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Scalable Route Map for Advanced Metering Infrastructure Based on Optimal Routing of Wireless Heterogeneous Networks

Esteban Inga, *Member, IEEE,* Sandra Céspedes *Member, IEEE,*
Roberto Hincapié, Member, IEEE, and Cesar Andy Cárdenas

***Abstract*—This paper presents a scalable route map for the least cost deployment of wireless heterogeneous networks that support traffic from the Advance Metering Infrastructure (AMI). We first explore the performance of a common scenario in which a single technology is employed to connect smart meters sending traffic to the Utility. Based on simulations with actual city maps, we study the coverage provided to smart meters by an LTE cellular network. In order to improve the coverage, an optimization model that considers network capacity and range is proposed to determine the optimal location of base stations to achieve a target coverage of smart meters. According to this preliminary results with a single access technology, we propose an evolved network architecture that considers several alternatives of wireless heterogeneous networks to guarantee the coverage to smart meters with the least use of resources. We introduce a heuristic model that involves elements from base stations, universal data aggregation points, number of smart meters, and an optimal routing to achieve the desired connectivity from the group of smart meters. We employ geo-referenced models to consider actual characteristics of cities as well as geographical conditions. Results from the evolved model demonstrates that by combining technologies and employing data aggregation points with optimized localizations, the network is able to achieve a target coverage of smart meters with a reduced cost in terms of technological resources.**

Keywords*—Advanced metering infrastructure, optimization, scalability, smart grids, routing, wireless heterogeneous networks.

I. Introduction

The Advanced Metering Infrastructure (AMI) in Smart Grid requires communication technologies able to support the large number of smart meters (SMs) deployed in both urban and rural scenarios. Accordingly, the wireless heterogeneous networks (WHN) have emerged as a candidate to provide the desired connectivity to the SMs [1]. Different from a traditional AMI network where only a single wireless technology (e.g., WiFi, IEEE 802.15.4g, GPRS/LTE) is employed for SMs' connectivity [2], [3], there are a plethora of technologies available in a heterogeneous architecture, hence, there should be an objective criteria or route map that allows to define the optimal use of resources in this new approach.

This work focuses on scenarios with different population densities where it is assumed each house has one SM installed. We introduce the wireless heterogeneous network architecture, which involves universal data aggregation points (UDAP) with multi-radio capabilities [4]. In this way, each UDAP may employ different wireless technologies and variable clustering capabilities to collect data from SMs [5],[6]. Therefore, thanks to the UDAPs, it is possible to reduce resources costs according to the number of houses with SMs to be covered. In addition, it also makes it possible to achieve a scalable deployment in the long run, according to the policies of Utility companies. Previous works propose clustering mechanism based for example in k-means [7] to create conglomerates. In this work we present an optimization process based on capacity and coverage, which is contrasted with simulations of a real scenario.

As illustrated in Fig. 1, the proposed architecture also considers multi-hop capabilities for routing traffic from the SMs to the UDAP. In this way, traffic from the SMs is concentrated in the closest UDAP with no need to incorporate cellular connectivity in each SM. Once the UDAP aggregates data from different SMs, a single aggregated packet will be sent to the closest base station (BS), hence reducing traffic overload in the cellular network, especially for dense deployments scenarios [8].

We present a heuristic model that solves the routing problem between SMs, UDAPs, and cellular BS, in order to obtain the optimal number and locations of UDAPs in the proposed WHN for AMI. In this way, we minimize the costs associated to the number of deployed UDAPs, but at the same time guaranteeing the coverage of the SMs. Different from other networks, such as wireless sensor networks, in AMI it is prevalent to guarantee coverage to be able to collect the readings from each SM, as well as to provide other services such as remote management (i.e., disconnection and reconnection), electric demand monitoring, failure detection in the distribution system, among others [9],[10].

The remainder of this paper is organized as follows. Section II elaborates on the concept of WHN in AMI and the proposed solution. Section III introduces the problem formulations and validations for a traditional AMI network model with only cellular connectivity. Section IV describes the optimization model proposed for the evolved AMI network with a wireless heterogeneous architecture and presents the performance analysis. Concluding remarks are presented in Section V.

E. Inga is with the Universidad Politécnica Salesiana, Quito, Ecuador, e-mail: einga@ups.edu.ec

S. Céspedes is with the Department of Electrical Engineering, Universidad de Chile, Santiago, Chile and with the Universidad Icesi, Cali, Colombia, email: scespedes@ing.uchile.cl

R. Hincapié is with the Universidad Pontificia Bolivariana, Medellín, Colombia, email: roberto.hincapie@upb.edu.co

C. A. Cárdenas is with the Universidad de Chile, Santiago, Chile, email: cesar.cardenas@ing.uchile.cl

[Fig. 1 about here.]

II. Wireless Heterogeneous Network for Advanced Metering Infrastructure

In order for the AMI to be considered an efficient and reliable component of the Smart Grid, it is necessary a guaranteed communication between SMs and Utility companies. Such a requirement involves important decisions both technical and economic that should be aligned to the goal of providing full coverage to the SMs, while considering variables such as customers geographic location, population density, and existing communication infrastructure that may help reduce connectivity costs, especially in the last mile [11].

In term of customers geographic location and population densities, in this work we are considering: *i)* urban scenarios with medium to high population densities, where it is required whether to expand the AMI based on pre-existent cellular communication infrastructure or to deploy a completely new communications infrastructure to support AMI traffic; and *ii)* rural scenarios with low population densities which may or may not have a pre-existent cellular communication infrastructure. With respect to the scalability of the proposed WHN, it is a requirement for the network to have a short deployment time, as well as the capability to guarantee coverage to the customers of the electric grid. An initial solution could consider the case in which SMs, depending on their location, connect to the closest cellular base station. Such a solution may meet the short deployment time, but given the expected number of SM clients, it will also require additional capabilities from the cellular network. Therefore, we proposed an intermediate entity, the UDAP, so as to minimize the load in the cellular network, at the same time that coverage is guaranteed to the SMs forming smaller clusters.

Furthermore, we consider the SMs may be equipped with wireless technology that also enables multi-hop connectivity. The multi-hop capacity in SMs has been previously considered to allow certain SMs to serve as a relay for other SMs that are out of range of the cellular network. However, capacity of a SM is limited, besides the fact that a single SM could become overloaded in serving a high number of out-of-range SMs at the same time that is trying to send its own traffic. Instead, we consider the additional UDAP entity, which would have a greater capacity than a SM, besides multi-radio capabilities and connectivity to the cellular infrastructure.

Considering the different configuration options depending on the available wireless technologies, it is necessary to define appropriate clusters of connectivity. In our case for example, we are considering that at least three different wireless technologies are available for connectivity of SMs and UDAPs. Moreover, since scalability of the AMI communications network has a close relationship with deployment and maintenance costs, there should be an optimal deployment that minimizes the number of resources when considering the combination of available wireless technologies and different technologies capacities. The aforementioned possibilities and restrictions makes it find the optimal network configuration a non-trivial problem.

In this work, we propose a scalable route map for a communication network that meets a short deployment time, with the least deployment costs, and that covers the largest number of clients according to a percentage of coverage defined by the Utility company. To solve the problem, we employ geo-referenced positioning in each scenario according to the capacity [12], coverage, and technology costs of the different network components: cellular base stations, universal data aggregation points, and smart meters.

Our objective is to identify the optimal planning conditions to obtain a scalable and efficient WHN for AMI. We employ theoretical models as well as simulations to characterize the different urban and rural deployment scenarios. The analysis provides the percentage of smart meters that have connectivity to the Utility's central office, as well as the number of resources that were required for a specific deployment or that will be required for a future deployment. In addition, we also provide a routing tree based on the Steiner Tree heuristic [13], [14], which is based on graph theory. With this, we are able to establish a routing graph between the different components employed to deploy the WHN. Therefore, in addition to determine the optimal locations of UDAPs, we also determine the interconnection of each SM to the UDAP and the corresponding path from each UDAP to the cellular base stations.

III. Problem Formulation - Single technology scenario

In a traditional AMI network a single communication technology is employed to connect the SMs to the Utility's office. In the scenario depicted in Fig. 1, it would be the case for which SMs connect directly to the cellular base stations. That could be a common case in a urban scenario where pre-existent infrastructure is available. The SMs traffic could for example share the network capacity with regular mobile users, or the Utility could become a virtual mobile operator that rents guaranteed capacity from another cellular operator while re-using existing infrastructure.

In this section, we explore the optimization of a scenario where a single cellular technology is employed for SMs connectivity. A model that optimizes the location of base stations according to their range and capacity is introduced and validated through simulations.

A. Optimization model for single technology scenario

This ILP optimization problem focuses in obtaining an optimal number and locations for cellular BS while considering restrictions in terms of coverage and capacity of each BS. To solve the problem, we first propose a set of feasible candidate locations from which we should be able to obtain the minimum number of BS that satisfies at least a given percentage of coverage of SMs. Each BS has a range of coverage according to the configuration parameters established by the network operator, as well as the maximum capacity of SMs that the BS is able to serve. In this model we do not consider interference from nearby BS, nor other impairments in the wireless channel.

The model considers the following parameters:

- A set of SMs with geo-referenced locations $U = \{u_1, u_2, ...u_N\}$.
- M candidate sites for locating the BS.

- A set of candidate sites $S = \{s_1, s_2, ..., s_M\}$, which provide the initial locations of BS and have been established in a geo-referenced map of the zone of interest.
- The position of the i^{th} candidate site is given by (xeb_i, yeb_i).
- The capacity C of a BS to connect a number of SMs simultaneously.
- The percentage P of customers to be served in a zone of interest.
- The number of covered SMs $\alpha_{i,j} \in \{0, 1\}$. If a SM j is covered by BS i, $\alpha_{i,j}$ is 1 and 0 otherwise.
- For each candidate site s_i we define $Z_i \in \{0, 1\}$, where Z_i is 1 if the candidate site is active and 0 otherwise.
- $X_{i,j}$ indicates if SM j is connected to BS i. $X_{i,j}$ is 1 if the connection exists, and 0 otherwise.

We formulate the optimization model with the following Objective Function:

$$\min \quad \sum_{i=1}^{M} Z_i \tag{1}$$

Eq. (1) intends to minimize the number of candidate sites that are active subject to: *i)* a relation between active sites and coverage to SMs, so that the condition is 1 if a SM is covered by at least one candidate site and 0 otherwise; *ii)* the capacity of the BS, so that a connection from a SM to a given BS is 1 if the BS has capacity to serve the node and 0 otherwise; *iii)* the requirement to cover at least a percentage P of SMs; and *iv)* the indication of a BS being active and to which SMs is connecting.

B. Performance evaluation

We have applied the aforementioned optimization model in a map that represents a real scenario. The number of deployed SMs is 384 in an area of 500m × 500m. The radio of coverage of each BS has been set to 500m. Two target percentages have been defined: 70% and 85%. The output from the optimization model should indicate the minimum number of BS required to cover such percentages, and also the geographical locations where they should be placed considering the SMs locations. The optimization method is MILP and has been solved with LPSolve in Matlab. Fig. 2a illustrates the numerical results from the model for an 85% of target coverage. In the case of a 70% target, the model indicates a single BS is enough to cover the area, however, in the second case, a single BS is not sufficient to provide the desired coverage, hence the model suggests to place the three BS observed in Fig. 2a.

[Fig. 2 about here.]

In order to validate the theoretical results, we have implemented the optimized scenario in the network simulator OMNeT++. The LTE network has been simulated with the package SimuLTE, which enables complex system level performance-evaluations of LTE and LTE Advanced networks (3GPP Release 8 and beyond) [15]. Two types of nodes have been defined, a SM node that generates traffic (i.e., consumption readings) over UDP, and the mobile user (UE) that generates voice over IP traffic. The locations of SMs and eNodeBs have been imported into the simulator to represent the same locations employed in the theoretical model. The SMs' locations have been placed following a Manhattan like grid over a reference map. In addition, different from the theoretical results, the network simulation accounts for physical layer and channel access characteristics of a typical LTE network.

The transmission power for each eNodeB has been set to the recommended 49dBm, and the propagation model follows the ITU-R Urban macro cell specification, with an expected eNodeB coverage of 500m. The channel model is Rayleigh with two noise levels: -101 dBm and -110 dBm. In terms of mobility, the SM nodes are stationary whereas mobile users follow a MassMobility model. The total number of SMs is 384, sending consumption readings of size 200KB every 30s to 10 minutes. On the other hand, the total number of UEs is 50, sending and receiving VoIP traffic with packet sizes of 40KB every 1ms.

Performance metrics were collected for both SMs and UEs, assuming the network is shared among users. In Fig. 2b we illustrate the coverage obtained after the simulation runs with the 85% target. We have tested two levels of noise, namely -101 dBm and -110 dBm. Only results for the latter are shown, however we discuss results from both. When employing the -101 dBm level, our results showed that the percentage of coverage falls under the expected: an actual 51% for the 70% target, and a 63% for an 85% target. However, when we reduce the noise level to -110 dBm, results show a coverage of 79% and 88% in each case, which are actually above the targets. The simulation results are consistent with the theoretical results if we consider that impairments from the wireless channel have not been included in the optimization model. Therefore, once we set better channel conditions with a reduced noise level, the percentages of coverage are close to the ones calculated by the optimization model.

In addition to verify coverage of the network, we have also extracted the packet delivery ratio (PDR) of SMs and UEs traffic. In Fig. 3 it is observed that for those SMs that achieve connection to the network, regardless of the noise level, there are no packet losses. This is the expected behavior considering the load from consumption readings should be small. However, when we observe the PDR from UEs traffic, only around a 30% and 50% PDR is achieved for each noise level. Hence, the quality of communications for the UEs decreases. Such reduction could be attributed to UEs mobility and propagation issues, but also due to network capacity sharing with traffic from the large number of SMs demanding resources from the network.

[Fig. 3 about here.]

The architecture and optimization model introduced in this section are useful in cases where the AMI network, supported by cellular communications between SMs and the Utility, is about to be deployed. In such a case, the optimized number and locations provided by the model would help reduce deployment costs. However, in cases where the cellular infrastructure already exists, there is little or non-flexibility that allows the re-allocation of BS, in addition to the performance issues that a shared capacity could mean to existent mobile users. In the following section we introduce a more flexible model based on a wireless heterogeneous network architecture.

IV. Problem Formulation - Wireless heterogeneous network scenario

Considering the disadvantages found with a single technology, in this section we address the wireless heterogeneous network architecture for AMI, and introduce a heuristic model to optimize the number and locations of UDAPs in a scenario that intends to be more flexible, scalable, and feasible to deploy than the single technology scenario.

A. Optimal Routing of Wireless Heterogeneous Networks

We propose a heuristic model that considers coverage, capacity (i.e., resources), and costs. The model should be able to generate a set of algorithms that meet requirements in terms of network size in an optimal or quasi-optimal way. The performance of the model is evaluated in terms of the efficiency when population densities vary, that means, in how well the model adapts the required resources (i.e., number of UDAPs) to different population sizes.

We employ the WHN described in Section II. Each UDAP connects a number of SMs, and the SMs may employ multi-hop connectivity up to a maximum of S hops. The geo-referenced candidate sites to install UDAPs are naturally placed in locations where lampposts are already installed (e.g., in street corners). We place all the elements, that is SMs (with random positions), BS, and candidate UDAPs, in an OSM map provided by OpenStreetMap. The distance among elements is calculated based on the Harvesine distance.

Our objective is to obtain a connectivity tree with the routing path required from each AMI component, in a way that coverage is provided for a number N of SMs, connected to a number M of UDAPs, and a number K of BS connecting each UDAP. We assume each UDAP has a capacity C, which may vary depending on the wireless technology that is being employed.

A minimum expansion tree model and the PRIM algorithm, both from graph theory, are employed to find the subset of edges that will form a tree with all the vertices. During the process, we introduce the restriction of the number of hops S. In each iteration, the algorithm is incrementing the size of the tree, starting from an initial UDAP vertex, and appending successive SMs vertices, so that the distances between UDAP and SMs are minimal. The distance supported should also depend on the wireless technology employed by each network element. Algorithms 1 and 2 describe the logic for this model, called the OPDWHN-AMI. The notations are presented in Table I.

[TABLE 1 about here.]

Once the PRIM stage is completed, we proceed to select the minimum number of UDAPs, so that the SMs are clustered according to the restrictions of capacity and number of hops. In order to solve this Set-Cover problem, we employ a greedy algorithm that allows us to select a quasi-optimal solution in each step, with the intention to achieve a general optimal solution. The objective is that the largest set of SMs are covered in a network with no loops.

Algorithm 1 $OPDWHN-AMI$ Optimal Planning for Deployment of Wireless Heterogeneous Networks on AMI

```
Step 1  Input: set 𝕀 of Internet
               set 𝕌 of UDAPs candidates, M = ||U||
               set 𝔹 of BS, K = ||B||
               set 𝕊 of SMs, N = ||S||
               parameter C_m, capacity of UDAPs
               Ns(j) = 0, ∀j ∈ {1, 2, ..., M}, Cov=0
Step 2  Output: Cov/||S|| , avg(Ns)
Step 3  forall U_j, j ∈ {1, ..., M}
            ψ_i = calculating − tree(U_j, S, C_m);
Step 4      U_r = SetCover(ψ_2, ψ_2, ...ψ_M)
Step 5      [nexthop, cost] = Dijkstra(G, I)
Step 6      forall SM ∈ S
            node = SM;
               while node ∈ S
                     node = nexthop(node)
               endwhile
                Ns(node) = Ns(node) + 1
               if node ∈ U
                    Cov + +
               endif
            endforall
        endforall
Step 7  return Cov/||S||
Step 8  return avg(Ns)
```

Algorithm 2 Function $\psi - calculating - tree(U_j, S, C_m)$

```
Step 1  Input: (U_j, S, C_m)
Step 2  Output: ψ
Step 3  Initialize: Nhop = 1, ψ = {Uj}
                    noCon = S
                    Ns(U_j) = ∅
Step 4  while ||ψ|| < C_m, && Nhops < Nhmax
            for  i ∈ ψ
                for  j ∈ noCon
                d = dist(i, j)
                if  d < dmin && Ns(i) + 1 ≤ Nhops
                 a = i, b = j, dmin = d
                endif
                endfor
            endfor
                if dmin <inf
                ψ = ψ ∪ {b}
                noCon = noCon \ {b}
                Ns(b) = Ns(a) + 1
                else
                Nhops = Nhops + 1
                endif
        endwhile
Step 5  return ψ
```

The final stage consists in finding the routing path between nodes subject to the restriction in terms of distances between network elements. To generate the minimum expansion tree, we employ the Steiner Tree: a heuristic applied to problems in combinatorial optimization. Our problem is defined as NP-complete: the search for the shortest distance between the set of UDAPs, SMs, and BS. We define a set of vertices V, a UDAP or SM vertex is introduced depending on their location and closeness to other SMs. In other words, the vertices (i.e., UDAP or SM) will be the Steiner points, and several Steiner trees are formed for the set of elements initially placed in the model. To calculate the shortest paths, we employ the Dijkstra heuristic, so that the costs matrix, which represents the distances, is used to find the trajectory from the Utility's central office up to each SM.

B. Performance evaluation

To evaluate the OPDWHN-AMI model, we implement the proposed heuristic in Matlab. To account for different population densities, we vary the number of SMs with N ={32 64 128 256 512}. Also, different capacities are considered for the UDAPs, C ={5 10 20 40}, and the total number of BS in a scenario is set to 3. Different from the scenario in Fig. 2, these scenarios account for real positioning of SMs using latitude and longitude coordinates over the map and calculating distances according to Haversine. Several iterations have been performed for the different combinations.

[Fig. 4 about here.]

Fig. 4 illustrates the geo-referenced map of an example scenario with $N = 128$. This is the result after all stages have been executed, including the Steiner Tree. In this final output, the model has defined the routing between the BS, the UDAPs, and the SMs. In the example we have set the capacity of each UDAP as $C = 20$. Note that, unless the distance between a given SM and the UDAP is less than the maximum, not all the SMs will be directly connected to a UDAP due to the multi-hop capabilities of the SMs.

A more general analysis of the OPDWHN-AMI performance with the different options is described as follows. Fig. 5a shows the load for each UDAP for all the possible capacities and population densities. When the number of SMs and the capacity are low, the load of each UDAP is also low; however, when the number of SMs increases and the capacity is low, the load of each UDAP barely increases. On the other hand, when C increases but also the number of SMs increases there is no substantial change in terms of UDAPs' load due to saturation. Therefore, regardless of how much C increases, the model reaches a constant load for each UDAP deployed in the map.

[Fig. 5 about here.]

We have also analyzed the coverage achieved by the model. In Fig. 5b, it can be observed that in order to achieve 100% coverage when C is low, the required number of SMs should be large enough to provide multi-hop connectivity, such is the case when the number of SMs is 256 or 512. It is also observed that for small populations and high UDAP capacity, there is no full connectivity to the SMs until the number of SMs is large enough to enable multi-hop connectivity.

The heuristic model obtains the number of pre-selected UDAPs based on the Set-cover and Greedy algorithms, after which the optimal number of UDAPs is obtained (Fig. 6). The final number of resources that were achieved by the model shows a reduction compared to the Greedy pre-selection of 29%, 32%, 18%, and 36% respectively, for each one of the proposed UDAP capacities, so the final cost of resources to achieve a total coverage of the AMI network can also be reduced.

[Fig. 6 about here.]

Results from this evolved model demonstrates that by combining wireless technologies and employing data aggregation points with optimized localizations, the network is able to achieve a target coverage of smart meters with a reduced cost in terms of deployment of technological resources.

V. Conclusions

In this work we have proposed a scalable routing model for a wireless heterogeneous network supporting the communications of the AMI in Smart Grid. The model defines the number of resources, clustering, and routing paths among the smart meters, the universal data aggregation points (UDAPs), and the cellular base stations that finally connect to the Utility's central office. We have provided comparisons with other models, in particular that in which a single wireless technology is employed to connect the smart meters. The results demonstrate that even for the case in which the single technology resources are optimized before deployment, our proposed model for Optimal Planning for Deployment of Wireless Heterogeneous Networks on AMI (OPDWHN-AMI) is better in defining the number of resources needed, the topology, and the costs for several possible scenarios that involve different population densities and geographical distribution of resources. With the OPDWHN-AMI model we have been able to determine aspects such as the number of UDAPs needed to guarantee a certain percentage of smart meters coverage, the best clustering for smart meters, the number of smart meters that can connect directly to UDAPs or to other smart meters in a multi-hop fashion, as well as the routing paths from the smart meters up to the Utility's office.

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References

[1] H. Guo, Y. Qian, K. Lu, and N. Moayeri, "Backbone construction for heterogeneous wireless ad hoc networks," in *2009 IEEE International Conference on Communications*, 2009, pp. 1–5.

[2] C. Shen and D. Pesch, "A heuristic relay positioning algorithm for heterogeneous wireless networks," in *VTC Spring 2009 - IEEE 69th Vehicular Technology Conference*, 2009, pp. 1–5.

[3] A. Aarthy, S. Brindha, and M. Meenakshi, "Power optimization in mobile stations using heterogeneous small cells for green cellular networks," in *2014 International Conference on Computer Communication and Informatics*, 2014, pp. 1–4.

[4] A. Ting, D. Chieng, K. H. Kwong, and I. Andonovic, "Optimization of heterogeneous multi-radio multi-hop rural wireless network," in *2012 IEEE 14th International Conference on Communication Technology*, 2012, pp. 1159–1165.

[5] Q.-D. Ho, Y. Gao, G. Rajalingham, and T. Le-Ngoc, "Performance and applicability of candidate routing protocols for smart grid's wireless mesh neighbor area networks," in *2014 IEEE International Conference on Communications (ICC)*, pp. 3682–3687.

[6] G. Rajalingham, Q.-D. Ho, and T. Le-Ngoc, "Evaluation of an efficient Smart Grid communication system at the neighbor area level," in *2014 IEEE 11th Consumer Communications and Networking Conference (CCNC)*, pp. 426–431.

[7] F. Aalamifar, G. N. Shirazi, M. Noori, and L. Lampe, "Cost-efficient data aggregation point placement for advanced metering infrastructure," in *Smart Grid Communications (SmartGridComm), 2014 IEEE International Conference on*, nov 2014, pp. 344–349.

[8] K. K. Gagneja and K. E. Nygard, "Heuristic clustering with secured routing in heterogeneous sensor networks," in *2013 IEEE International Workshop on Security and Privacy of Mobile, Wireless, and Sensor Networks (MWSN)*, 2013, pp. 9–16.

[9] E. Inga-Ortega, A. Peralta-Sevilla, R. C. Hincapie, F. Amaya, and I. T. Monroy, "Optimal dimensioning of fiwi networks over advanced metering infrastructure for the smart grid," in *2015 IEEE PES Innovative Smart Grid Technologies Latin America (ISGT LATAM)*, 2015, pp. 30–35.

[10] G. Rolim, D. Passos, I. Moraes, and C. Albuquerque, "Modelling the data aggregator positioning problem in smart grids," in *2015 IEEE International Conference on Computer and Information Technology; Ubiquitous Computing and Communications; Dependable, Autonomic and Secure Computing; Pervasive Intelligence and Computing*, 2015, pp. 632–639.

[11] G. Iyer, P. Agrawal, and R. Cardozo, "Analytic model and simulation study for network scalability in smart utility networks," in *2013 IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia)*, pp. 1–6.

[12] B. Lichtensteiger, B. Bjelajac, C. Müller, and C. Wietfeld, "Rf mesh systems for smart metering: system architecture and performance," in *2010 First IEEE International Conference on Smart Grid Communications (SmartGridComm)*, 2010, pp. 379–384.

[13] H. L. Nguyen and U. T. Nguyen, "Bandwidth efficient multicast routing in multi-channel multi-radio wireless mesh networks," in *International Conference on Ultra Modern Telecommunications & Workshops, 2009. ICUMT '09*, pp. 1–8.

[14] I. Senturk, K. Akkaya, and F. Senel, "An effective and scalable connectivity restoration heuristic for Mobile Sensor/Actor Networks," in *2012 IEEE Global Communications Conference (GLOBECOM)*, pp. 518–523.

[15] A. Virdis, G. Stea, and N. G., "Simulating LTE/LTE-Advanced Networks with SimuLTE," in *Simulation and Modeling Methodologies, Technologies and Applications*, M. Obaidat, J. Kacprzyk, T. Ören, and F. J., Eds. Springer, 2016, pp. 83–105.

Esteban Inga graduated from the Universidad Politécnica Salesiana; receive his M.Ed. degree in Education and Social development from the Universidad Tecnológica Equinoccial in 2008. He is currently working toward his Ph.D. degree in Engineering with the Universidad Pontificia Bolivariana, Medellín, Colombia and is the Coordinator of the GIREI Research Group. His research interests are in green communications, advanced metering infrastructure, smart grid, wireless heterogeneous networks, wireless network planning. He is a Professor of Universidad Politécnica Salesiana, Ecuador, and the Director of the Electrical Engineering Program.

Sandra Céspedes (S'09, M'12) received her B.Sc. (2003) and Specialization (2007) degrees in Telematics Engineering, and Management of Information Systems, from Universidad Icesi, Colombia, and a Ph.D. (2012) in Electrical and Computer Engineering from the University of Waterloo, Canada. She is an Assistant Professor with the Department of Electrical Engineering, Universidad de Chile, Santiago, Chile and an Adjunct Professor at Universidad Icesi, Cali, Colombia. She serves as an Associate Editor for the journal IET Communications. Her research focuses on the topics of vehicular communications systems, smart grid communications, and IPv6 integration and routing in the Internet of Things.

Roberto Hincapié received a B.S. degree in Electronic Engineering, a M.S. degree in Engineering, and a Ph.D. degree in Engineering from the Universidad Pontificia Bolivariana, Medellín, Colombia, in 1996, 2005, and 2009, respectively. He is currently an Assistant Professor of telecommunications engineering with the Universidad Pontificia Bolivariana and is the Director of the GIDATI Research Group. His work is based on mathematical modeling and simulation techniques. His research interests include resource allocation in wireless mesh networks, network planning, and tele-traffic engineering, with applications to quality of service and rural coverage.

Cesar Andy Cárdenas received a Systems Engineering degree from the Universidad Privada Telesup, Lima, Perú in 2011 and M.Eng. degree in Communication Networks at the Universidad de Chile, Chile in 2016. He has 5 years of experience in the industry of telecommunications with fixed and mobile telephony operators, mobile communications, VoIP, among others. His research interests include Smart grid networks and LTE.

LIST OF FIGURES

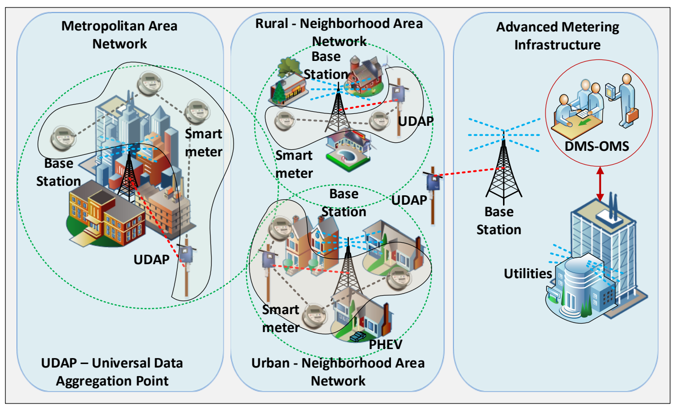
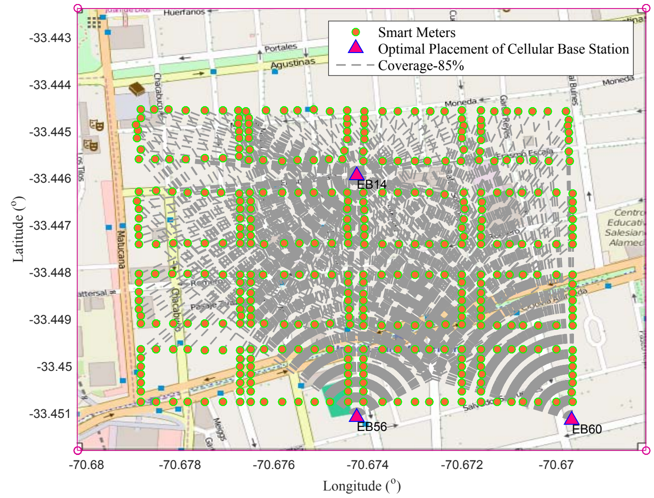
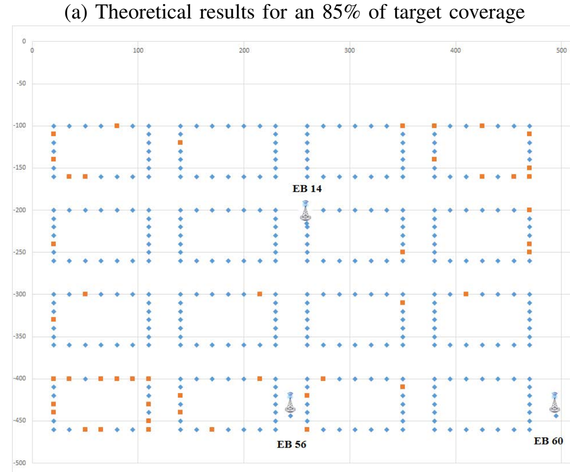


Fig. 1. Wireless heterogeneous network architecture for AMI



(a) Theoretical results for an 85% of target coverage



(b) Simulation results: achieved 88% coverage. Blue: connected SMs. Orange: disconnected SMs.

Fig. 2. Performance evaluation of optimal BS placement in a single technology AMI network

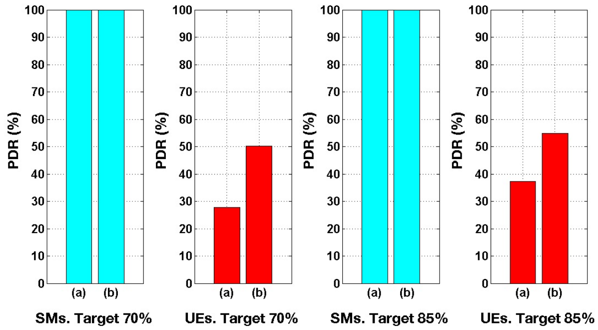


Fig. 3. Packet delivery ratio from Smart meters (green) and Mobile users (red) to central office. Noise levels (a)-101 dBm and (b)-110 dBm.

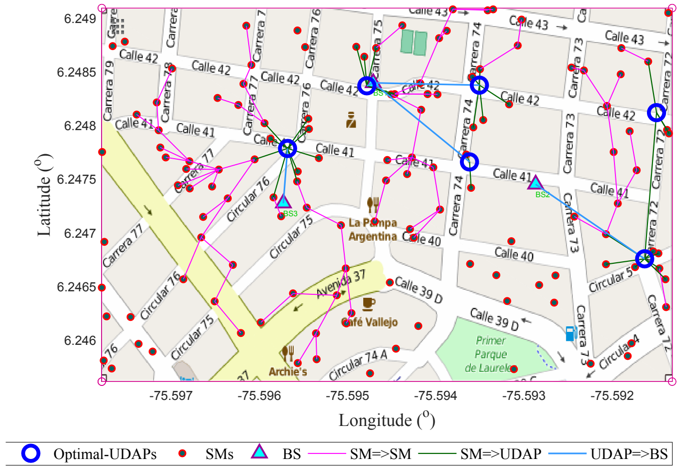
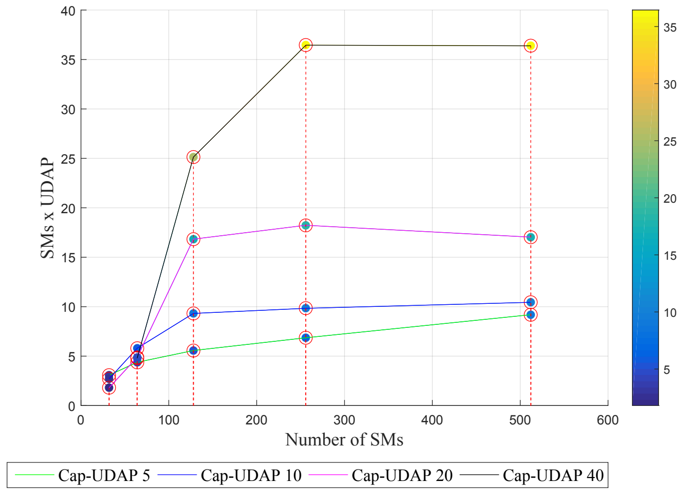
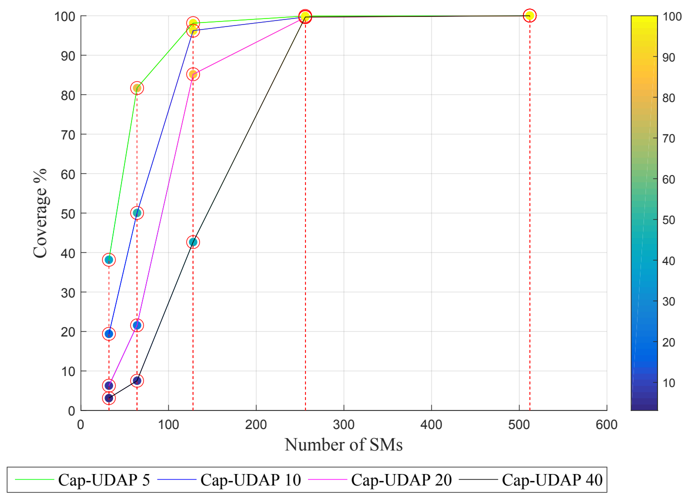


Fig. 4. Optimal number of UDAP, coverage 77%, $C = 20$



(a) Average load of UDAPs



(b) Coverage of SMs

Fig. 5. Load and coverage for different capacities and densities

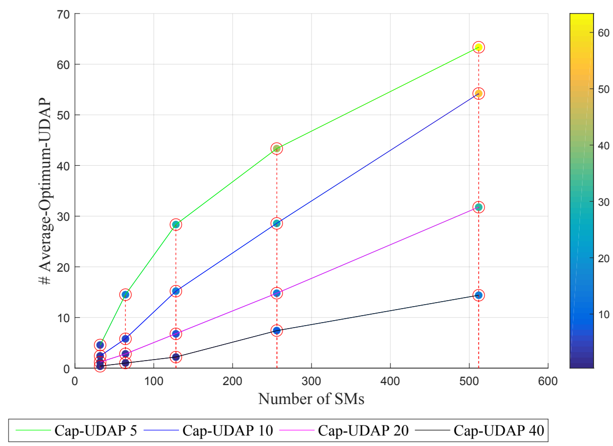


Fig. 6. Optimal number of UDAP

List of Tables

TABLE I. NOTATIONS-VARIABLES

$\mathbb{I}$	The set of internet
$\mathbb{B}$	The set of base stations (BS)
$\mathbb{U}$	The set of universal data aggregation points (UDAPs)
$\mathbb{S}$	The set of smart meters (SMs)
C_m	Capacity of UDAPs
G	Cost matrix
$dist$	Harvesine distance between resources
Cov	SMs covered
ψ	Steiner tree
U_r	Set Cover
Ns	Set of SMs connected
ψ_i	Set of SMs for UDAP, Direct; multihop
$noCon$	disconnected SMs
$Nhops$	Number of hops
$Nhmax$	Max hops
$dmin$	Minimal distance
a	Variable i
b	Variable j
U_j	Subset of U