids Considering Routing in Mesh Networks

Gustavo Batista de Castro Souza
Universidade Federal de Goiás - UFG
CEP: 74605-010
Goiânia - GO - Brazil
gustavo2x4@gmail.com

Flávio Henrique Teles Vieira
Universidade Federal de Goiás - UFG
CEP: 74605-010
Goiânia - GO - Brazil
flavio@eee.ufg.br

Cláudio Ribeiro Lima
AGX Energia
Houston - Texas - USA
crlima100@gmail.com

Getúlio Antero de Deus Júnior
Universidade Federal de Goiás - UFG
CEP: 74605-010
Goiânia - GO - Brazil
getulio@eee.ufg.br

Marcelo Stehling de Castro
Universidade Federal de Goiás - UFG
CEP: 74605-010
Goiânia - GO - Brazil
mcastro@eee.ufg.br

Sergio Granato de Araújo
Universidade Federal de Goiás - UFG
CEP: 74605-010
Goiânia - GO - Brazil
granato@eee.ufg.br

***Abstract*— RF Mesh networks have become increasingly present in telemetering systems. The main equipment to incorporate remote measurement functionality is the electricity meter, providing great support for the future Smart Grids. Since ZigBee Mesh networks is a mature technology and widespread, this technology has been chosen to be used in AMI (Advanced Metering Infrastructure). This paper proposes a methodology for locating concentrators points in a ZigBee based Mesh network of meters, optimizing the performance of the network. The method consists of an algorithm to determine the GPRS concentrator position, i.e., the position of a device that join data meters and send to the utility. In order to validate the results presented by the algorithm, a real scenario is simulated.**

***Index Terms*— Smart Grid, Simulator, Mesh Networks, AMI, ZigBee.**

I. Introduction

The main purpose of a smart metering system based on RF (Radio Frequency) Mesh is to allow utilities to perform automatic data readings at regular time intervals and offer programs such as Demand Response (DR) for controlling of critical loads. Such systems require reliable bi-directional communication between the measurement points and the utility final host (Head-End System - HES). Currently, more than 10 million measurement points worldwide are managed by RF Mesh technology [1].

However, most solutions are proprietary and not standardized for Neighborhood Area Networks (NAN), being part of the Smart Grid Networks architecture, established in Technical Standard for Smart Grid IEEE 2030 [2]. This new standard, launched in September 2011 by IEEE Standards Association (IEEE SA) defines Smart Grids standardized architectures, concepts, elements, connections and interoperability. A new standard specific to Mesh Networks based on IEEE Technical Standard 802.15.4g [3] (802.15.4 evolution) will attain the current and future requirements, functionality and interoperability of mesh networks with NAN topology at Smart Gird Networks defined in IEEE 2030.

In the network architecture considered in [1], meters located at endpoints transmit and receive data at a speed of 9.6 Kbps while collector nodes (concentrators) are able to transmit and receive at speeds of 9.6 Kbps or double, 19.2 Kbps. The concentrators are usually strategically placed at top of light poles, presenting high-speed line-of-sight communication path to several meters. Collectors are installed throughout the whole area covered by the utility, covering the full range of meters. One of the most commonly used network topologies NAN considers the use of smart meters based on ZigBee Mesh IEEE 802.15.4 communication protocol in the access communication and GPRS (Global Packet Radio Service) for the concentrator which is connected directly with the utility Head-end System. This GPRS connection is considered as a backhaul network.

By definition, smart meters, communication network and the Head-End System comprise the basic modules that define the AMI (Advanced Metering Infrastructure) technology, predominant in Smart Grid with respect to remote sensing. Figure 1 presents this architecture.

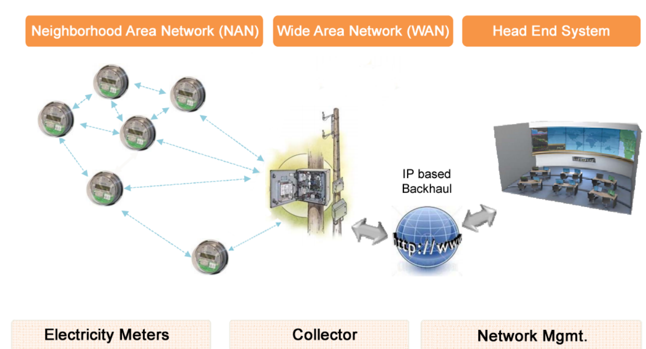

Fig. 1. RF Mesh System Architecture Adapted from [1].

One of the great difficulties in designing NAN metering network is positioning of the node collectors to optimize costs and improve the performance of remote reading system. In this paper, we propose a new methodology for optimizing the placement of concentrators in a ZigBee mesh network of smart meters to minimize the number of messages hops from the meters to the concentrator. We also evaluate the proposed algorithm performance in identifying the optimal use of GPRS concentrators in the ZigBee Mesh Networks through simulations in a network simulator.

II. The IEEE 802.15.4 Standard (ZigBee Technology)

The IEEE 802.15.4 standard specifies the physical layer and the data link layer to a wireless personal area network with low transfer rate - LR-WPAN (Low-rate wireless personal area network), which focuses on low cost applications. This kind of devices has lower network communication capabilities and is power limited, but is expected to operate for long periods of time. As a result, energy saving is a critical point in that projects.

In IEEE 802.15.4, there are two basic types of network topology, star topology and the peer-to-peer (mesh). Devices on an LR-WPAN can have full function and are classified as Full Function Devices (FFD) or have reduced function and be called Reduced Function Devices (RFD). A device is chosen to be the coordinator PAN (Personal Area Network), which is responsible for keeping the network running and managing other devices. Basically, ZigBee devices can be classified as [4]:

- Coordinator (FFD);
- Router (FFD);
- End-Device (FFD ou RFD).

ZigBee allow architecture mesh implementation, and has low cost, low power, low data rate and complexity ideal for applications in Smart Grid. For example, ZigBee can be used in real-time monitoring system, load control and building automation. A ZigBee sensor network can reduce the cost of Smart Grids deployment.

III. ZigBee Routing Algorithms

ZigBee networks present some kind of routing packets methods, which are divided into two groups of protocols, the Table-Driven Routing Protocol (Proactive) and the Source-Initiated On-Demand Routing (Reactive) [5].

In the Protocols using tables (Table-Driven Routing Protocol), each node can store routing information in form of one or more tables, which contain information about the network nodes. The filling of the tables occurs following simple communication criteria through upgrade packets. As an example of this type of protocol, we can cite the DSDV (Destination-Sequenced Distance-Vector Routing), which uses a well known packet routing implementation, the Bellman-Ford algorithm [5].

In routing on-demand protocols (Source-Initiated On-Demand Routing) the establishment of the routes is made on demand, in other words, in the moment of the communication between source node and destination node. The main representative type of this protocol is AODV (Ad-hoc On-Demand Distance Vector). This algorithm is similar to DSDV, the routes are discovered by a simple mechanism based on origin. In order to calculate the best route, the procedure of the AODV is as follows [5]:

1) The source node sends to all its neighbors a packet called RouteRequest (RREQ);
2) The neighbors will send to its neighbors successively until it finds the destination node.

It should be noted that once a node receives a RREQ, and this is not a destination node, it stores in its routing table the address of neighbors in order to produce a reverse path. Thus, it is possible to dispose of repeated RREQ arriving at a node by different paths.

IV. Method for Positioning Concentrators

In this section, we propose a method for positioning concentrators on power grid poles, in order to minimize the number of data packet hops between the meter and the concentrator. The number of hops degrades network performance because routing is mainly responsible for the data traffic delay [6].

The AODV protocol is the established standard algorithm for packet routing in ZigBee networks [7]. If the ZigBee devices configuration is not changed, this is the routing protocol that is running on the network. Once the protocol AODV relies on shortest path algorithms, we considered the implementation of such algorithms, which minimizes the cost of routes in the meters of the mesh network.

To determine the best routes between the meters and the concentrator node, we used different algorithms that seek the best route between two distinct points. Thus, the Dijkstra, Bellman-Ford and BFS (Breadth-First Search) algorithms were all tested in this work [5]. In the next section, will be briefly describ how the minimum path algorithms are applied in our proposal.

A. *Case Study - Smart Metering Scenario*

In Smart Grids, communication networks are the main support system. Therefore, the resources needed for communication between equipment should be well dimensioned, because the most part of the budget relates to this important part of the Intelligent Power Grids.

The intelligent network scenario considered in this work is a ZigBee mesh network between meters, they will be connected to a concentrator that sends the messages via GPRS to the power utility. The objective is to find the ideal position/location for the concentrator to obtain a network as efficient as possible.

The real intelligent network which is deployed in our Research and Development Project (P&D) involves a ZigBee network that operates at a frequency of 2.4 GHz with transmission rate of approximately 115 Kbps. Following the real implementations, meters send data every 15 minutes to GPRS concentrator.

The main simulation purpose of this work is to evaluate network performance considering different positions for the

GPRS concentrator (remote), so we can determine which is the best position among the alternatives in the two scenario shown in Figure 2 and 3 . The considered scenarios represent real networks, where all the meters connected to the same transformer, containing one or more concentrators GPRS modules, will be remote controlled.

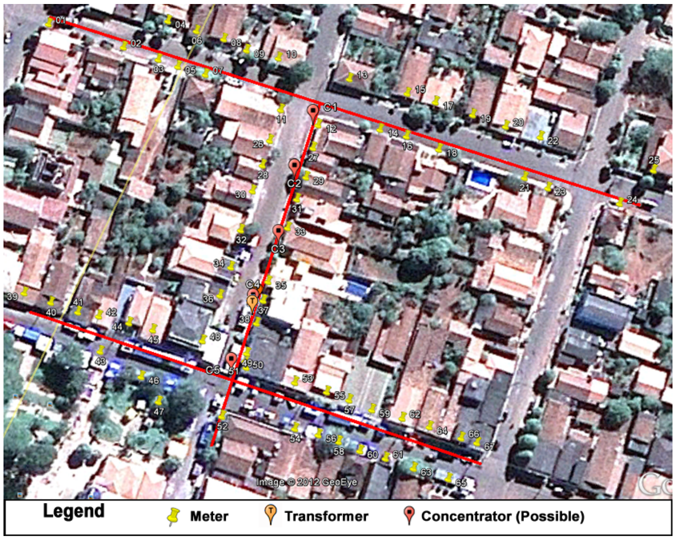

Fig. 2. Meter Positions (Case Study 1)

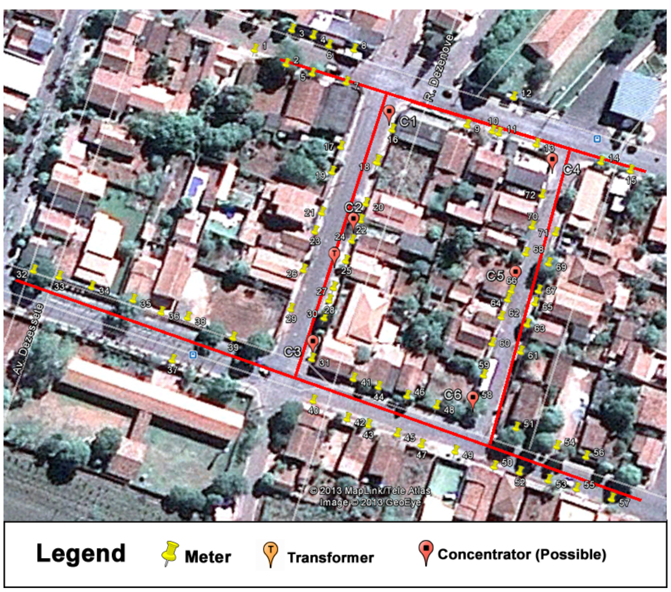

Fig. 3. Meter Positions (Case Study 2)

B. Minimum Path Algorithms

Dijkstra's algorithm is the most famous and used algorithm for calculating minimum cost path between graph vertices.

A vertex is chosen as root search, this algorithm calculates the minimum cost of this vertex to all other graph vertices. The algorithm can be used on directed graphs (digraphs), or not, and admits that all edges have non-negative weights (null is possible). This restriction is possible in the communication networks context, where edges represent distances or times and average route [8].

The Bellman-Ford algorithm, created by Richard Bellman and Lester Ford, calculates for a given digraph (directed graph) with weighted edges, the shortest path from a source node to each other graph nodes. This algorithm instead of Dijkstra's algorithm imposes no restriction on the weight sign of the edges, which makes a more generic solution [9].

Finally, the BFS (Breadth-First Search) algorithm is analyzed. Formally, a breadth search is a method of non-informed (or misinformed) searching that expands and systematically examines all directed or undirected graph vertices. We can say the algorithm performs an exhaustive search in a graph going through all graph edges and vertices. Therefore, the algorithm must ensure that no vertex or edge will be visited more than once and, thus, uses a queue data structure to ensure the arrival order of the vertices [10].

The BFS algorithm, unlike the others presented in this paper, does not consider the graph with edges distances. In other words, what matters in this algorithm is the data in each node jumps, trying to find a best path passing through a lower number of nodes.

C. Algorithm for Positioning of Mesh Network Concentrators

Routing protocols use metrics to choose a best path to a destination in a network in order to reduce the delay in data transmission and the system load. When ZigBee has a physical obstacle (houses) between a link, the signal degradation can be high. Thus, we considered as a possible link between two meters or between meters and concentrator only links with line-of-sight and shorter distances than 100 meters.

One of the first metrics used in computer networks due its simplicity, is the lowest number of hops between the source and destination, which is used in this study to select the best position for the concentrator [11]. Thus, we propose a function that represents the cost of choosing each possible concentrators, where the element to be minimized is the amount of hops between each meter to the concentrator. The cost function is represented by the following equation:

$$Cost_{Ci} = \sum_{n=1}^{N} q_{ni} \tag{1}$$

where,

Ci - Concentrator Point;

N - Number of meters;

q_{ni} - Number of hops in the path of Meter n to Concentrator Point i.

The proposed algorithm consists of the following steps:

- **Step 1:** Obtain the geographic coordinates of the meters and the poles;
- **Step 2:** A clustering algorithm such as the k-means algorithm [12] is used if more than one concentrator will be positioned;
- **Step 3:** Choose the position of the concentrator among existing poles. In case of application of the k-means

algorithm, the poles closest to the points obtained by the algorithm are considered;

- **Step 4:** Apply a shortest path algorithm (BFS, Dijskstra or Bellman-Ford);
- **Step 5:** Evaluate the number of hops;
- **Step 6:** Move the position of the concentrator;
- **Step 7:** The position chosen is the one with the minimum number of hops.

Note that in the proposed algorithm we used three shortest path algorithms (BFS, Dijskstra and Bellman-Ford) in question. The algorithms exhibit some differences in the routes, because the BFS algorithm does not aim of minimizing the distance, but just the number of hops, while the other minimizes the distance. However, the minimization results always point to the same position, independent of the algorithm chosen to minimize the route.

To scenario 1 the algorithm gives a solution to minimize the number of packet hops the position C5, the Figure 4 shows routes from each meter to concentrator C5.

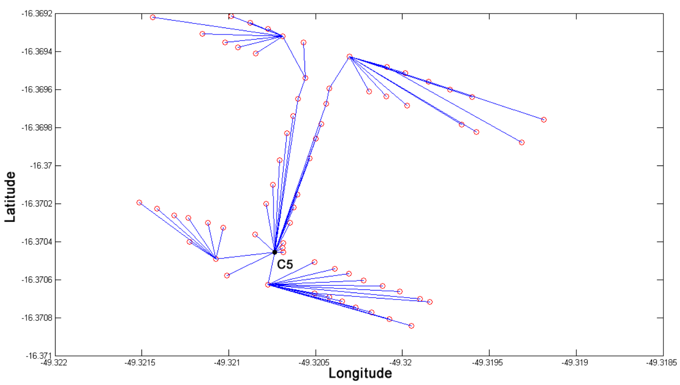

Fig. 4. Routes to the best Concentrator Point (C5) - Scenario 1.

To scenario 2 the algorithm gives to minimize the equation (1) the position C1, the Figure 5 shows routes from each meter to concentrator C1.

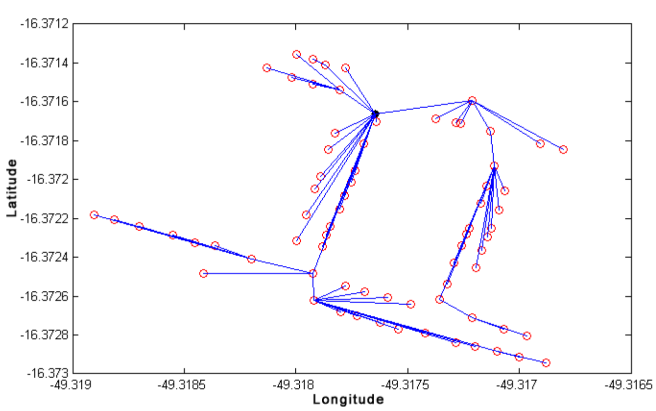

Fig. 5. Routes to the best Concentrator Point (C1) - Scenario 2.

The objective is to show that application of proposed algorithm as a method for positioning concentrator provides for improving in network performance (less delay, queue size, and other parameters).

V. Simulations and Results

ZigBee devices can provide mesh capability to the communication network. In other words, a ZigBee device installed in a meter can communicate with another device, and so on until the message is delivered to the concentrator. In the ZigBee technology, the network find the shortest paths between nodes and concentrator [1] [13]. Therefore, we assumed in simulations below that after a certain time, the network finds these shortest paths. Note that this is different of when the nodes send packets only considering neighboring closer nodes (meters).

Once the average packet size in Smart Metering ZigBee network varies between 100 to 200 bytes, we assumed that the packets have an average size of 200 bytes [1].

A. Smart Metering with a Single Concentrator - Scenario 1

In this section, the scenario 1 of the ZigBee metering network was implemented in the Opnet simulator with 67 meters as shown in Figure 2. Thus, for each concentrator position (C1, C2, C3, C4, C5), we evaluated the behavior and network performance in terms of delay, throughput and queue size in the concentrator.

The parameters of the simulations were chosen according to the considered scenario in the case study. For this scenario, we analyzed the delay and queue length in the concentrator and the system traffic load for the positions C1, C2, C3, C4 and C5. Figure 6 shows the average packet transmission delay (in seconds) in the concentrator.

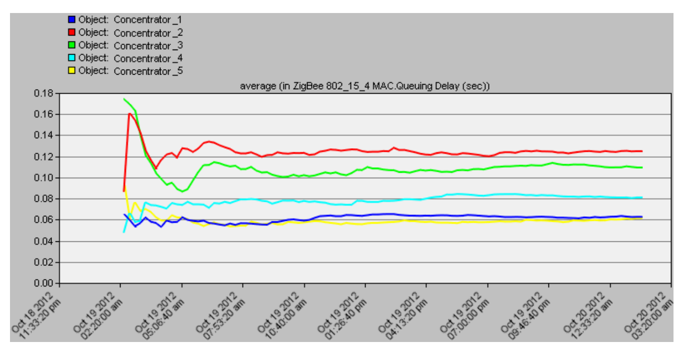

Fig. 6. Average delay for the five concentrator positions where the meters send data every 15 minutes.

From Figure 6, it can be seen that concentrator at position C5 provided the lowest mean packet transmission delay from concentrator to utility power. As expected, the the concentrator queue size (number of packets) is also the lowest among the considered positions when the concentrator is at position C5, as depicted by Figure 7.

The buffer of the real concentrator possess 512 kB of memory. Therefore, according to Figure 7 , we can say that the buffer concentrator will be able to support the sent packet demand (data) because on average there will be only one packet, 200 bytes, in queue.

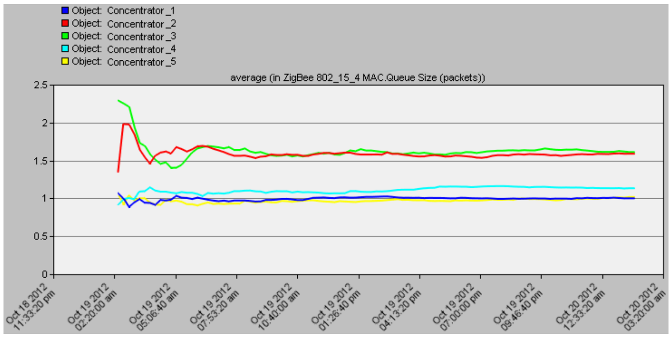

Fig. 7. Average queue size for the five concentrator positions positions where the meters send data every 15 minutes.

Note that when positioning the concentrator in the position C3, nearest the center of mass of the network, the average queue size becomes bigger than those of other concentrator positions. Furthermore, the flow rate in bits/s will be lower in this position (Figure 8).

The positions C1 and C5 provide the lowest average delays in the concentrator, and the position C5 offers lower average delay than C1. In the position C1 the concentrator presents a throughput sligthly less than in position C5. For this scenario configuration and taking into account only questions concerning traffic, the position C5 was chosen once it presents an average delay smaller than in the position C1 and a throughput almost equal to that of the C1 position.

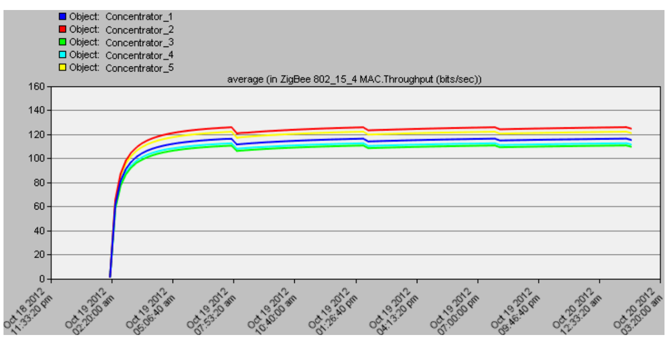

Fig. 8. Average throughput for the five concentrator positions where the meters send data every 15 minutes.

Considering time intervals greater than 15 minutes for sending packets by meters, the trend is an advantage evidence of the concentrator at the position C5 detriment to the others. Figure 9 presents the average delay in queue concentrator with meters configured to send data every 30 minutes. We noted an advantage (lower average delay) of position C5 still higher than simulation with sending data every 15 minutes.

Decreasing the time of sending the packets to intervals shorter than 15 minutes, the values of average delays and throughput for the network concentrator becomes more constant with time. Figure 10 shows that the values of average delay in the concentrator buffer tend to be constant for a scenario of sending data every 7 minutes.

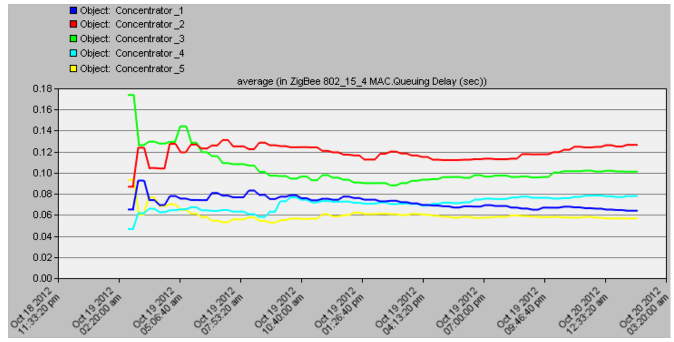

Fig. 9. Average delay for the five concentrator positions where the meters send data every 30 minutes.

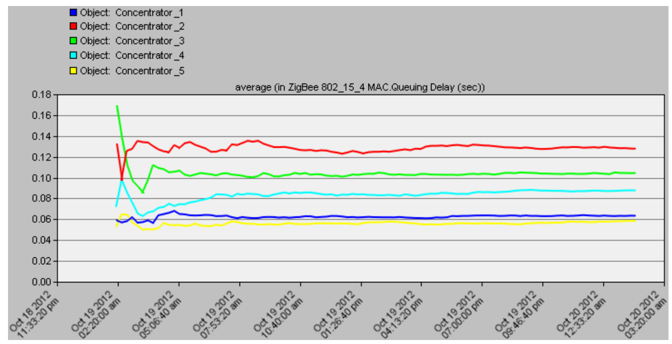

Fig. 10. Average delay for the five concentrator positions where the meters send data every 7 minutes.

The simulations with different configurations show that for the considered scenario 1, the algorithm can find the best concentrator position in terms of network traffic performance.

B. Smart Metering with a Single Concentrator - Scenario 2

Considering the same methodology done to scenario 1, we simulate a network with 72 meters as shown in Figure 3 to scenario 2. Thus, for each concentrator position (C1, C2, C3, C4, C5, C6) we evaluated the network performance and behavior.

Figure 11 shows the average packet transmission delay (in seconds) in the concentrator, from which we can infer that the queue length in the concentrator is the lowest to the position C1 (Figure 12).

By analyzing these results, we can say that the position C1 has better conditions to be the chosen point to concentrate data, because C1 provides lowest delay in the concentrator and the concentrator is less required.

C. Smart Metering with two concentrator - Scenario 1

Increasing the number of meters can prevent the use of only one data concentration point. Besides, more than one concentrator can be used to avoid the concentrator be overloaded. The positioning of these concentrators is not limited to the best route, but also to distribution of the meters that communicate with each concentrator.

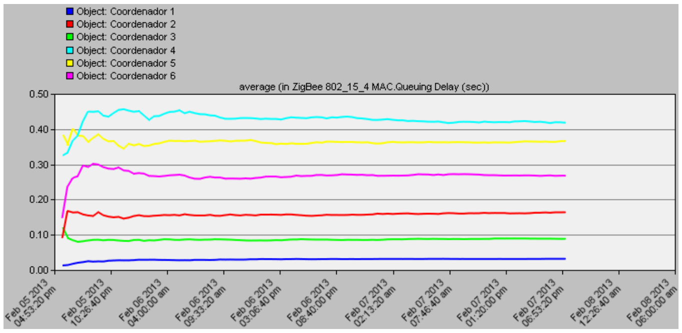

Fig. 11. Average delay for the six concentrator positions where the meters send data every 15 minutes.

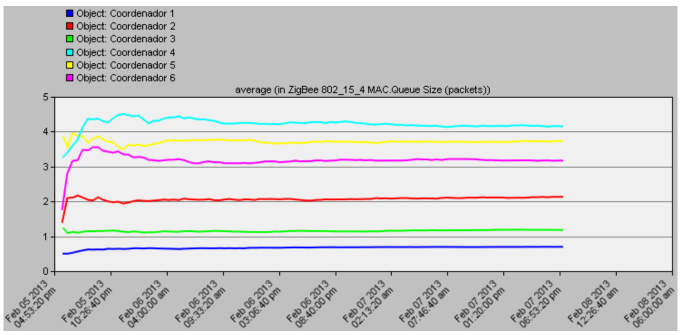

Fig. 12. Average queue size for the six concentrator positions where the meters send data every 15 minutes.

Using Clustering techniques [14], we can determine the positioning of more than one concentrator. In this case, the network is not limited to a single data concentration point. The clustering algorithm used in this work is the k-means [12].

The k-means algorithm determines the placement of the centers, grouping the elements closest to them. The center can also be established as a facility. In this work, the center may be seen as a concentrator that provides a GPRS link to be used by several meters inserted in a mesh network [14].

The proposed algorithm was used to also determine the positioning of two concentrator, where they operate independently. Independent networks are created, and the data concentration divided between the two points of data concentration. Figure 13 shows the result of using the k-means algorithm for the scenario 1 considered.

Were positioned two concentrators to simulate that solution, testing the solution given by algorithm. The positions C1 and C5 were chosen, reproducing the solution presented in Figure 13. The network performance was compared the positioning of only one hub at positions C1, C2 and C5 against allocating two data concentration points.

Figure 14 shows the average delay at each concentrator, we noted that the delay in concentrators placed in pair are less than with a single one, this observation was expected due to lower demand in each concentrator after network split. The simulation was performed for a scenario where the meters send their data every 15 minutes.

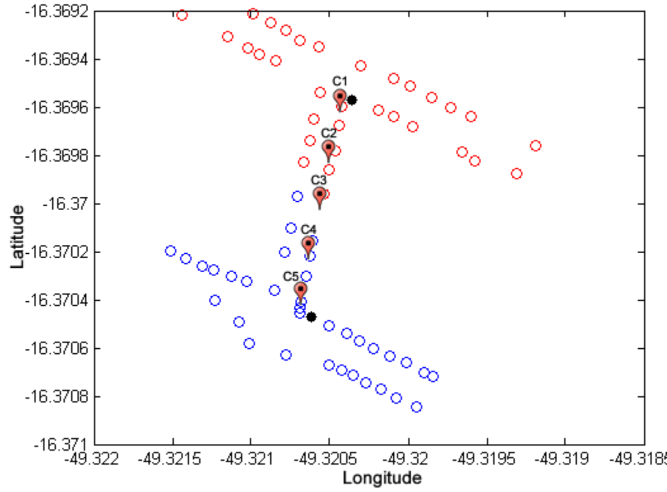

Fig. 13. Positioning two points concentrators - Scenario 1.

The dark blue curve represents the average delay in the concentrator C1 obtained using two concentrators in the network at positions C1 and C5. The light blue curve represents the average delay in the concentrator C5 obtained using two concentrators at positions C1 and C5. The red curve represents the average delay obtained with just a concentrator at position C1. The green curve represents the average delay with just a concentrator at position C2. Finally, the yellow curve represents the average delay with only one concentrator at the position C5.

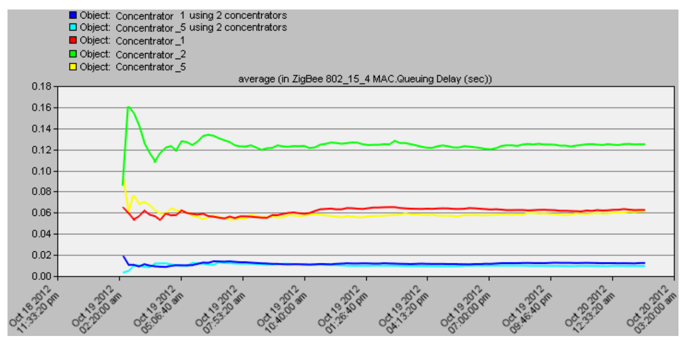

Fig. 14. Average delay in concentrator comparison with two concentrators.

Comparing each separate concentrator is logically expected that values of network performance are improved. A more insightful comparison is shown in Figure 15, where average delays are compared considering all network meters and not just grouping by concentrator. The graph shows that the average delay is drastically reduced to a system with two concentrators, improving network performance. The increase in network performance is visible when comparing the average delay system with only one concentrator and two working together.

In Figure 15 the blue curve represents the average network delay considering use of two concentrator at positions C1 and C5. The red curve represents the average network delay using only one concentrator at position C1. The green curve represents the average network delay using only one concentrator at position C2. The light blue curve represents the average network delay using only one concentrator at position C5. Finally, to validate the clustering model two scenarios were simulated with two concentrator, the first one being the solution presented by algorithm and another using two other concentrators. Figure 16 shows the average network delay using two concentrators at positions C1 and C5 is less than using two concentrators at positions C2 and C4. The use of concentrators at positions C1 and C5 also have a smaller average load on the system, as shown in Figure 17.

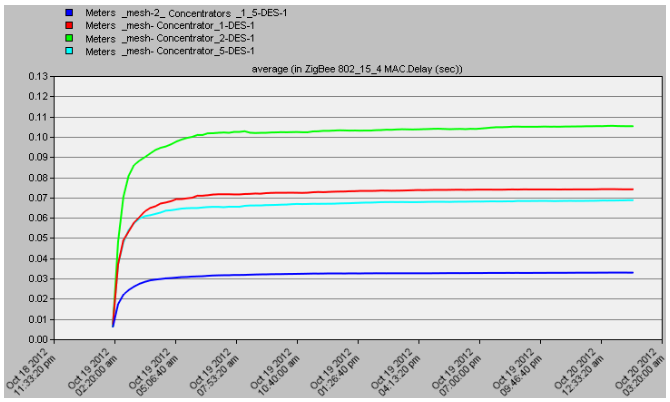

Fig. 15. Average network delay comparison with two concentrators.

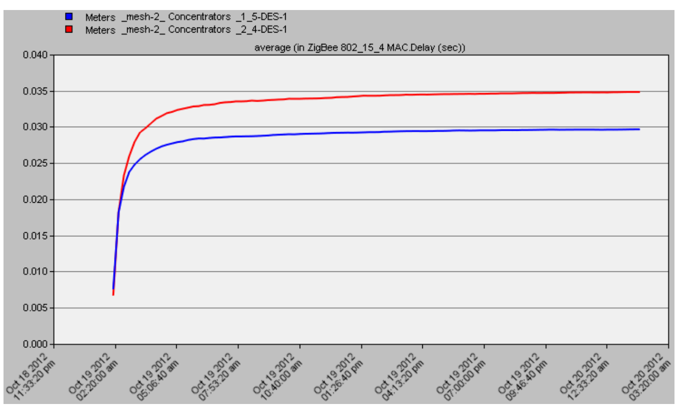

Fig. 16. Average network delay using two concentrators.

VI. Conclusions

This paper presented a methodology for positioning GPRS concentrators in mesh networks, aiming to minimize the number of message hops in the network to improve network traffic performance.

The analysis shows that for the scenarios considering only the minimum distance to be traveled by the messages of the meters to the concentrator in a network without mesh, the center of mass would be chosen. However, assuming that ZigBee network uses the shortest paths between meters and concentrator, the position chosen by algorithm provides smaller number of packet hops, improving the network traffic parameters.

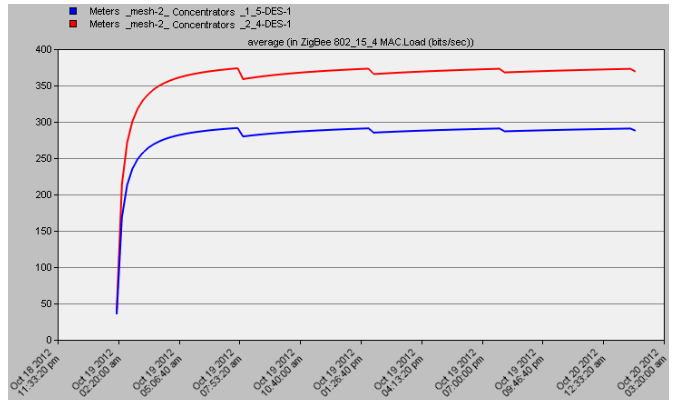

Fig. 17. Average network load using two concentrators.

The concentrator positioning algorithm presented in this work can be applied in different settings with many different configurations and quantities of nodes.

As main contributions of this work, we highlight: The creation of a methodology for choosing concentrators points in AMI systems mesh networks in terms of number of messages hops; Improved Smart Grid performance through planning placement of concentrators; Finally, the presentation of technical evidence of importance in planning the architecture of a meters network.

We intend as future work, to evaluate the proposed algorithm in several different Smart Grid scenarios, making it as general as possible and transforming it in a methodology for efficient planning and deployment of AMI to Smart Grids.

References

[1] LICHTENSTEIGER, B. et al. Rf mesh systems for smart metering: System architecture and performance. *Smart Grid Communications (SmartGridComm), 2010 First IEEE*, Gaithersburg, p. 379–384, Out. 2010.

[2] Smart Grids IEEE 2030. *ETSI Smart Grid 2011*. 2011. Disponível em: <https://standards.ieee.org/findstds/standard/2030-2011.html>. Acesso em: Janeiro de 2013.

[3] IEEE 802.15 WPAN^{TM} Task Group 4g (TG4g). *Smart Utility Networks*. 2011. Disponível em: <http://www.ieee802.org/15/pub/TG4g.html>. Acesso em: Janeiro de 2013.

[4] BILGIN, B.; GUNGOR, V. Performance evaluations of zigbee in different smart grid environments. *Computer Networks*, v. 56, p. 2196–2205, 2012.

[5] TELECO. *Protocolos de roteamento*. 2012. Disponível em: <http://www.teleco.com.br/tutoriais/tutorialprotocolo/>. Acesso em: Janeiro de 2013.

[6] LAWRENCE LIVERMORE NATIONAL LABORATORY. *Recommended Practices Guide For Securing ZigBee Wireless Networks in Process Control System Environments*. USA, April 2007.

[7] KIM, Y.-D.; MOON, I.-Y. Improved aodv routing protocol for wireless sensor network based on zigbee. *Advanced Communication Technology (ICACT)*, South Korea, v. 1, p. 859–862, Feb. 2009.

[8] INF-UFSC. *Algoritmo de Dijkstra*. 2012. Disponível em: <http://www.inf.ufsc.br/grafos/temas/custo-minimo/dijkstra.html>. Acesso em: Janeiro de 2013.

[9] DAUDT, C. G; MIRANDA, C. L. P. *A Programação Dinâmica: Algoritmo de Bellman-Ford*. 2010. Disponível em: <http://www.inf.ufrgs.br/c̃gdaudt/inf05515/art2.pdf>. Acesso em: Janeiro de 2013.

[10] INSTITUO DE MATEMÁTICA - USP. *Busca em Largura*. 2010. Disponível em: <http://www.ime.usp.br/p̃f/algoritmos_para_grafos/aulas/bfs.html>. Acesso em: Janeiro de 2013.

[11] ARAUJO, R. C. et al. Uma métrica baseada em reconhecimento de padrões para redes sem fio. In: *XXIX Simpósio Brasileiro de Telecomunicações*. Curitiba - PR: SBrT, 2011. v. 1, p. 1–5.

[12] WEBB, A. R. *Statistical Pattern Recognition*. Second edition. USA: John Wiley & Sons Ltd, 2002.

[13] OBINSON, J.; UYSAL, M.; SWAMINATHAN, R. *Adding Capacity Points to a Wireless Mesh Network Using Local Search*. 2010. Disponível em: <http://networks.rice.edu/papers/gateways.pdf>. Acesso em: Janeiro de 2013.

[14] IYIGUN, C.; BEN-ISRAEL, A. The multi-facility location problem: A probabilistic decomposition method. *2000 Mathematics Subject Classification*, 2012.